Review of field studies of aircraft noise-induced sleep disturbance*

David S. Michaud
Consumer & Clinical Radiation Protection Bureau, Acoustics Division, Health Canada, Ottawa, Ontario, K1A 1C1 Canada

Sanford Fidell
Fidell Associates, 23139 Erwin Street, Woodland Hills, California 91367, USA

Karl Pearsons
Pearsons Psychoacoustics, 22689 Mulholland Drive, Woodland Hills, California 91364, USA

Kenneth C. Campbell
School of Psychology, University of Ottawa, Ottawa, Ontario, K1N 6N5 Canada

Stephen E. Keith
Consumer & Clinical Radiation Protection Bureau, Acoustics Division, Health Canada, Ottawa, Ontario, K1A 1C1 Canada

Aircraft noise-induced sleep disturbance (AN-ISD) is potentially among the more serious effects of aircraft noise on people. This literature review of recent field studies of AN-ISD finds that reliable generalization of findings to population-level effects is complicated by individual differences among subjects, methodological and analytic differences among studies, and predictive relationships that account for only a small fraction of the variance in the relationship between noise exposure and sleep disturbance. It is nonetheless apparent in the studied circumstances of residential exposure that sleep disturbance effects of nighttime aircraft noise intrusions are not dramatic on a per-event basis, and that linkages between outdoor aircraft noise exposure and sleep disturbance are tenuous. It is also apparent that AN-ISD occurs more often during later than earlier parts of the night; that indoor sound levels are more closely associated with sleep disturbance than outdoor measures; and that spontaneous awakenings, or awakenings attributable to nonaircraft indoor noises, occur more often than awakenings attributed to aircraft noise. Predictions of sleep disturbance due to aircraft noise should not be based on over-simplifications of the findings of the reviewed studies, and these reports should be treated with caution in developing regulatory policy for aircraft noise.

I. INTRODUCTION

Aircraft noise-induced sleep disturbance (AN-ISD) is often viewed as a potential public health hazard because common experience suggests that adequate sleep is essential to overall well being. Therefore, it is reasonable to explore whether the prevalence of AN-ISD can act as the basis for regulatory policy regarding tolerable levels of community exposure to aircraft noise. This paper reviews recent studies of aircraft noise and sleep to examine how they can be used to yield inferences about the prevalence of AN-ISD.

The effects of noise on sleep are mediated by many factors, including sound level, number, duration, time of occurrence, short- and long-term intermittency and consistency of

*Reprinted with permission, licence no. 1834801438285. Originally published. *Journal of the Aeroacoustical Society of America*, 121(1) 2007

distributions of aircraft noise intrusions into sleeping quarters. Uncertainty in estimates of at-ear aircraft noise levels and the degree to which noise events exceed at-ear background noise levels in sleeping quarters, as well as individual differences such as age, sex, noise sensitivity, sensitization and habituation, health status and the salience of intruding noises also affect the ability of aircraft noise to disturb sleep (Nordic Council of Ministers, 1994). Thus, it is challenging to summarize and predict population-level sleep disturbance by aircraft noise (Finegold and Elias, 2002; Anderson and Miller, 2005; Passchier-Vermeer, 2003). As is the case with efforts to predict other population-level environmental noise effects, the limitations and reliability of the underlying sleep disturbance data and interpretive methods merit close attention.

After a short review of sleep patterns and methods used for assessing them, this article focuses on findings of field studies of AN-ISD reported between 1990 and 2003. Information is reviewed about the ability of aircraft noise to (1) interfere with the ability to fall asleep, (2) curtail sleep duration, (3) lessen the perceived quality of sleep, (4) awaken people from sleep, and (5) increase bodily movements during sleep. Physiological changes associated with aircraft noise exposure, such as changes in stress hormone levels, are reviewed elsewhere (e.g., Health Canada, 2001). Laboratory findings are considered only to the extent that they relate to physiological costs of accumulated sleep debt, as it is unclear how sleep disturbance information collected in places other than familiar sleeping quarters can be generalized to in-home environments (Pearsons et al., 1995; Michaud et al., 2005), and recent field experiments provide direct information about in-home AN-ISD in any event.

II. CHARACTERIZATION OF DISTURBANCE OF SLEEP PATTERNS

Sleep cycles, as determined from polysomnography (PSG), typically last from 90 to 110 min and occur between four and six times during a full night. People cycle through lighter and deeper sleep stages throughout the night, with considerable individual differences in patterns from night to night. Electro-encephalographic (EEG) activity during sleep is classified with respect to the frequency and shape of wave forms into Stages 1, 2, 3, 4, and rapid eye movement (REM). Stage 1 is the lightest sleep. Deeper stages of sleep are associated with decreases in respiration and heart rates in Stages 2, 3, and 4. Since EEG wave forms during Stages 3 and 4 exhibit the lowest frequency, they are also referred to as slow wave sleep (SWS).

A typical night's sleep that is undisturbed by noise includes about 2 h of slow wave sleep, three quarters of which accumulate in the first half of the night. In contrast, REM sleep, which also lasts for about 2 h, occurs predominantly during the latter half of the night. Passchier-Vermeer et al. 2002, among others, suggested that REM sleep interruption is most likely to occur in the presence of continuous noise, while slow wave sleep interruption is more sensitive to intermittent noise intrusions, such as those produced by aircraft noise. Recovery from sleep loss is characterized by protracted periods of time spent in the stage of sleep that has been curtailed. Slow wave sleep is generally restored before other stages (De Gennaro et al., 2005). Awakening is more likely to occur from the REM stage of the ultradian non-REM/REM sleep cycle. People probably do not fully adapt to accumulated sleep debt (Dinges et al., 1997; van Dongen et al., 2003).

While people are capable of some degree of accommodation to a sleepdepriving schedule, a modicum of evidence suggests that cognitive functioning as measured by judgment, reaction time, and other tasks may remain impaired (Pilcher et al., 1996; Williamson et al., 2000; Harrison et al., 2000) despite apparent adaptation. While noise exposure can increase the likelihood of a shift from a deeper to a lighter sleep stage, spontaneous awakenings or shifts in body position often occur in the transition from SWS to Stage 1 or Stage 2 sleep, even in the absence of noise intrusions. Also, REM sleep may also terminate with an abrupt arousal or awakening. Arousals from sleep may be due to normal physiological processes, and can also serve functional purposes in calling attention to imminent danger. Bodily movements are a necessary means of relieving pressure points.

Although PSG remains the most sensitive means for assessing changes in sleep states, it has disadvantages of cost, intrusiveness to sleepers, and complexity of interpretation that limit its usefulness in field settings. Behaviorally confirmed awakening (BCA) as well as actimetry, both indirect behavioral measures of sleep, have become useful alternatives to PSG as field methods for assessing several aspects of sleep. (Rylander et al. 1972 and Horonjeff et al. 1982) demonstrated that subjects in familiar sleeping quarters can reliably push a button upon awakening for periods of many nights, and that their responses can be usefully related to nearby field measurements of nighttime noise levels, whether produced by aircraft or other noise sources.

An actimeter is a wristwatch-like device that detects and stores acceleration or motion in excess of user-defined thresholds within successive temporal “epochs.” Since people are more active during waking than sleep, actimetric data can be analyzed to infer values of sleep parameters from patterns of activity and inactivity. As a convenient and cost effective alternative to PSG, actimetry can provide reasonable measures of total sleep time, total wake time, and numbers of awakenings. Actimetry can also provide a useful approximation of “arousal” (originally a term that implied a shift from deeper sleep stages into lighter or Stage I sleep) that has been shown to be consistent with EEG-measured awakenings (Ollerhead et al., 1992).

Sleep actimetry cannot, however, yield information about time spent in different sleep stages, amounts of non-REM and REM sleep, or fragmentation due to brief arousals. Further, a high correlation between total sleep time defined by PSG criteria and total sleep time defined by actimetry can occur if actimetry overestimates total sleep time, as by misclassifying time awake without movement as sleep. Ancoli- Israel et al. (2003) suggested that actimetry is more likely to detect sleep than to detect wake states, leading to high sensitivity but low specificity and accuracy. Thus, correlations between PSG- and actimetrically defined sleep may not fully justify reliance on the simpler technique.

III. FINDINGS FROM RECENT FIELD STUDIES

Most recent field studies of AN-ISD have relied on actimetric, BCAs techniques and questionnaires to assess sleep disturbance due to nighttime aircraft noise exposure. Only one study (Horne et al., 1994) has attempted to cross validate actimetric with EEG information. All recent field studies included male and female adult subjects exposed to a range of nighttime aircraft noise levels. Not all of these studies were able to definitively attribute nighttime noise intrusions in sleeping quarters to aircraft. They are reviewed nonetheless, because reasonable analysis assumptions were made to support the

Table I. Comparison of methodological aspects of five recent field studies of aircraft noise-induced sleep disturbance

Reference	Sample size (Number of Subjects/ Subject-Nights)	Definition of Aircraft noise Events	Measurement Locations	Indications of Sleep Disturbance
Passchier-Vermeer *et al*. (2002)	418/4598	Time of occurrence of overflight as defined by airport noise monitoring system	Indoors and outdoors	Motility in 15 s epochs; questionnaire responses; reaction times
Ollerhead *et al*. (1992)	400/5742	Simultaneous outdoor A-weighted sound levels at several monitoring locations, checked against airport logs	Outdoors	Motility in 30 s epochs; limited EEG; sleep logs
Fidell *et al*. (1995a)	85/1887	A-weighted outdoor and indoor sound levels in excess of site-specific thresholds for more than 2 s	Indoors and outdoors	Behavioral awakening; questionnaire responses
Fidell *et al*. (1995b)	77/2717	A-weighted outdoor sound levels in excess of sitespecific thresholds 60 or 70 dB at different airports for more than 2 s; A-weighted indoor sound levels in excess of site-specific thresholds (50 or 60 dB at different airports) for more than 2 s	Indoors and outdoors	Behavioral awakening; two forms of motility in 30 s epochs; questionnaire responses
Fidell *et al*. (2000)	22/686 Indoor	A-weighted sound level in excess of 50 dB for 10 s; outdoor A-weighted sound level in excess of 60 dB for 10 s	Indoors and outdoors	Behavioral awakening; motility in 30 s epochs; questionnaire responses

inference that the sources of the noise events were very likely to have been aircraft. Aircraft noise levels were measured both indoors and outdoors in some studies, while noise levels in sleeping quarters were estimated in others by assuming typical structural noise reductions. In nearly all cases in which both indoor and outdoor sound measurements were made, outdoor sound levels failed to predict sleep disturbance. Table I summarizes the basic methods of each field study.

A. OLLERHEAD ET AL. (1992)

Ollerhead et al. (1992) and Hume et al. (2003) describe a large-scale study of awakenings and actimetrically monitored movements at two sites around each of Heathrow, Gatwick, Stansted and Manchester airports. The subjects at the eight sites included 211 female and 189 male residents between the ages of 20 and 70 years, sleeping in their own homes. Subjects completed sleep diaries and wore actimeters for 15 nights. The sleep of a subsample of subjects was also monitored with in-home EEG instrumentation (Hume et al., 2003). Outdoor noise measurements were taken of aircraft noise event data to link with actimetric data recorded in successive 30 s epochs. Responses collected by actimetry from the 50 subjects at each site were pooled and averaged for comparison with aircraft noise events for that site. The actimeter clocks remained synchronous within ±5 s. An aircraft noise event in the Ollerhead et al. study was defined as the occurrence of an outdoor sound in excess of a 60 dB threshold. The number of aircraft noise events during the night varied across the eight sites from 1 to 20.

The 400 subjects awakened from sleep 6457 times, of which 351 (5.4%) awakenings could be attributed to aircraft noise events. Awakenings attributable to aircraft noise events were far less common than those ascribed to toilet visits, tending to children, and other non-noise specific reasons. Sleep became more disturbed in general as the night progressed, but not necessarily because of exposure to aircraft noise events.

The main finding of Ollerhead et al. (1992) was that very few of the test subjects were at risk of substantial sleep loss due to aircraft noise. Ollerhead et al. (1992) noted that sleep was largely unaffected by aircraft noise events at outdoor L_{max} values lower than about 80 dB (SEL ~90 dB). Ollerhead et al. 1992 showed that above 90 dB SEL, the awakening rate due to an aircraft noise event was somewhere between 1 in 60 and 1 in 100. Ollerhead et al. (1992) attributed the infrequency of AN-ISD to the familiarity and adaptation of neighborhood residents to the noise source.

Although large variations in numbers of aircraft noise events were observed across the eight study locations, variability in actimetric responses was relatively small. Ollerhead et al. (1992) further noted that sensitivity to aircraft noise was lower during the earlier part of the sleep period than during the later part of the sleep period.

Ollerhead et al. (1992) also noted that individuals who classified themselves as most sensitive to noise were 2.5 times more likely to be awakened by an aircraft noise event than individuals who classified themselves as the least sensitive to noise.

B. FIDELL ET AL. (1995A, 1995B, 2000)

Fidell et al. 1995a reported a field study of 1 month duration in which simultaneous measurements were made of aircraft noise and sleep disturbance in the homes of 27 individuals living near the main runway of a military airfield, and of 35 subjects living near Los Angeles International Airport LAX. An additional 23 subjects living in neighborhoods without appreciable aircraft noise exposure served as controls. Among the 85 subjects, who ranged in age from 19 to 79 years of age, 38 were men and 47 were women. Subjects were instructed to press a bedside button upon awakening for any reason whatsoever. No actimetric or EEG measurements were made.

Noise measurements were taken outdoors in the vicinity of residents living near the two airport locations and within the bedrooms of each test participant. Average A-weighted sound levels were recorded every 2 s between 2200 and 0800 h. Each subject also completed an evening and morning questionnaire intended to assess subjective tiredness during the day, overall sleep quality, and recalled number of awakenings during the night, as well as their estimated time to fall asleep.

Fidell et al. (1995a) were able to attribute about 16% of the awakenings to noise events. For those awakenings that could be attributed to aircraft noise intrusions in sleeping quarters, each 1 dB increase in SEL increased the likelihood of awakening by only 0.17%. Like Ollerhead et al. (1992), Fidell et al. (1995a) observed that the likelihood of awakening due to a noise event, although not necessarily an aircraft noise event, increased throughout the sleep period. Fidell et al. (1995a) found an increase of a factor of 1.06 in the likelihood of awakening for each 15 min since retiring. Subjective reports of evening tiredness were related to awakenings by noise events.

Ambient noise levels in the bedrooms were inversely related to awakenings, such that the odds of awakening were reduced by a factor of 0.05 for each 1 dB increase in ambient noise levels. This finding resembles the observation of Passchier-Vermeer et al. (2002) (described below) that indoor average sound levels are inversely related to the probability of motility attributable to individual aircraft noise events. For an increase of one spontaneous awakening, Fidell et al. (1995a) showed that the probability of awakening due to a noise event was reduced by a factor of 0.26.

The mean indoor SEL that awakened subjects was 81 dB, while the mean indoor SEL that failed to awaken subjects was 74 dB. No change in the awakenings was observed when nighttime aircraft noise exposure at the military airfield was reduced by 6 dB (from L_{eq} 54 to 48 dB) over weekends. Fidell et al. (1995a) found that indoor SEL was the only reliable predictor of sleep disturbance within 2 and 5 min of a noise event. Although greater SEL values were associated with a greater likelihood of awakening to aircraft noise, the slope of the relationship was quite shallow: an increase of 10 dB in SEL was associated with only a 1.7% increase in awakenings. Cumulative noise exposure over the entire night did not predict sleep disturbance, and hence the study did not support adoption of L_{night} as a useful predictor of sleep disturbance.

Fidell et al. (1995b) reported another field study in which motility and BCA were used as indices of sleep disturbance. The venue for the second study was Denver, Colorado, where an opportunity was available to observe both the effect of reductions in aircraft noise on sleep among people living near Stapleton International Airport (DEN), which was scheduled to close, and the effect of increases in aircraft noise on sleep among people living near the new Denver International Airport (DIA), which was about to open. As in the prior study by these authors, simultaneous noise measurements were made both outdoors and in sleeping quarters. In total, 2717 subject nights of observations were made. Subjects ranged in age from young adults to the elderly, and were evenly distributed by gender.

In addition to subjective reports from evening and morning questionnaires, both actimetric and behavioral awakening measurements of sleep disturbance were made in 30 s epochs during three nighttime periods: 0100–0130, 0300–0330, and 0500–0530. The percentage of noise-induced behavioral awakenings increased 0.25% per 1 dB increase in indoor SEL. It was also found that for each increase of 1 dB in ambient L_{eq} levels, the actimetric and behavioral awakening responses due to noise events decreased by 2%–6%. Noise events were more likely to awaken men than women.

A statistically significant negative trend in behavioral awakenings was noted following the start of aircraft operations at DIA, despite a large increase in the number of indoor noise events. Prior to the opening of DIA, an average of 1.71 behavioral awakenings was observed per night. Following the opening of DIA, the average awakenings decreased to 1.13 per night. Average numbers of behavioral awakenings per night before (1.8) and after (1.64) the closing of DEN were not reliably different from one another. The similar number of awakenings per night may have been related to the failure of indoor noise levels to change appreciably, despite a decrease in outdoor levels from a nighttime L_{eq} of 58–46 dB.

The percentage of 30 s epochs containing actimetrically detected bodily movements ranged from 17% for noise events between 65 and 69 dB L_{max}

indoor to 31% for events between 70 and 74 dB L_{max} indoor. Considerable variability was observed between indoor L_{max} values and motility. Motility was greater than 17% for noise events when L_{max} was below 65 dB, but less than 31% for noise events when Lmax was higher than 74 dB.

Subsets of the subjects around DEN prior to its closure wore two types of actimeters. It was found that an actimeter of Swiss manufacture was more likely to detect motility 1.23% increase/dB increase in SEL with respect to a U.S. model 0.4% increase/dB increase in SEL. The probability of motility occurring within 5 min of a noise event was 0.90 Swiss model and 0.84 U.S. model for the indoor SEL. No such relationship with outdoor SEL values was reliably observed. The linear relationship between indoor SEL and the percentages of subjects exhibiting motility following a noise event was:

$$\% \text{ motility Swiss} = -23.74 + 1.23\text{SEL}, \quad (1)$$

$$\% \text{ motility U.S.} = 47.16 + 0.4\text{SEL}, \quad (2)$$

where applicable indoor SEL values are in the range of 50–100 dB.

Fidell et al. (2000) reported another pre/post study of the effects of aircraft noise on sleep in anticipation of an expected increase in air traffic at a general aviation airport DeKalb-Peachtree. Indoor and outdoor sound levels were again monitored in the sleeping quarters of 22 participants during a total of 686 subject nights before, during, and following the summer Olympic games in Atlanta. The number of noise events between 76 and 80 dB L_{max} increased slightly during the games. The number of events prior to the game in the range of 61–75 dB L_{max} was greater than during the games, but fewer following them.

Behaviorally confirmed awakenings were greatest (1.8 per night) prior to the games, and dropped slightly to 1.3 per night during the games, and to 1.0 per night following the games. Indoor SEL predicted actimetrically monitored arousals (at a 5% rate of increase per 10 dB increase in SEL), while outdoor SEL predicted behavioral awakenings (1.3% rate of increase per 10 dB increase in SEL). The variability in this response was greater at the higher outdoor SEL values, so that the prevalence of awakening at 100 dB ranged from 0% to 20%, but only from 0% to 2% at 60 dB. Even at high noise levels most people in this study were not awakened by aircraft overflights.

C. PASSCHIER-VERMEER ET AL., 2002

Passchier-Vermeer et al. (2002) reported a study of sleep disturbance conducted in the vicinity of Amsterdam's Schiphol Airport (AAS). Aircraft noise in this study was monitored within the bedrooms of 418 subjects and at several outdoor locations over an 11 day period. Aircraft noise exposure levels varied with distance from AAS. Subjects ranged in age from 18 to 81 years, and were evenly divided by gender. They answered morning and evening questions regarding sleep quality, recalled awakenings due to aircraft noise, and their annoyance due to aircraft noise. Motility was monitored throughout full 24 h days for the duration of the study. The wrist-mounted actimeter was also equipped with an event marker, which subjects pressed to indicate that they had been awakened. Subjects reported their subjective sleepiness at five designated time periods over the course of the day. They also performed a reaction time test intended to assess the effects of sleep loss on performance.

The effects of aircraft noise on sleep were assessed on "instantaneous," 24 h, and long-term time scales. For instantaneous effects, the probability of aircraft noise-induced motility (and onset of motility) was actimetrically measured during consecutive 15 s interval epochs and related to indoor L_{max} and SEL.[1] The authors defined aircraft noise-induced motility as movement occurring within any 15 s interval of an aircraft noise event and aircraft noise-induced onset of motility as movement within a 15 s epoch immediately following an interval in which movement had not occurred during an aircraft noise event.

The analysis of effects on a 24 h time scale included the sleep period time and the waking period after the overnight sleep period. In addition to the instantaneous measures, Passchier-Vermeer et al. (2002) examined perceived sleep quality, BCA, and questionnaire responses. Noise metrics of interest were the indoor equivalent aircraft sound level and the number of aircraft during sleep period time.

For the long-term time scale, the authors considered variables aggregated over the 11 nights of the study, including mean motility and responses obtained from morning questionnaires for this time scale. Noise metrics included indoor aircraft sound levels assessed over 11 sleep periods for individual subjects, and outdoor metrics representative of long-term nighttime aircraft noise exposure at 15 designated locations. The equivalent indoor aircraft sound level from 2300 to 0700 h was used to assess aircraft noise effects on responses to questionnaire items.

For the instantaneous effects, Passchier-Vermeer et al. (2002) found that aircraft noise events increased probabilities of both motility and onset of motility. The probability of motility increased with increasing indoor L_{max}, such that at 68 dB, the probability of motility during an aircraft noise event was about three times greater than the probability of motility in the absence of aircraft noise. The authors showed that an indoor L_{max} of 32 dB and an indoor SEL of 38 dB were the thresholds for increased probability of motility. The corresponding thresholds for probability of *onset* of motility were indoor L_{max} of 32 dB and indoor SEL of 40 dB.

Equations (3) through (6) from this study predicted motility and onset of motility during the 15 s epoch of an aircraft noise event, where the indoor L_{max} occurs

$$P(\text{motility}) = 0.00063(L_{max} - 32) + 0.0000314(L_{max} - 0.0000314)^2, \quad (3)$$

$$P(\text{motility}) = 0.000532(\text{SEL} - 38) + 0.0000268(\text{SEL} - 0.0000268)^2, \quad (4)$$

$$P(\text{onset of motility}) = 0.000415(L_{max} - 32) + 0.00000884(Lmax - 0.00000884)^2, \quad (5)$$

$$P(\text{onset of motility}) = 0.000273(\text{SEL} - 40) + 0.00000357(\text{SEL} - 0.00000357)^2, \quad (6)$$

where applicable indoor L_{max} values are in the range 32–70 dB for Eqs. (3) and (5). The applicable SEL values are in the range of 38–80 dB and 40–80 dB for Eqs. (4) and (6), respectively. Passchier-Vermeer et al. indicated that these L_{max} and SEL thresholds for increases in the probabilities of motility and onset of motility are about 15 dB lower than those estimated by Ollerhead et al. (1992). Passchier- Vermeer et al. also found that subjects indicated an awakening, by way of marker pressing, in 5951 of the 7 864 899 15 s epochs assessed in this study (i.e., 0.0757%). Of these marker presses, 763 (0.0807%) occurred during the 945 939 15 s epochs that coincided with an aircraft noise event and 5188 (0.075%) occurred during the 6 918 960 15 s epochs monitored outside of the aircraft noise event. This difference was reported to be statistically different using a 1 tailed test, at $p<0.05$.

Consistent with an observation

made by Fidell et al. (1995b), Passchier-Vermeer et al. (2002) found that the instantaneous measures were strongly influenced by the average equivalent indoor ambient sound level assessed over the 11 sleep periods. When indoor equivalent levels were low, the probability of motility due to aircraft noise was greater, especially at the higher L_{max} levels. This suggests that people accustomed to sleeping in quieter quarters may be more likely to experience motility when exposed to intruding noise than people who customarily sleep in noisier quarters. The authors also showed that the probability of motility increased as a function of time after sleep onset. After 7 h of sleep, aircraft noise was 1.3 times more likely to increase motility as at the start of the sleep period. Thus, the probability of motility was found to be greater at the end than at the beginning of the night. It is unknown whether this finding is related to sleep stage, and also why motility due to aircraft noise peaked at 46 years of age.

Factors that had no demonstrable effect on the instantaneous measures included the type of aircraft noise event (takeoff vs. landing), median sound level within the bedroom during sleep in the absence of aircraft noise, or the estimated equivalent indoor aircraft sound level from 2300 to 0700 h. Individual factors such as a subject's gender or attitude towards aircraft noise were not related to the extent of disturbance.

On a 24 h time scale, Passchier-Vermeer et al. (2002) observed a statistically significant increase in mean motility during sleep, number of BCA and number of recalled awakenings due to aircraft noise as a function of indoor equivalent aircraft sound level, and the number of aircraft during the sleep period time. Although statistically significant, the increase in BCAs and recalled awakenings was reported as being small. Mean motility over the night was higher: (1) when average noise within the bedroom not due to aircraft noise increased, (2) when the transmission loss from outdoors to indoors was low, (3) when subjects indicated a difficulty falling asleep due to aircraft noise, and (4) in subjects who attributed awakenings to aircraft noise exposure. Motility was 15% higher in subjects who recalled being awakened each night by aircraft noise compared to subjects that never indicated such an awakening. The study found that when aircraft noise was noted as the cause for difficulty in falling asleep (increasing sleep latency time), the delay to sleep onset was about 15 min.

While perceived sleep quality was reduced as mean motility increased, equivalent indoor aircraft sound levels and number of aircraft events were not statistically related to perceived sleep quality. Compared to mean motility and sleep latency time, perceived difficulty falling asleep had a stronger influence on perceived sleep quality, sleepiness during the waking state (i.e., fatigue), the number of subjectively recalled awakenings, and the number of BCA. Aircraft noise had a slight impact on self-reported sleepiness the following day at 1000 h, but not at any other time point. It should, however, be noted that 1000 h was the first sampling period and that it is entirely possible that results may have been different at earlier sampling times. Aircraft noise exposure at night did not have any statistically significant impact on the speed of responding as measured by the Wilkinson reaction time task. This simple cognitive task was conducted prior to retiring for bed and required the subject to button press as fast as possible following presentation of a visual stimulus.

Over the long term, it was found that when the average sound level within the bedroom over the 11 day study period due to aircraft noise increased, mean motility as determined over the 11 day period was also higher and sleep latency time was longer. Mean motility was also related to the frequency of recalled awakenings, BCA, the use of sleeping medication, self-reported sleep quality, the number of general sleep complaints, and the number of health complaints. The number of health complaints collected from the questionnaires at the end of the 11 day study period increased, regardless of age, from 2.5 to 4 on a scale from 0 to 13, if the average sound level in the bedroom due to aircraft noise increased from 5 to 35 dB during the sleep period over the 11 study days.

Difficulty falling asleep due to aircraft noise was reported in 12 of the 4600 subject nights (0.26%). On 21 occasions, subjects reported being awakened by aircraft noise at the end of the sleep period time (0.46%). During the nighttime, 159 (~2%) of reported awakenings were attributed to aircraft noise. Window position was altered 121 times during the nighttime and on 13 occasions (10.7%) the window was closed because of aircraft noise.

Subjects were asleep before 2300 h in about one-third of the study nights. However, there were only minor effects (~4%), from aircraft noise between 2300 and 2400 h, on endpoints such as motility, BCAs, and number of recalled awakenings. Between 0600 and 0700 h, in about 50% of subject nights, participants were still sleeping; however, aircraft noise at this time contributed about 27% of all effects and 27% of the aircraft noise events occurred within this time period. There was no association between outdoor aircraft noise metrics and aircraft noise-induced increase in the probability of motility.

IV. SUMMARY RELATIONSHIPS

The U.S. Federal Interagency Committee on Noise (FICON) proposed an interim dose-response curve in 1992 to predict the percentage of people that might be awakened by noise based on findings arising from both laboratory and field studies. Field studies published since 1992 have suggested that the prevalence of awakening in familiar sleeping quarters is considerably smaller than observed in the laboratory and the initial curve proposed by FICON likely overestimated awakenings in exposed populations (Pearsons et al., 1995).

Two relationships more recent than that of FICON summarized much of the behavioral awakening data described in this article. The first [shown in Eq. (7) and Fig. 1], developed by Powell but published by FICAN (1997), does not purport to be a dosage-effect relationship, but simply an upper limit on some of the behavioral awakening data. The FICAN relationship is not a formal policy position of the U.S. government, but a recommendation intended to protect the public from sleep disturbance in *any* degree.

Prevalence of Awakening due to individual aircraft noise intrusions = 0.0087 ¥ (SEL – 30)1.79, (7)

where applicable indoor SEL values are in the range of 40–110 dB.

The second of the post-FICON relationships, adopted by ANSI (2000), is the result of a regression analysis on a superset of the FICAN behavioral awakening data, as seen in Fig. 2 and in Eq. (8).

Prevalence of Awakening due to individual aircraft noise intrusions $= -7.02 + 0.14(SEL)$, (8)

where applicable indoor SEL values are in the range of 50–100 dB.

Neither the FICAN nor the ANSI relationship includes the findings of Passchier-Vermeer et al. (2002, 2003). Figure 3 revises the ANSI (2000) relationship by including the behavioral awakening data reported by Passchier-

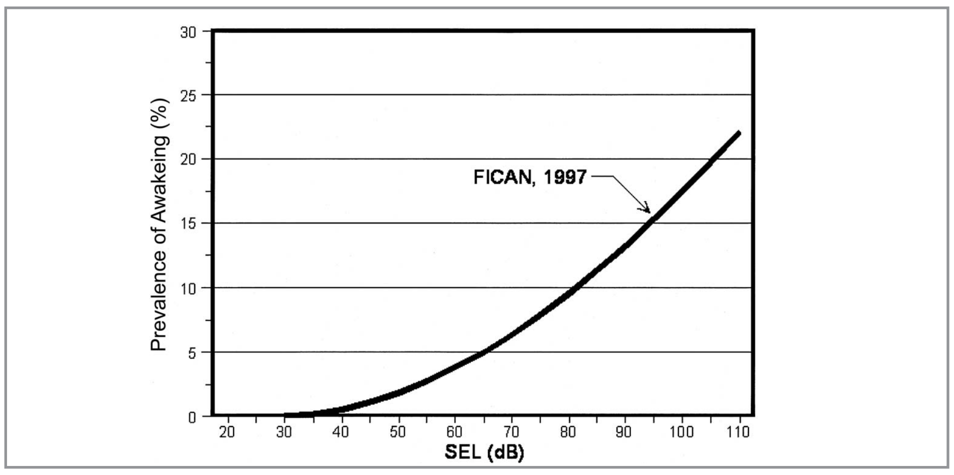

Figure 1. *Powell's analysis (FICAN, 1997) of upper limit of field observations of sleep disturbance as a function of indoor sound exposure levels.*

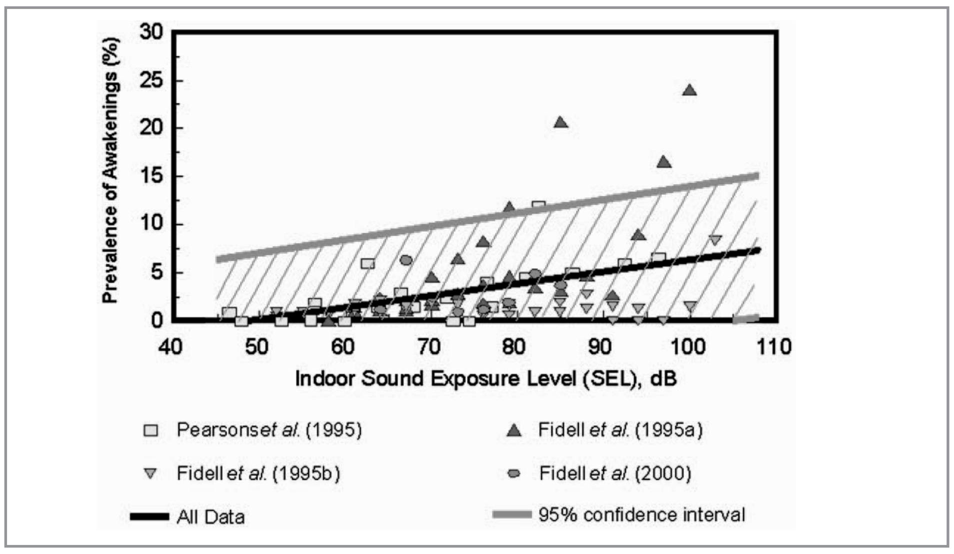

Figure 2. *ANSI S12.9-2000/Part 6 relationship between prevalence of awakening due to single aircraft noise intrusions and indoor sound exposure levels, with 95% confidence interval on prediction equation.*

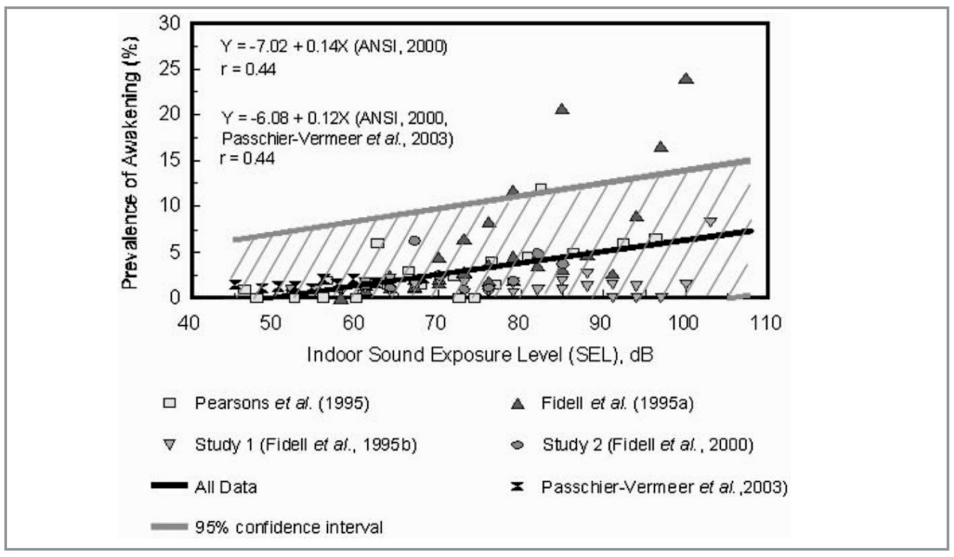

Figure 3. *ANSI S12.9-2000/Part 6 relationship and field data with observations of Passchier-Vermeer et al. 2003.*

Vermeer et al. (2002, 2003). The regression on the combined ANSI and Passchier-Vermeer data differs little from that of the ANSI standard, as shown in Eq. (9). Neither of these relationships accounts for as much as 20% of the variance in the relationship between indoor SEL and the prevalence of awakenings.

$$\text{Prevalence of Awakenings due to single aircraft noise intrusions} = -6.08 + 0.12(\text{SEL}), \quad (9)$$

where applicable indoor SEL values are in the range of 45–110 dB.

Figure 4 shows linear regressions between motility and indoor SEL for four studies, including one in which two different actimeters were employed. The figure also includes the ANSI relationship between awakening and indoor SEL for purposes of comparison. The regression equations for the four relationships between motility and indoor SEL may be found in Table II.

Although the summary relationships for the motility findings from the four studies all suggest at least a superficially greater sensitivity to indoor SEL than the ANSI (behavioral awakening) relationship, the motility findings of the various studies do not agree well with one another. This lack of agreement is probably due in large part to differences in details of measurement, analysis and definitions of "motility" and "onset of motility" in the various studies.

V. CONCLUSIONS

Table II summarizes the major findings of the reviewed studies. Findings about noise-induced sleep disturbance differ considerably both with respect to the measure of sleep disturbance motility or behavioral awakening, and by study. The findings of the reviewed studies are inconclusive about the effects of aircraft noise on changes in sleep states that do not result in awakenings. Neither behavioral awakening nor motility measurements are capable of detecting more subtle interference with sleep quality, such as brief changes in sleep stage or so-called "microarousals," that might also reflect a state of disrupted sleep.

On the other hand, the findings are in reasonable agreement with respect to several consequences of nighttime

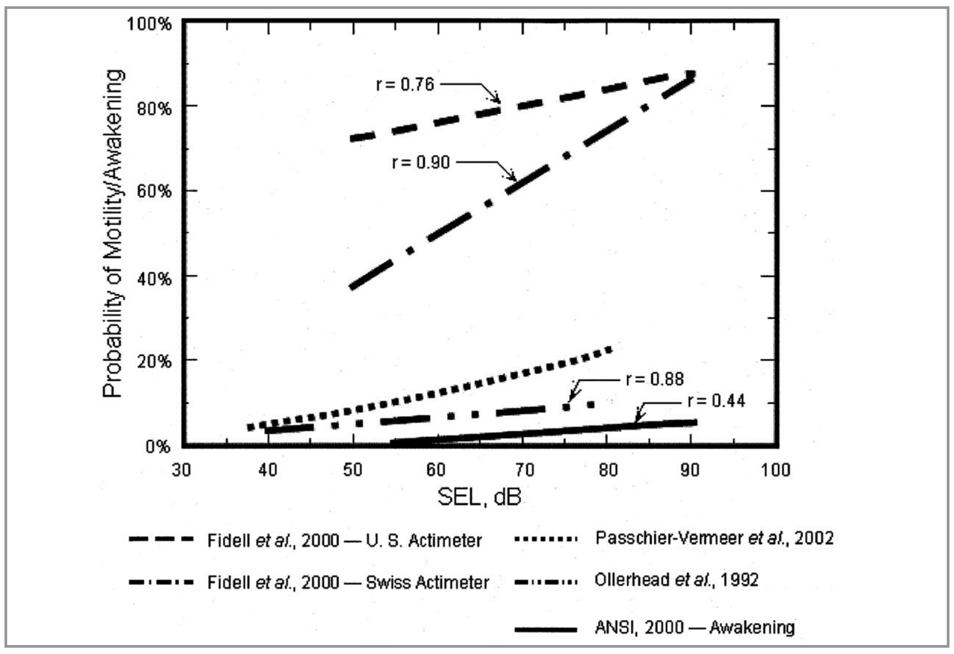

Figure 4. Functions relating motility to indoor sound exposure levels inferred from four field studies, in comparison with ANSI S12.9-2000/Part 6 awakening relationship.

Table II. Comparison of relationships inferred from five recent field studies of aircraft noise-induced sleep disturbance between indoor noise levels and arousal, motility, and awakening.

Reference	Prediction of arousal	Prediction of motility from noise events	Prediction of onset of motillity	Prediction of awaking
Passchier-Vermeer *et a*l. (2002, 2003)	Not applicable	P(motility)=0.00063(L_{max}-32)+0.0000314(L_{max} 0.0000314)^2	P(onset of motility)= 0.000415(L_{max}-32)+ 0.00000884(L_{max}- 0.00000884)^2	Prevalence of eventrelated awakening %=0.51+ 0.000353(SEL)^2
		P(motility)=0.000532(SEL -38)+0.0000268(SEL- 0.0000268)^2	P(onset of motility)= 0.000273(SEL-40)+ 0.00000357(SEL- 0.00000357)^2	(Note: Equation pertains to original data from Passchier-Vermeer *et al*. (2002) who recommend that prevalence of eventrelated awakening be reduced by 1.523% to obtain the prevalence of *aircraft* noise-induced, event- related awakening)
Ollerhead *et al*. (1992)	Not applicable	% of events leading to motility=-2.96+ 0.162(SEL)	Not applicable	Prevalence of eventrelated awakening % =0.4*[-2.96+ 0.162[(SEL)]
Fidell *et al*. 1995a	Not applicable	Not applicable	Not applicable	Prevalence of eventrelated awakening % =-10.24+0.167 (SEL)
Fidell *et al*. (1995b)	Prevalence of event-related arousal per Cole *et al*. (1992) (%)=1.306+0.279(SEL)	US actimeter: %of events leading to motility =47.16+0.4(SEL) Swiss actimeter: %of events leading to motility =-23.74+1.23(SEL)	Not applicable	Prevalence of eventrelated awakening % =-15.041+0.246(SEL)
Fidell *et al*. 2000 (incombination with Fidell, 1995a and b)	Prevalence of event-related arousal per Cole *et al*.(1992) % =4.579+0.218(SEL)	US actimeter: % of events leading to motility = 53.041+0.386(SEL)	Not applicable	Prevalence of eventrelated awakening % =-17.371+0.294(SEL)

aircraft noise in habitually exposed populations: Spontaneous that is, nonaircraft related awakenings are more common than aircraft noise-induced awakenings in airport neighborhoods; a small percentage of habitually exposed people are actually awakened from sleep by aircraft noise intrusions; and although AN-ISD increases as a function of time in bed, this observation is confounded by the fact that sleep in general becomes more easily disturbed, such that noise intrusions in the latter part of the night are more likely to disturb sleep than in the earlier part of the night.

A. NOISE MEASUREMENTS AS PREDICTORS OF SLEEP DISTURBANCE

The clearest and most consistent relationships between measurements of aircraft noise levels and sleep disturbance were observed between indoor sound levels and BCAs. Except in one case (Fidell *et al*., 1995b), neither long nor short term measures of outdoor noise levels were reliably associated with any measure of sleep disturbance.

One of the more consistent findings from the reviewed field studies was that a single event noise metric such as SEL or L_{max} could be used to describe the effect of aircraft noise on sleep. However, summary relationships between indoor SEL and the prevalence of awakening due to single aircraft noise intrusions have shallow slopes, and do not account for more than about 20% of the variance in the relationship between sleep disturbance and acoustic measures of aircraft noise exposure. As such, single event metrics do not by themselves provide robust guidance for regulatory purposes. Also, given the mediating factors for awakenings (e.g., time after sleep onset and ambient noise levels in sleeping quarters) the summary relationships between indoor SEL and awakenings should not be over-interpreted for other predictive purposes.

Regarding the effects of the totality of nighttime aircraft noise events on awakenings, Passchier-Vermeer et al. (2002) was the only reviewed study that showed a statistically significant relationship, albeit small, between subjective and objective measures of awakening and both the indoor equivalent sound level due to aircraft and the number of aircraft events.

Such practical limitations on interpretations of empirical findings about noise effects are not unique to aircraft noise and sleep disturbance. For example, Fidell and Silvati (2004) reviewed similar difficulties of interpretation of findings about noise-induced annoyance and complaints.

B. MOTILITY AS AN INDEX OF SLEEP DISTURBANCE

Motility may be a more sensitive measure of sleep disturbance than behavioral awakening, in that motility can be associated with indoor SELs of noise intrusions at lower levels than can awakenings. This may be too simple a characterization of motility as an indicator of noise-induced sleep disturbance, however. Relationships between indoor sound exposure levels and motility inferred in the reviewed studies are inconsistent with one another. Also, clock time, time after sleep onset, and ambient noise levels in the sleeping quarters also mediate the likelihood of noise-induced motility.

Interpretations of motility findings are complicated by methodological differences in their measurement. For example, Passchier-Vermeer et al. (2002) monitored motility in 15 s epochs, while Ollerhead et al. (1992) and Fidell et al. (1995a, 1995b, 2000) assessed motility in 30 s epochs. Analyses conducted in epochs of greater duration may underestimate the effect of AN-ISD as measured by onset of motility, especially for aircraft noise intrusions of greater SEL and hence, of potentially longer durations. In such cases, the onset of motility may occur in the interval prior to the L_{max} of a noise intrusion. Since the onset of motility might not be noted in a 30 s interval that includes the Lmax, onset of motility might be attributed to nonaircraft noise events rather than to an aircraft noise event.

The convenience of onset of motility as a metric of sleep disturbance for regulatory purposes is further hindered by its complexity of interpretation. It is conceivable, for example, that focusing on the *onset* of motility among those not yet disturbed by ongoing noise intrusions of long duration could lead to a perverse focus on the effects of noise intrusions on hardier sleepers – those not already awakened or otherwise disturbed by intruding noises of shorter duration or lower sound level.

ACKNOWLEDGMENTS

The authors extend their appreciation to Ken Hume, John Bradley, Larry Finegold, and Willy Passchier-Vermeer for their feedback on earlier drafts. Portions of this review have been presented by the senior author in "Aircraft noise and sleep disturbance: A review of field studies," Journal of the Canadian Acoustical Association Proceedings, Ottawa, Canada, October, 2004.

NOMENCLATURE

AAS	=	Amsterdam's Schiphol airport
AN-ISD	=	aircraft noise-induced sleep disturbance
BCA	=	behaviorally confirmed awakening
DEN	=	Stapleton international airport
DIA	=	Denver international airport
EEG	=	electroencephalographic
FICAN	=	U.S. federal interagency committee on aircraft noise
FICON	=	U.S. federal interagency committee on noise
LAX	=	Los Angeles international airport
PSG	=	polysomnography
REM	=	rapid eye movement
SEL	=	sound exposure level
SWS	=	slow wave sleep

[1]Indoor equivalent sound level of an aircraft noise event, normalized to 1 s, taken over the time interval that the aircraft sound level is greater than the indoor L_{max}-10 dB

REFERENCES

American National Standards Institute ANSI. (2000). "Quantities and procedures for description and measurement of environmental sound—Part 6: Methods for estimation of awakenings associated with aircraft noise events heard in homes," ANSI S12.9–2000/Part 6.

Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, W., and Pollak, C. P. (2003). "The role of actigraphy in the study of sleep and circadian rhythms," *Sleep* 26, 342–392.

Anderson, G. S., and Miller, N. P. (2005). "A pragmatic re-analysis of sleep disturbance data," *Noise-Con 2005*, Minneapolis, MN.

Cole, R., Kripke, D. F., Gruen, W., Mullaney, D., and Gillin, J. C. (1992). "Automatic sleep/wake identification from wrist activity," *Sleep* (N.Y). 15, 461–469.

De Gennaro, L., Vecchio, F., Ferrara, M., Curcio, G., Rossini, P. M., and Babiloni, C. (2005). "Antero-posterior functional coupling at sleep onset: Changes as a function of increased sleep pressure," *Brain Res. Bull*. 65, 133–140.

Dinges, D. F., Pack, F., Williams, K., Gillen, K. A., Powell, J. W., Ott, G. E., Aptowicz, C., and Pack, A. I. (1997). "Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night," *Sleep* 20, 267–267.

Federal Interagency Committee on Aviation Noise FICAN. (1997). "Effects of aviation noise on awakenings from sleep," http://www.fican.org/ pages/sleepdst.html (accessed on 08/30/2005).

Fidell, S., Pearsons, K., Tabachnick, B. G., Howe, R., Silvati, L. (1995a). "Field study of noise-induced sleep disturbance," *J. Acoust. Soc. Am.* 98, 1025–1033.

Fidell, S., Howe, R., Tabachnick, B. G., Pearsons, K., and Sneddon, M. (1995b). "Noise-induced sleep disturbance in residences near two civil airports," NASA Contractor Report No. 198252.

Fidell, S., Pearsons, K., Tabachnick, B. G., and Howe, R. (2000). "Effects on sleep disturbance of changes in aircraft noise near three airports," *J. Acoust. Soc. Am.* 107, 2535–2547.

Fidell, S., and Silvati, L. (2004). "Parsimonious alternatives to regression analysis for characterizing prevalence rates of aircraft noise annoyance," *Noise Control Eng. J.* 52, 56–68.

Finegold., L., and Elias, B. (2002). "A predictive model of noise induced awakenings from transportation noise sources," *Proceedings for the International Congress and Exposition on Noise Control Engineering*, N444.

Harrison, Y., and Home, J. A. (2000). "The impact of sleep deprivation on decision making: A review," *J. Exp. Psychol., Appl.* 6, 236–249.

Health Canada. (2001). "Noise from civilian aircraft in the vicinity of airports-Implications for human health 1. Noise, stress and cardiovascular disease," http://www.hc-sc.gc.ca/ewh-semt/pubs/noise-bruit/01hecssecs256/ index-e.html accessed on 10/30/2005.

Horne, J., Pankhurst, F., Reyner, L., Hume, K., and Diamond, I. (1994). "A field study of sleep disturbance: Effects of aircraft noise and other factors on 5,742 nights of actimetrically monitored sleep in a large subject sample," *Sleep* 17, 146–159.

Horonjeff, R., Fidell, S., Teffeteller, S., and Green, D. M. (1982). "Behavioral awakening as functions of duration and detectability of noise intrusions in the home," *J. Sound Vib.* 84, 327–336.

Hume, K., Van, F., and Watson, A. (2003). "Effects of aircraft noise on sleep: EEG-based measurements," TSO, UK, available at: http://www.cate.mmu.ac.uk/documents/Publications/CAAreport0603.pdf (accessed 08/08/2006).

Michaud, D. S., Miller, S., Ferrarotto, C., Konkle, A. T. M., Keith, S. E., and Campbell, K. C. (2005). "Waking levels of salivary biomarkers are altered following sleep in a lab with no further increase associated with simulated nighttime noise exposure," *Noise & Health* 8(29), 1–15.

Nordic Council of Ministers. (1994). Hygge, S. ed. "Health effects of community noise," Nordic Council of Ministers, Copenhagen.

Ollerhead, J. B., Jones, C. J., Cadoux, R. E., Woodley, A., Atkinson, B. J., Horne, J. A., Pankhurst, F., Reyner, L., Hume, K. I., Van, F., Watson, Al, Diamond, I. D., Egger, P., Holmes, D., and McKean, J. (1992). "Report of a field study of aircraft noise and sleep disturbance," Department of Safety, Environment and Engineering, Civil Aviation Authority, London.

Passchier-Vermeer, W., Vos, H., Steenbekkers, J., van der Ploeg, F., and Groothuis-Oudshoorn, K. (2002). "Sleep disturbance and aircraft noise exposure: Exposure-effect relationships," TNO Inro Report No. 2002.027, 1–245.

Passchier-Vermeer (2003). "Night-time noise events and awakening," TNO Inro Report No. 2003-32, 1–61.

Pearsons, K., Barber, D., Tabachnick, B. G., and Fidell, S. (1995). "Predicting noise-induced sleep disturbance," *J. Acoust. Soc. Am.* 97, 331–338.

Pilcher, J. J., and Huffcutt, A. I. 1996. "Effects of sleep deprivation on performance: A meta-analysis," *Sleep* 19, 318–326.

Rylander, R., Sorensen, S., and Berglund, K. 1972. "Sonic boom effects on sleep—a field experiment on military and civilian populations," *J. Sound Vib.* 24, 41–50.

van Dongen, H. P., Maislin, G., Mullington, J. M., and Dinges, D. F. 2003. "The cumulative cost of additional wakefulness: Dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation," *Sleep* 26, 117–126.

Williamson, A. M., and Feyer, A. M. 2000. "Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication," *Occup. Environ. Med.* 57, 649–655.