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ANIMA

Aviation Noise Impact Management through Novel Approaches

D3.2 Development of indicators for night noise protection zones

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[1] Use one of the following codes: R=Document, report (excluding the periodic and final reports)
DEM=Demonstrator, pilot, prototype, plan designs
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1. Executive Summary

Sleep is an active and extremely complex event in which a variety of physiological processes take place (e.g. protein biosynthesis, excretion of specific hormones, or the consolidation of memory contents). So sleep serves in the broadest sense as recovery and preparation for the next waking period. Undisturbed sleep of sufficient duration is therefore essential for maintaining psychomotor performance and health.

Nowadays, ‘sleep disturbance’ is the most obvious and immediate impact reaction due to environmental noise in the European Union. According to the World Health Organization (WHO) it currently causes the biggest loss of healthy life years (DALYs lost).

This underlines the importance of protecting airport residents from nocturnal aircraft noise. In almost all countries, nocturnal noise protection zones are defined solely on the basis of the energy equivalent continuous sound level L_{eq}. An acoustic averaging level like the L_{eq}, however, is inadequate as it does not reflect the human sleep physiology and therefore just can hardly protect airport residents from the harmful consequences of nocturnal aircraft noise (provided that it is not unrealistically low).

The present deliverable pursues the principle of minimizing acute effects (additional aircraft noise induced awakening reactions) so that long-term consequences (increased health risks) do not occur. For this aim, the analysis of the data from the currently only two worldwide available field studies on the impact of aircraft noise on sleep, that used the “gold standard” polysomnography for sleep and simultaneous acoustical measurements, have been improved and a pooled analysis was operated. The data were measured at one airport with continuous nocturnal aircraft noise (Cologne/Bonn) and at the other airport with a night flight ban between 11 pm and 5 am but very busy traffic in the shoulder hours (Frankfurt airport).

The results show that the probability to awake from an aircraft overflight (aircraft noise event) with the same maximum level in both cases just differs within the reasonable confidence intervals so that the results of the exposure-response function of the pooled data promise a fairly good transferability to other airports.

Having the aircraft type mix and the nocturnal flight schedule at an airport available, acousticians can calculate a maximum level distribution for the nocturnal aircraft noise events for outdoors, and, under some assumptions, also for indoors. Therefore, under consideration of the population data, for all areas around an airport the aircraft noise induced additional awakenings (= sum of awakening probabilities for all aircraft noise events in a night) can be calculated and illustrated in a map.

Aircraft noise annoyance of airport residents does not just depend on acoustic measures but also largely on non-acoustical factors like “Attitude towards the noise source”, “fairness aspects with regard to the distribution of noise and opportunities for participation in the planning process”, “the perceived health risk due to aircraft noise”, “satisfaction with the living environment” etc. These non-acoustical factors might differ from airport to airport and might also be temporally changeable. So far, it is not known that physiological body functions such as the awakening reaction also depend on these non-acoustical factors. This makes them particularly suitable for communicating the effects of nocturnal aircraft noise in a facile understandable metric for lay residents but also for policy makers. Trends of the aircraft noise development of the recent years can easily be shown. The metric “noise-induced awakenings" can also be used for planning purposes as e.g. when establishing future flight routes the sum of all aircraft noise-induced awakenings in the affected area has to be minimized.

In this deliverable, also considerations are reported how the aircraft noise- induced awakenings can be used in order to define night noise protection zones. Subsequently an outlook on future research needs is given.

2. Overview “Noise and Sleep”

Undisturbed sleep of sufficient length is a vital process for human beings providing the necessary daytime alertness, performance ability and health. Therefore it is very important for the general quality of life (Watson et al., 2015) and hence the night should be especially protected against sleep disturbing influences.

During sleep time human beings are usually unconscious. The ear, however, has an alerting function to prevent harm from possible ambient threats and therefore continually inspects the environment acoustically whilst sleeping. Within the last decades the growing need for mobility and transport of goods has led to increasing night noise which is potentially identified as such a threat by some individuals and can lead, amongst other outcomes, to disturbed sleep. The consequences of such interrupted sleep from transport noise can be classified as follows:

- immediate reactions can be additional awakenings, palpitations and reduced deep and Rapid Eye Movement (REM or ‘dream’) sleep during the night;
- short-term reactions the following day can be fatigue, lack of concentration and therefore a higher risk of accidents and a reduced quality of life perception;
- long-term consequences after years of permanent night traffic noise can be increased risks e.g. of high blood pressure, ischaemic heart diseases, dysfunction of blood vessels (Basner et al., 2017 (2)).

In particular, the connection between immediate and long-term effects is still completely unclear, since besides noise and the resulting immediate effects, a large number of confounders can lead to an increase in these disease risks after many years of exposure to noise. Both a reliable calculation of the perceived noise over many years and a nearly complete and accurate detection of the confounders is currently almost impossible, so that the long-term effects investigated by epidemiological studies must be content with approximations. This disadvantage can be partly compensated by averaging over very high case numbers.

Experimental studies to investigate the acute effects of noise at night, on the other hand, are usually very accurate in measuring the perceived noise and the physiological variables to be examined. The number of subjects, however, can usually only be limited due to the high study effort and associated budgets.

Schmidt et al. (2015) for the first time have demonstrated in such an experimental study on the acute effects of nocturnal aircraft noise which potential mechanisms could contribute to the development of cardiovascular diseases after many years of exposure to noise. However, significant major research efforts in this area will be needed in the future to understand the effects of long-term noise exposure on health.

Although there is not one single, generally accepted, definition of "healthy sleep", it is undisputed that disturbed nocturnal sleep leads to an increased risk of metabolic syndrome, associated coronary heart disease, hypertension and diabetes, as well as depression and mortality (Buysse, 2014). Shortened sleep is also associated with attention deficit / concentration disorders, important functions of sleep for the consolidation of memory contents (storage of experiences in long-term memory, solidification and separation of nerve connections) and disturbed sugar metabolism and immune system. A permanently reduced sleep time (usually defined as 7 hours or less) is associated with obesity, cardiovascular disease, diabetes, decline in cognitive performance, and mortality.

A concept for the protection of the population against noise at night must be designed in a way to avoid the immediate effects of noise, because according to current knowledge then also potential health risks will be minimized after many years of exposure. The strongest effect in human sleep to noise is the wake-up reaction and a concomitant greater sleep fragmentation. Effects such as changes in the total number of sleep stages at night are generally less pronounced (Basner et al., 2005).

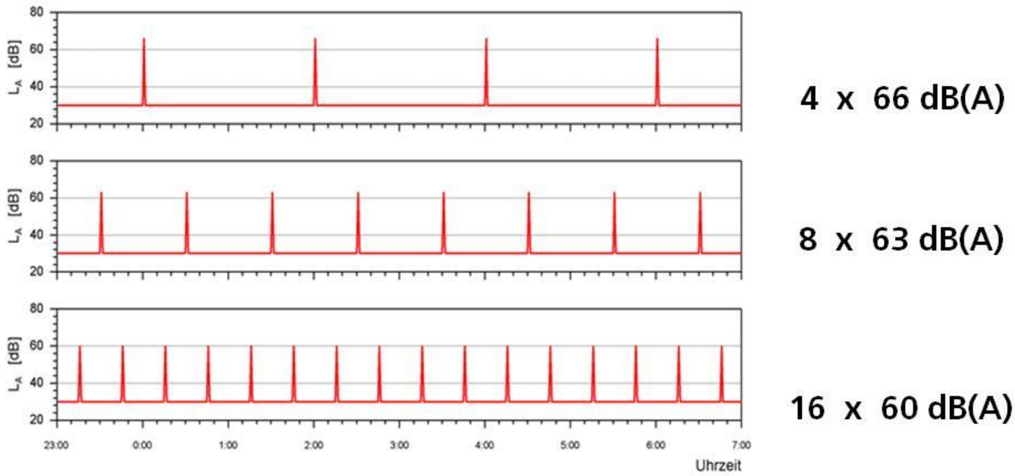

Figure 1 : 3 different aircraft night noise scenarios with the same indoor energy equivalent continuous sound level $L_{AS,eq}$ = 38.3 dB at the sleeper's ear. Reducing the maximum level of the aircraft noise events by 3 dB(A) leads to a doubling of the number at the same $L_{AS,eq}$

In order to report transport-noise induced annoyance the habitually employed acoustical metric is the energy equivalent noise level L_{eq} or its derivatives L_{dn} or L_{den}. Figure 1 highlights why this might not be optimal for describing single event noise effects on sleep. In this figure three different aircraft night noise scenarios are illustrated which have the same indoor energy equivalent level $L_{AS,eq}$ = 38.3 dB, measured at the sleeper's ear. Reducing the maximum level of each aircraft noise event by 3 dB(A) (which is half of the physical sound energy but normally only a much greater reduction of up to 10 dB(A) would be required to be perceived as half as loud by the human ear) permits a doubling of the number of aircraft noise events at the same $L_{AS,eq}$. From Figure 1 it is already intuitively obvious that an L_{eq} is not an adequate metric to describe transport noise effects on sleep and therefore not eligible for developping a nocturnal protection concept against aircraft noise (provided that it is not unrealistically low).

The human organism in sleep reacts to the single noise event (overflight) which must be therefore characterized by corresponding acoustic quantities (e.g., maximum level, SEL, etc., see Porter et al., 2000). The probabilities of awakening for such single aircraft noise events must then be summed up over all nocturnal aircraft noise events to determine the additional noise-induced wake-up reactions at night (a probability of awakening of 100% means one additional aircraft noise induced awakening).

In a protection concept the number of these additional aircraft-noise-related wake-up reactions must then be limited.

A comprehensive sleep survey, however, does not just include the measurement of physiological body functions, but also records the subjective perception of sleep. An optimal sleep quality implies both, an objectively measured undisturbed sleep of sufficient length and positive subjective sleep ratings.

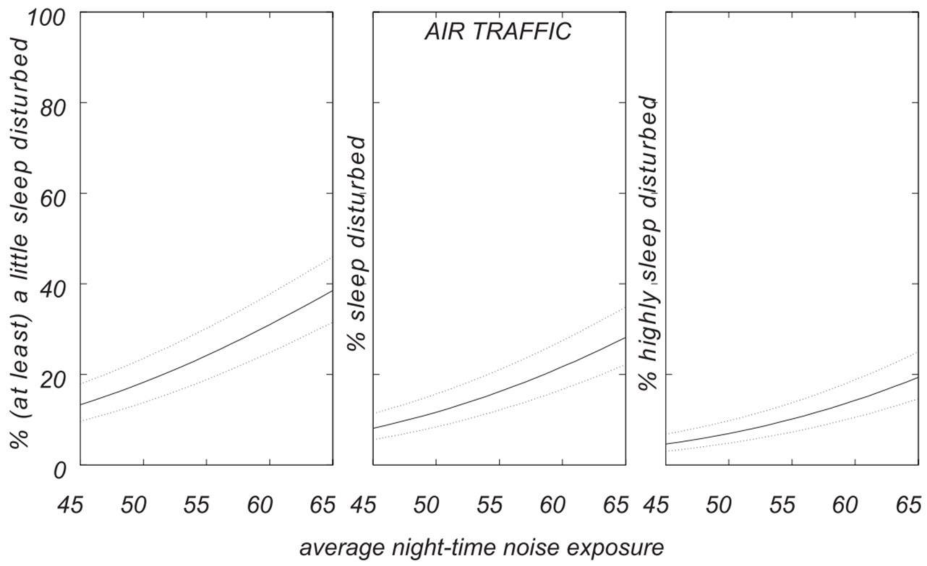

Figure 2: The functions specify three sleep disturbance measures (solid lines) in relation to the average night-time exposure outside at most exposed façade, and their 95% confidence intervals (broken lines) for air traffic (Source: Miedema et al., 2007).

Due to the fact that humans are mostly unconscious during sleep, subjective sleep assessments do not necessarily agree with the objective measurements though. The subjective assessment usually includes questionnaires about number of (noise-induced) awakenings, time to fall asleep, general sleep quality etc. As for annoyance surveys (see e.g. Guski et al., 2017), these assessments can be confounded by non-acoustical factors, for example, attitude towards the noise source, procedural fairness in processes relating to the noise source, or simply to make a political statement. This also means that the results of such studies can vary from airport to airport and might presumably also fluctuate over time.

Since assessments using questionnaires are relatively cheap and easy to implement, there are numerous published examples which have been used for calculating 'mean' exposure-response curves of 'at least a little sleep disturbed', 'sleep disturbed' and 'highly sleep disturbed' people over an energy equivalent noise level $L_{eqNight}$ (Miedema et al, 2007, Figure 2) neglecting the problem that those 'mean' levels, if not unrealistically low, are not really suitable for communication or protection purposes for noise effects on sleep as many different noise situations lead to the same L_{eq} but have different effects on sleep. The World Health Organization recommends in its 2018 "Environmental Noise Guidelines for the European Region" an L_{Night} of 40 dB(A) for aircraft due to the number of 'Highly Sleep Disturbed people' (HSD), assessed by questionnaires (WHO, 2018). In reality a Boeing 747 on take-off with a distance of 10 km from the runway, 600 m height, one movement per 8 hours already would lead to an L_{Night} of 51 dB(A), or for an Airbus 320, 10 km distance from the runway on take-off, 770 m height, eight movements per 8 hours would lead to an L_{Night} of 50 dB(A).

With this information in mind, however, in order to develop a night noise protection concept it seems very advisable to revert to objective sleep assessment techniques that mainly depend on acoustical factors, consider the single noise events during sleep time and avoid the influence of potential non-acoustic influences over months or years. Measuring the 'objective' physiological body reactions could do that although the assessment is much more complex and laborious.

The 'gold standard' in clinical research for studying sleep is the multi-parametric polysomnography technique (Perron et al., 2012). It consists of a continuous monitoring of the Electroencephalography (EEG, electrical activity of the brain), Electrocardiography (ECG, electrical activity of the heart), Electrooculography (EOG, eye movements) and Electromyography (EMG, electrical activity by skeletal muscles) (Iber et al., 2004).

If the sound pressure level and the sound itself are continuously recorded at the same time as the sleep data, these controlled experimental studies allow a very exact event-related evaluation at any time during the night. Then it is possible to build up an optimal statistical model, sorting out all relevant acoustical measures (e.g. L_{ASmax}, SEL, level rise time, noise length), sleep measures (e.g. previously passed sleep duration, sleep stage before noise event, time spent in sleep stage before noise event) and personal parameters (age, gender), providing an exposure-response function that delivers the probability to awake for every noise event dependent on its maximum sound pressure level (Figure 3).

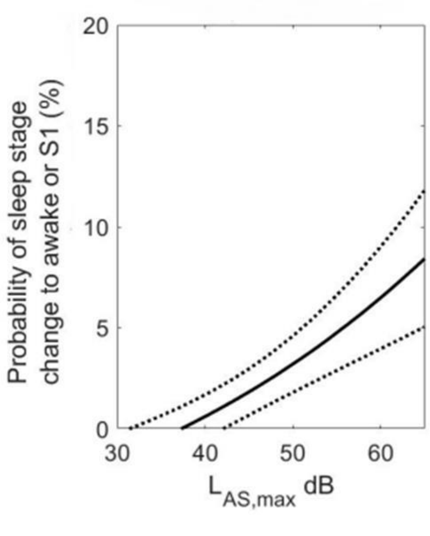

Figure 3: Probability of additional sleep stage changes to awake or S1 in a 90 s time window following noise event onset depending on the maximum indoor sound pressure level ($L_{AS,max}$) for aircraft (STRAIN study, N = 61). 95% confidence intervals (dashed lines). Results are for the unadjusted model. (Source: Basner et al., 2018).

These additional noise-induced awakenings per night can be calculated for every household around an airport and are easy to understand by laypersons like e.g. residents. They are currently used in the Zurich Aircraft noise ZFI and Frankfurt night noise index FNI since 2006 resp. 2007 in order to communicate the nocturnal aircraft noise development over the years and for the development of a night noise protection concept at airport Leipzig/Halle in 2007 (Brink et al., 2010; Basner et al., 2006).

The investigation methodology demands that only subjects without any inherent sleep disorders and without any diseases which have side effects on sleep are examined. Otherwise any sleep effects during an aircraft noise event and total sleep quality parameters couldn't unambiguously inferred. The high time and cost expenses of these kind of experimental studies also just allow the examination of subjects in the two- to lower three-digit number range of subjects per study. These limitations should be kept in mind.

Therefore, especially when developing night noise protection concepts, additional assumptions must be made in order to protect also vulnerable groups of residents. Ecologically valid data for such night noise protection concepts also require that they have been collected in field studies within the residents' home environment.

Due to the very complex examination method, there are just very few research groups worldwide that investigate the effects of noise on sleep by means of polysomnography and provide exposure-response functions. A literature review by the World Health Organization WHO "WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep" (Basner et al., 2018) for the years 2000-2014 found only one field study on the effects of aircraft noise on sleep providing necessary data for the development of a night-protection concept. This was the STRAIN (STudy on human Response on AIrcraft Noise, Figure 3, Basner et al., 2006) study of the German Aerospace Center DLR, realized in 2001 to 2002 around Cologne/Bonn Airport (Germany) which is characterized by a lot of night time traffic.

In this ANIMA Deliverable 3.2, the data of the STRAIN study will be newly analyzed with additional acoustic metrics (Chapter 4) which significantly improved the published model (Basner et al., 2006) and compared to the sleep data of the NORAH (Noise-Related Annoyance, Cognition, and Health) study from the year 2012 around Frankfurt airport (Müller et al., 2015) which used the same methodology like in the STRAIN study. In Frankfurt airport there are high numbers of movements around the night flight ban from 11 pm to 5 am. Also these NORAH data were analysed and improved for this D3.2 with additional acoustic metrics. **A common model will then be firstly presented here.**

Beyond that, the German Aerospace Center recently finished a field study on the effects of aircraft noise around Cologne Airport on the sleep of 8-10 year old children using again the complex polysomnography methodology. Results of this study are not published yet, but first results can be reported here anecdotally.

Within the last years, additional attempts have been made to increase the number of subjects in those field studies at constant costs by simplifying the methods to detect awakenings. Awakenings often go along with a heart rate increase and body movements. So these ECG and actimetry measures have been validated in the NORAH sleep study around Frankfurt Airport 2011-2015 with polysomnography data. First results indicate that these vegetative-motoric measures might be a bit more sensitive than EEG awakenings. This simplified method then has been used in a pilot study around Philadelphia airport by the University of Pennsylvania (McGuire et al., 2014; Müller et al., 2015; Basner et al., 2017). Further studies in the U.S. are envisaged.

3. Methodology

For the upcoming analysis on calculating an exposure-response function for the awakening probability of aircraft noise (Chapter 4) the worldwide two only available field studies providing ecological-valid polysomnographic sleep data will be considered. Both studies were operated by the German Aerospace Center DLR and used nearly the same methodology which is introduced in this Chapter 3. Any methodological differences will be mentioned when characterizing the data sets in Chapter 4.1.1 resp. Chapter 4.2.1.

3.1 Sleep

Sleep quality, duration and wake-up reactions in scientific studies have been measured so far by pressing push-buttons, questionnaires, actigraphy and polysomnography. As e.g. for detecting awakenings these methods considerable differ in terms of positive-predictive value, usability, ease of analysis and costs, it turns out that only the polysomnography is been regarded as having a high positive-predictive value among these methods (Perron et al., 2012). Polysomnography is also called the “gold standard” in clinical sleep research. Due to the fact that only polysomnography measures can guarantee a high quality basis for the development of an aircraft night noise protection concept, will be referred to hereinafter only on this method.

3.1.1 Polysomnography

The polysomnography includes the recording of the EEG (electroencephalography = brain activity), the eye movements (electrooculography = EOG) and the muscle activity (electromyography = EMG) for the evaluation of sleep in quantity and quality. In order to derive the sleep EEG, electrodes are glued to the scalp and face at predetermined positions (Figure 4).

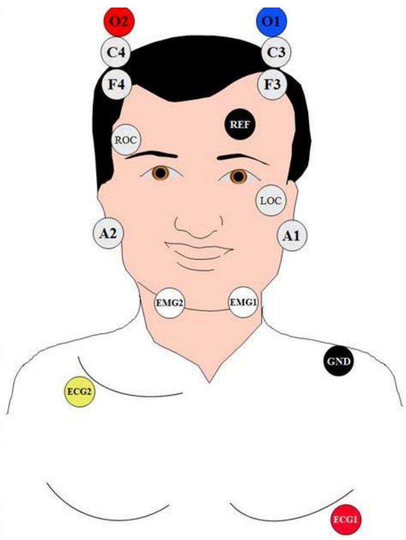

Figure 4: Schematic representation of the electrode positioning for the measurement of polysomnography

Thus, the electrical surface activity of the brain in the form of potential fluctuations can be continuously displayed. During sleep, the amplitude and frequency of the wave patterns in the EEG, the type of eye movements and the muscle activity typically change and allow the division into five sleep stages and the stage awake. In the relaxed wakeful state, brain activity shows a low-amplitude and high-frequency rhythm. The sleep state is divided into four stages S1-S4, whereas S1 and S2 characterize the light sleep, S3 and S4 the deep sleep (Rechtschaffen et al., 1968). Nowadays S3 and S4 are also often summarized to one deep sleep stage.

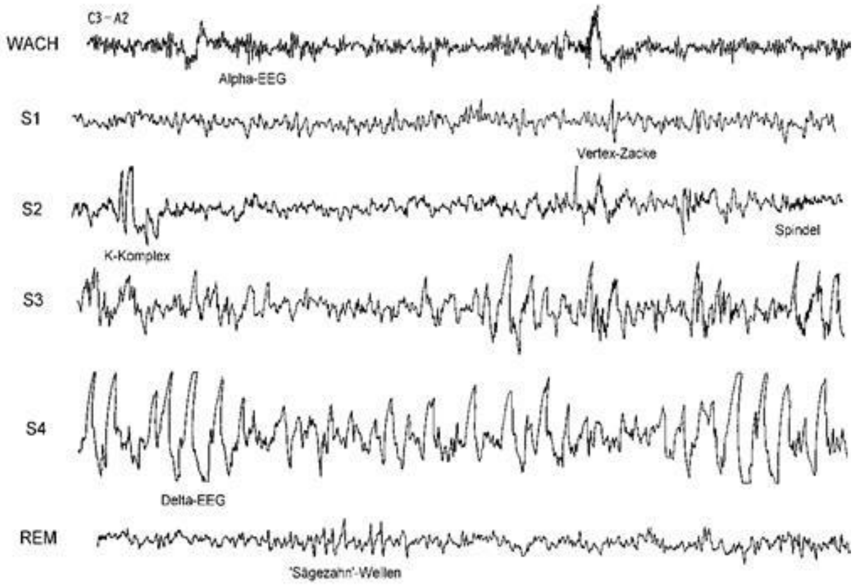

Figure 5: Sleep Stage Classification: Excerpt from (Rechtschaffen et al., 1968).

In the deeper sleep stages, the amplitude of brain activity increases and the frequency slows down. For deep sleep, for example, particularly slow waves are characteristic, which are referred to as delta waves (≥ 75 µV,> 500 ms). REM (Rapid Eye Movement) sleep plays a special role. It is characterized by a low-amplitude mixed-frequency EEG in which sawtooth wave patterns can occur. Muscle tone is extremely low with the exception of short-term phasic activations. Fast conjugated eye movements are typical of REM sleep. Figure 5 illustrates typical characteristics of each sleep stage.

Preparing subjects for the measurements before going to bed nearly takes an hour by trained personnel, detaching the electrodes after awaking takes around 25 min (Figure 6). The method is slightly invasive and subjects on the first night might sleep a bit worse than usual. Therefore the first night should serve as an adaption night and not be used for analysis.

Figure 6: Preparing subjects for polysomnographic recordings

The evaluation of the polysomnographic data has to be visually rated by trained personnel and per default in 30s - epochs (Rechtschaffen et al., 1968), which can lead to a certain inter-rater variability, especially for the deep sleep stages (Danker-Hopfe et al., 2009). In this way, it is possible to provide a total overview of the night called the hypnogram (Figure 7). Due to the high manpower required by both the application of the electrodes and the subsequent manual assessment of sleep, polysomnography is time-consuming and expensive, making it difficult to use outside the sleep laboratory and limiting the number of subjects studied. But, on the other hand, the use of polysomnography in a field study, e.g. at home of the subjects, allows the recording of sleep with a high ecological validity.

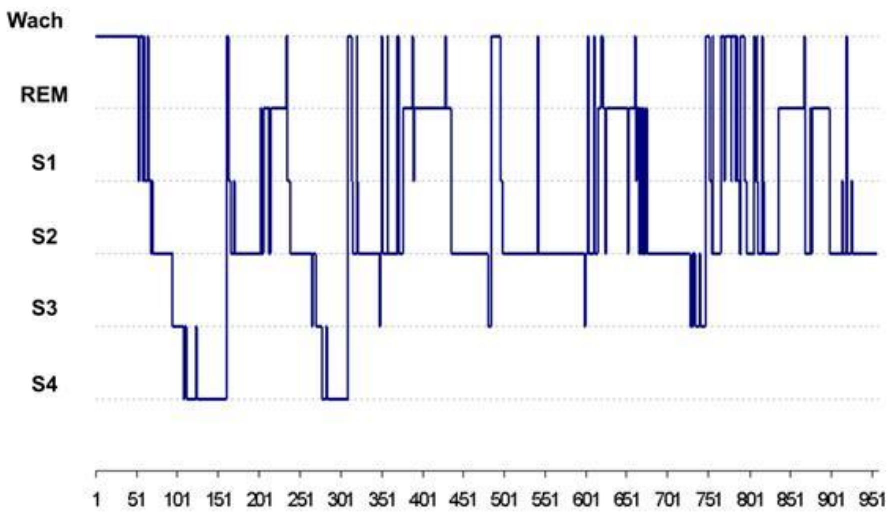

Figure 7: Example of a Hypnogram of an undisturbed noise-free night

3.1.2 Sleep parameters

The following total-night parameters can be derived from a sleep EEG:

1. Sleep stage shares:	Awake, S1, S2, S3, S4 and REM
2. Sleep period time:	SPT – Time from first to last sleep epoch
3. Total sleep time:	TST – SPT without Awake-Epochs
4. Sleep onset latency:	SOL – Time from turn-off the light to first sleep epoch
5. Sleep efficiency:	SE – TST divided by the time in bed (lights turned off)
6. EEG-Arousal:	EEG-Frequency acceleration with a duration of 3 s - 10 s (Bonnet et al., 1992)

As the sleep parameters 2 to 6 just showed slight aircraft noise affected variability in the STRAIN and NORAH study and do not sufficiently consider single noise effects, they are not as appropriate for developing a night protection concept as aircraft noise-induced wake-up reactions are.

Wake-up reactions are a good compromise in terms of sensitivity and specificity so that all relevant sleep disorders are encompassed. The potential recallability of awakening reactions and the association of wakefulness reactions with single and prolonged activation of the autonomic nervous system (Sforza et al., 2004), which may be the long-term cause of cardiovascular diseases (Muzet, 2007), determine the medical relevance here. Arousals, i.e. shorter activation reactions, however, lead neither to a recognizable awakening nor to pronounced vegetative activations (Basner et al., 2008; Sforza et al., 2000).

The number of additional wake-up reactions correlates well with changes in the sleep structure, which are also classified as sleep disorders. Thus, about 45% of the variance in the change of the deep sleep rate is elucidated by the number of additional wake-up reactions (Basner et al., 2005).

Ever since the first field studies to investigate the influence of aircraft noise on sleep by means of polysomnography, there has been consensus among sleep researchers that noise-induced wakefulness is a relevant sleep disorder (Ollerhead et al., 1992). More recent research also suggests that awakening reactions are a suitable indicator of noise-induced sleep disorders (Basner et al., 2008; Griefahn, et al., 2008).

3.1.3 Spontaneous awakenings

It is part of the normal, physiological sleep process during the night sleep to wake up without external disturbances. In the STRAIN laboratory study of DLR (1999-2001), an average of 24 wake-up reactions per night were observed in 112 undisturbed nights. The probability of reacting to noise is usually higher for subjects in the laboratory than in the home environment (field). Much of these spontaneous wake-up reactions are only 15-45 seconds long, too short to be remembered the next day. As shown in another controlled laboratory study on nocturnal traffic noise (Basner et al., 2011), part of this awakening is replaced by noise-induced awakening reactions as the human organism strives to maintain its sleep structure.

It can thus be argued that only those awakening reactions are considered to be noise-induced exceeding the natural number of spontaneous awakenings (Basner et al., 2011). In the DLR aircraft noise field study STRAIN, the probability of additionally awakening due to aircraft noise was calculated from the difference between the aircraft-noise-related (= wake-up reaction observed at the time of an aircraft noise event) and the spontaneous probability of awakening (Basner et al., 2006). Since noise effects in the laboratory are usually more pronounced than in field studies (Pearsons et al., 1995), (Horne et al., 1994), (Fidell et al., 1995) and noise-exposed subjects in field usually have no longer noise-free periods, in which the individual spontaneous probability of awakening could be determined, in the past the spontaneous probability of awakening could only be approximated by complex calculations and assumptions. At the time of falling asleep in a noisy night, it was looked at what time noise events took place, in order to determine at the same moment of time in the further noise nights whether the test person spontaneously woke up if no noise event occurred at that moment of time. By determining the probability of awakening at these control times, logistic regression calculations based on the modeling for the probability of awakening by noise was used to calculate the spontaneous probability of awakening (Brink et al., 2006).

However, this procedure is based on the assumption that the temporal distribution of the spontaneous probability of awakening is always very similar in noise-free nights. This is basically a plausible and reasonable assumption, but it has not yet been scientifically confirmed. The main problem with this approach is that even the "reference" nights are by no means noise-free. Rather, it must first be assumed that the time distribution and number of spontaneous awakening reactions change as a result of the noise-induced awakening reactions. Scientifically "clean" this could only be assessed if the same subjects would be examined in their home environment for several nights in a row without noise (after a certain period of habituation), which in a field study usually cannot be realized as traffic noise sources cannot be turned off.

The algorithm described above is also only applicable if enough nights are measured in the same subject with a not too big traffic density. Otherwise, there are not enough "reference nights" and therefore not enough noise-free time windows, which are needed to use the algorithm. By contrast, the design of recent field and laboratory studies on the effects of nocturnal traffic noise on sleep tends to examine more subjects in fewer nights in order to accommodate more interindividual differences in sleep behavior (see, for example, the Railway Noise Laboratory Study, Gothenburg University (Smith et al., 2013) or the aircraft noise field study NORAH, (Müller et al., 2015) For this reason, the algorithm described above could beneficially not be used, e.g. for the NORAH study (few study nights, night flight ban, very dense traffic in the marginal hours). So the calculation of the spontaneous probability of awakening using this algorithm led to clearly implausible results in the NORAH study. The algorithm would also not be applicable for a field study on the effects of road traffic noise on sleep due to the significantly higher incidence of noise events (car pass-bys) which has been recently finished at DLR.

Therefore, DLR has opted for the following procedure for estimating the spontaneous probability of awakening, as long as there are no new scientific findings:

- All awakening reactions at maximum levels below the median of the background levels before the noise events considered in the statistical model (1-min L_{eq} before) are defined as spontaneous awakening reactions.
- First awakening reactions are not already expected when the background level is exceeded. Therefore 3 dB are added to this median of the background level (doubling of the sound energy, which is considered to be relevant in noise impact research)

Figure 8 shows the procedure for the NORAH- compared to the STRAIN study. In the NORAH study, conducted at Frankfurt Airport, the median background level was 29.7 dB, first awake responses are thus observed at 32.7 dB according to the algorithm, and 5.1% spontaneous probability of awakening must be subtracted from the exposure-response curve. This result is plausibly within the scope of the previously published studies (Dutch aircraft noise study Amsterdam / Schiphol (only motion, no polysomnography measurements), first reactions at 32 dB, (Passchier-Vermeer et al., 2002), aircraft noise study STRAIN, Cologne / Bonn, 33 dB (Basner et al, 2006).

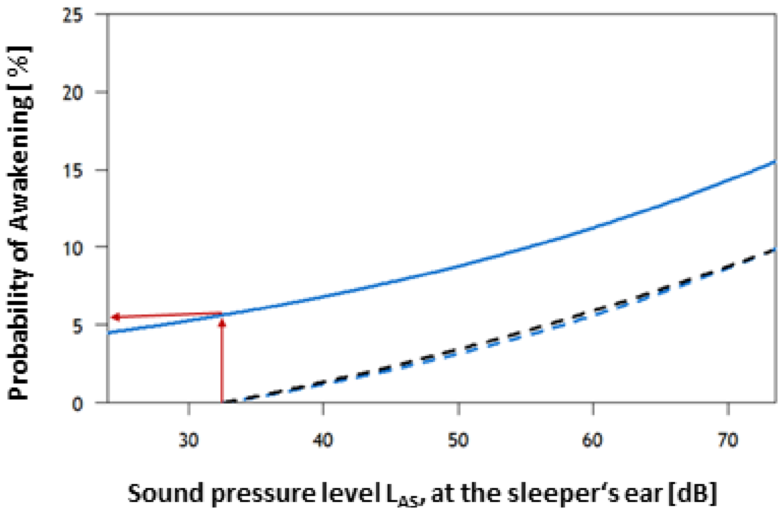

Figure 8: Exposure-effect curve NORAH 2012 before and after deduction of the spontaneous probability of awakening (blue), STRAIN study 2001/2002 after deduction of the spontaneous probability of awakening (black)

3.2 Acoustics

In order to ensure a noise event-related evaluation of the electrophysiological data, in the field studies class-one sound level meters were placed near the sleeper's ear (see e.g. Figure 6). They continuously measured the sound pressure levels (SPL) L_{AS} respectively L_{AF} and, in addition, also recorded the noise events. In the STRAIN study also the outside SPL was measured 2 m in front of the bedroom window according to German standards.

The acoustical data then were analysed by trained students who listened, marked and commented every noise event that had reached the sleepers ear (Figure 9).

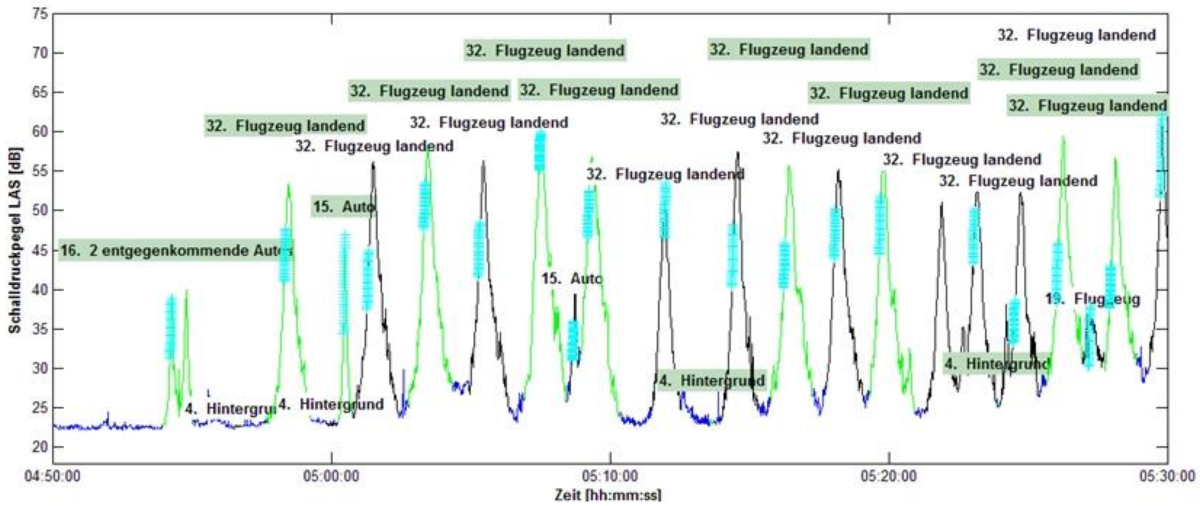

Figure 9: Screenshot DLR-Acoustic Evaluation Software, 40-minute Sound Pressure Level history at the sleeper's ear, 28th July 2011, Offenbach, window open, NORAH study

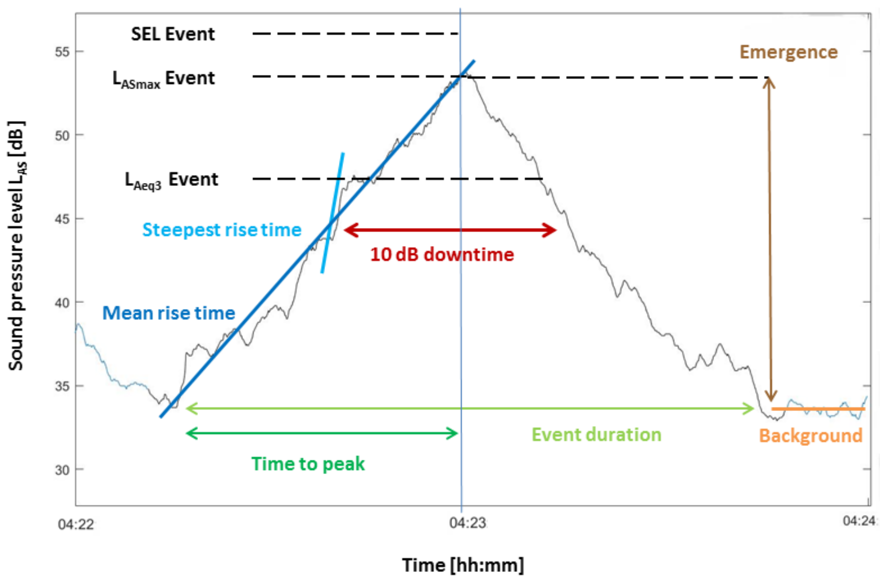

Figure 10: Schematic description of how the acoustic parameters for the statistical analysis were determined.

The time settings of the sound level meters and the EEG recorders were synchronized and the deviations were usually less than 1 s.

Figure 10 shows schematically the following acoustic parameters that were used for the event-related statistical analysis with the sleep parameters:

• L_{ASmax}	A-weighted maximum sound pressure level, time weighting slow [dB(A)]
• L_{Aeq3_Event}	A-weighted equivalent continuous sound level of the aircraft noise event, based on an exchange rate of 3 [dB(A)]
• $SEL_{\_Event}$	Sound Exposure Level of the aircraft noise event [Pa^2*h]
• Background	Sound pressure level in the absence of any alleged noise nuisance sources [dB(A)]
• Emergence	Maximum Sound pressure level minus the background level [dB(A)]
• Event_duration	Time duration for an aircraft noise event above the background noise [s]
• Time_to_peak	Time duration from an aircraft noise event start right above the background noise up to the maximum sound pressure level [s]
• T10 db downtime	Time within a single noise event where the level is below 10 dB of the maximum level [s]
• Steepest rise time	Steepest increase of sound pressure level from start of the noise event to the maximum level [dB(A)/s]
• Mean rise time	Mean increase of sound pressure level from start of the noise event to the maximum level [dB(A)/s]
• L_{Aeq3_1min}	A-weighted equivalent continuous sound level 1 min before the aircraft noise event, based on an exchange rate of 3 [dB(A)]. Can be labelled as the background noise of the specific aircraft noise event
• $N_{Aircraft\_before}$	Number of previous aircraft noise events before the analysed aircraft noise event

3.3 Statistical Analysis Methods

3.3.1 Event-related evaluation

Polysomnography data are evaluated in a standardized way in 30 s sleep epochs (see Chapter 3.1.1).

For the event-related evaluation, an epoch is defined as the "first aircraft noise epoch" when an aircraft noise event starts within 15 seconds of the beginning of the epoch. Then the noise epoch and the next two epochs are checked for a wake-up reaction, which is conservatively defined not just as a change to the stage "awake" but also to the “light” sleep stage S1. As a result, the noise window, which is checked for a wake-up reaction, is 90 seconds long.

An aircraft noise event is excluded if the subject is already awake in the epoch before the first noise epoch. This also logically implies that only aircraft noise events occurring during the sleep period are included in the analysis.

Further on, aircraft noise events are excluded from analysis if in the 60 s before or during the considered aircraft noise event other noise events occur at the same time. Then a bijective correlation to the aircraft noise event is no longer given when a subject awakes.

3.3.2 Multivariable regression analysis

For the calculation of the exposure-response relationship with regard to the awakening reaction, first it is necessary to calculate the probability of awakening. The calculation of the probability of awakening as a function of the maximum level of the aircraft noise event and other influencing variables is carried out by means of a regression model. Since the awakening reactions of a subject can take place several times in one night and are spread out over several nights, repeated measurements are available. In addition, the dependent variable is dichotomous (awakening reaction yes / no). Therefore, a regression model using random effects logistic regression (Diggle et al., 2002) is used. Logistic regression makes it possible to calculate probability values as a function of the various influencing factors in terms of exposure-response curves.

The selection of predictive factors that enter into the regression model is carried out by means of a Stepwise Selection (Hosmer et al., 2000). One starts with an intercept model and in each step a variable is added or a variable is removed. The decision to include or remove a variable in the model is based on the AIC (Akaike Information Criterion), which is a measure of the goodness of fit of a regression model (Pinheiro et al., 2009). This procedure is repeated until there is no improvement with respect to the AIC.

In addition, the assumption of linearity on the logit scale is checked for the metric variables. This is done on the one hand by descriptive graphical method, on the other hand it is tested whether a transformation of the metric variables improves the model quality based on the AIC, e.g. by quadratic and cubic terms or logarithmic and root transformations (Hosmer et al., 2000). Furthermore, it is examined whether interactions exist between the influence variables found by the stepwise selection. This is also done by means of the AICs.

A variety of acoustic, personal and situational variables may have a potential impact on the probability of awakening. For the calculation of the exposure-effect relationships, in addition to the acoustic variables listed in Chapter 3.2 the influence of the following variables for the probability of awakening was examined:

- Sleep stage transition to Sleep Stage „S1“ or Stage „Awake“
- Sleep stage before Awakening
- Time in Sleep stage before Awakening
- Sleep period time before Awakening [in 30s epochs]
- Age
- Sex

3.4 Subject inclusion and exclusion criteria

In the field studies, the homes of residents living in the vicinity of the study airports were selected in a way that the exposure to aircraft noise was high on one hand, but the exposure to other kinds of traffic noise and neighbourhood noise was as low as possible on the other hand. That guaranteed that indeed noise effects on sleep were based on aircraft noise and no other noise sources. At every measurement site before the study start an acoustic and fingerpulse measurement was made for one night. Just those residents were included in the study where other dominant noise sources couldn't be perceived in the sleeping room other than aircraft noise and who did not show any signs of apnoe. Residents were allowed to have their window position during the study nights on their own choice.

Special care was taken by appropriate subject selection to ensure that the subjects were age-related sleep healthy. The aim of the studies was to determine the influence of nocturnal aircraft noise on sleep. However, if a subject simultaneously suffers from an intrinsic sleep disorder which is not caused by environmental influences, it cannot longer be distinguished if sleep disturbances are caused by the nightly air traffic noise or the sleep disorder. Moreover, sleep disorders can fluctuate unsystematically in different nights.

Applicants with cardiac arrhythmias were excluded because they made the analysis of the Electrocardiogram ECG considerably more difficult or impossible.

Further on, applicants who regularly take medicines with sedating effects or consume excessively alcohol/drugs/nicotine and regular shift-workers have been excluded, as that may lead to a shift in the wake-up threshold during sleep.

All study participants should show at least a "nearly normal hearing ability" according to age. Therefore, a hearing loss in the poorer ear was not allowed to exceed 10% (18 to 33 years), 15% (34 to 49 years), and 20% (50 to 65 years).

Other than the diseases described above and the peculiarities associated with them were explicitly allowed, as long as they did not hinder the course of the experiment or question the validity of the results found.

During the study periods subjects were asked not to drink coffee or other caffeinated beverages after 3 p.m. and not to nap during the day. Minimum age of inclusion was 18.

Both study protocols were approved by the ethics commission of the Medical Association of the district North Rhine, Germany. Subjects were instructed according to the Helsinki declaration, participated voluntarily and were free to discontinue their participation at any time without explanation.

4. Study data and Analysis results

In this chapter, the statistical analysis of the two studies is carried out by means of the methodology described in chapter 3. In a first step in Chapters 4.1 and 4.2 the studies will be analyzed independently and, as the analysis here is more complex and accurate due to the inclusion of further acoustical parameters than in the original publications, those optimal models will be compared to the published ones.

In Chapter 4.3 for the first time an optimized statistical pooled model with all data from both studies will be presented as well as a slightly modified, more noise-effects' research based "standard" model. One will see that this model is already well suited to be used to calculate aircraft noise-induced awakenings around airports as well as to define aircraft night noise protection zones around them.

4.1 STRAIN study

The STRAIN (STudy on human Response on AIrcraft Noise) study took place between 1999 and 2003 and examined the influence of nocturnal aircraft noise on sleep by means of polysomnographic laboratory (128 subjects à 13 consecutive nights each) and field studies (64 residents à 9 consecutive nights each). The project was completely funded by the German Aerospace Centre DLR and the Helmholtz Association of German Research Centres HGF in their project "Quiet Air Traffic" (Basner et al., 2004; Basner et al., 2005; Basner et al., 2006).

Here, for ecological-validity reasons it will be concentrated on the analysis of the field study. The field study data were measured between September 2001 and November 2002 around Cologne/Bonn Airport CGN. Together with Airport Leipzig/Halle LEJ CGN does not have any night time restrictions and the highest number of night flights in Germany. Peak hours in the night are usually from 11 p.m. to 1 a.m. and 3 a.m. to 5 a.m.

4.1.1 Data set

All in all, 64 subjects (35 female) from age 18 to 65 (mean age = 37 ± 13 STD) years at 46 different measuring points were investigated for 9 nights each (in 18 cases, 2 persons were examined simultaneously at one measuring point). Measurement campaigns always started Monday evening and finished Wednesday morning the other week. 9 campaigns were in spring, 11 in summer, 19 in autumn and 7 in winter time. Subjects could choose their bed time every evening; they were just obliged to be in bed between midnight and 6 am.

The long-term aircraft noise annoyance of these subjects was measured by means of the ICBEN scale (Fields et al, 2001). 3.1% of the subjects were "not at all", 21.9% "slightly", 39.1 % "moderately", 28.1 % "very" and 7.8 % "extremely" annoyed. So the study sample was significantly higher aircraft noise annoyed than a representative sample in Germany in the year 2000 suggests (Ortscheid et al., 2002).

Before the individual measurement campaigns, subjects got a medical check-up in the DLR Aeromedical Centre Cologne in order to test for the exclusion criteria.

After finishing the campaign, the subjects received an allowance of 75 € / night.

For the event-correlated statistical analysis the data of three subjects had to be discarded because of constant snoring or an intrinsic sleep disorder which led to significant uncertainties in the acoustic respectively sleep data. So in the statistical analysis the data of 61 subjects and 401 nights with full dataset were considered (first night always served as an adaption night and was not evaluated). 34 of the subjects were female, 27 male, they were 19 – 65 years old (mean age was 37 ± 12.9).

All in all 10.759 undisturbed aircraft noise events contributed to the calculations whose indoor maximum levels (measured at the sleeper's ear) ranged from 21.8 dB(A) to 73.2 dB(A) with a median maximum level of 44.4 dB(A) (1st Quartile 37.4 dB(A), 3rd Quartile 50.5 dB(A)).

4.1.2 Results

As described in Chapter 3.2 and Chapter 3.3.2 a variety of acoustic, personal and situational variables may have a potential impact on the probability of awakening at every aircraft flyover. On the whole, all these 12 acoustic and 6 sleep parameters listed in the Chapters were tested here in altogether 22 different models that are scientifically plausible by means of a Stepwise Selection Procedure (see Chapter 3.3.2). For all models, the AIC (Akaike Information Criterion) was calculated as a measure of the goodness of fit for the regression model. This procedure was then repeated until there was no improvement with respect to the AIC any more.

Table 1 shows the optimal model for the STRAIN data. One can see that the probability of awakening for one single aircraft noise event in the STRAIN study depended on the acoustical variables "maximum sound pressure level $L_{pAS\_Max\ indoors}$", the "t_{10}-dB-downtime », the noise's « steepest level rise time » and the « background noise before the noise event » and the interaction term of « maximum sound pressure * background noise before the noise event ». All the acoustical parameters refer to indoor measurements. In addition, the « time since sleepstart » (sleep becomes lighter throughout the night, see Figure 7) and the « sleep stage before awakening » have an influence on the probability to awake from an aircraft noise event. It must be mentioned here that the model using the « event duration » instead of the « t10-dB-downtime » (see Appendix, Table 10) is just slightly worse, so that the decision which of the parameters characterizing the « time length of the aircraft noise event » for the STRAIN model should be used should depend on the maybe better availability of one measure compared to the other.

Table 1: STRAIN study, optimal model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ».

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-4.3290189	0.3833369	-11.293	< 2e-16	***
L_{pAS_Max} indoors	0.0410328	0.0076067	5.394	6.88e-08	***
t_{10}_dB_downtime indoors	-0.0081337	0.0020807	-3.909	9.26e-05	***
L_{pAS}_steepest_level_rise_time indoors	0.0314468	0.0093956	3.347	0.000817	***
Background_before_ noise_event indoors	0.0410951	0.0146402	2.807	0.005000	**
Time_since_Sleepstart	0.0017093	0.0002932	5.831	5.52e-09	***
Sleepstage3_before	-0.3556270	0.1349939	-2.634	0.008429	**
Sleepstage4_before	-0.6679755	0.2395509	-2.788	0.005296	**
SleepstageREM_before	0.3412581	0.0744270	4.585	4.54e-06	***
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-0.0009422	0.0002711	-3.475	0.000511	***
Signif. codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***

Since the exposure-response curve depends on the current sleep stage before the occurrence of the aircraft noise event, different formulas arise depending on the assumed sleep stage before. Here in this report, all formulas will be given for the previous sleep stage 2 (light sleep) which is the most protective approach for airport residents.

Here, the resulting exposure-response function in Figure 11 is given by:

$$\% \text{ awakening probability} = \frac{e^A}{1+e^A} * 100$$

whereas A is given by:

A= -4.3290189 + 0.0410328 * L_{pAS_Max} indoors -0.0081337 * t_{10}_dB_downtime indoors + 0.0314468 * L_{pAS}_steepest_level_rise_time + 0.0410951 * Background_before_ noise_event indoors + 0.0017093 * Time_since_Sleepstart -0.0009422 * SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors

In order to get a 2-dim exposure-response function for the main impact factor «L_{pAS_Max} indoors » then, the other factors must be kept constant. Table 2 shows the values used for the function in Figure 11. The parameters « time_since_sleep_start » and the « sleepstage_before » are both conservatively set by 300 min (5 hrs) respectively « sleepstage 2 » which means that subjects are already in the lighter sleep stages and are therefore more easily to awake than when being in a deeper sleep stage. The spontaneous awakenings were calculated according the procedure described in Chapter 3.1.3. All other parameters were set to the median values from all undisturbed aircraft noise measurements in STRAIN that were used for this statistical analysis.

Table 2: Parameters used for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors LpAS,max,indoors of one overflight ». Median parameters were calculated from all undisturbed aircraft noise measurements of the STRAIN study.

Event duration (Median)	79.8 s
t_{10}_dB_downtime indoors (median)	31.4 s
L_{pAS}_steepest_level_rise_time indoors (Median)	2.6 dB(A)/s
Background_before_ noise_event indoors (Median)	27.2 dB(A)
Time_since_sleep_start (Specification)	300 min
Sleepstage_before (Specification)	2
Spontaneous Awakening (calculated, optimal model)	8.3 %
Spontaneous Awakening (calculated, published model)	8.6 %

Figure 11 shows that first awakening reactions can occur at around 30 dB(A) maximum level of an aircraft noise event indoors at background levels of around 27 dB(A). Confidence intervals (grey) are smallest around 45 dB(A) which reflects the fact that the median of the maximum level of all measured aircraft noise events is at 44.4 dB(A) at most of the measured maximum levels are around this median. Very loud indoor levels above 70 dB(A) or hushed ones under 30 dB(A) are rarer.

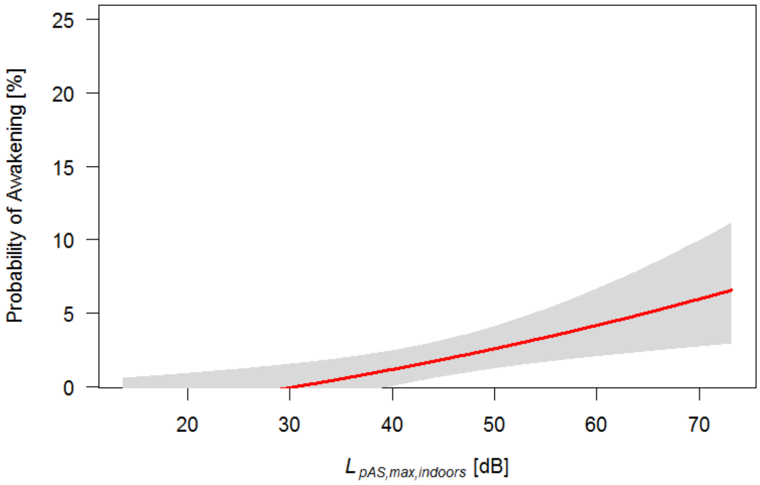

Figure 11: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight + confidence intervals (STRAIN study, optimal model). Parameters see Table 2.

When being evaluated after the year 2002, some acoustical parameter calculations like e.g. the steepest and rise time, time to peak etc. were not yet available for the published STRAIN analysis (Basner, 2006). Table 3 shows the « optimal » model found that time and Figure 12 the corresponding Exposure-Response function, using the same parameters from Table 2 like for the ANIMA re-analysis (Figure 11).

Table 3: STRAIN study, published model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight » (Basner et al., 2006).

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-4.3557697	0.6164211	-7.066	1.59e-12	***
SPL L_{pAS_Max} indoors	0.0406003	0.0131829	3.080	0.00207	**
Background_before_ noise_event indoors	0.0285423	0.0227994	1.252	0.21061	
Time_since_Sleepstart	0.0016890	0.0002927	5.770	7.93e-09	***
Sleepstage3_before	-0.3561453	0.1348581	-2.641	0.00827	**
Sleepstage4_before	-0.6597470	0.2391988	-2.758	0.00581	**
SleepstageREM_before	0.3505599	0.0741659	4.727	2.28e-06	***
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-0.0007505	0.0004684	-1.602	0.10907	
Signif. codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***

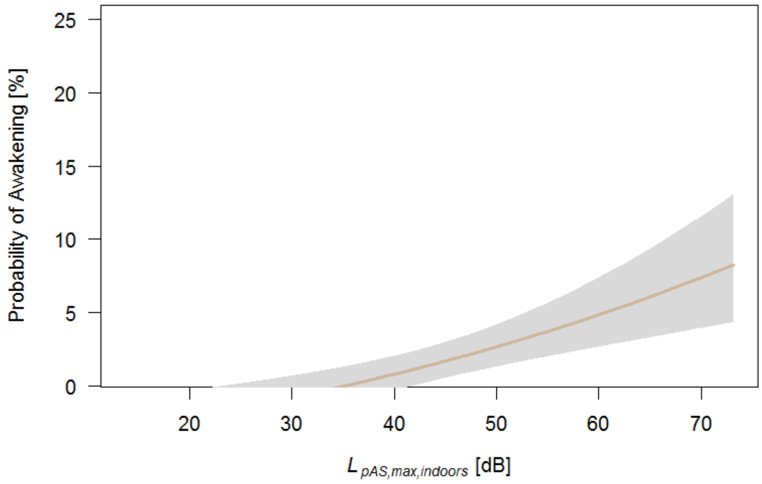

Figure 12: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight + confidence intervals (STRAIN study, published model (Basner et al., 2006). Parameters see Table 2.

From Figures Figure 11 and Figure 12 one can see that the ANIMA re-analysis shows already first awakening probabilities at 3 dB(A) lower maximum levels of aircraft noise events than the "original" analysis. Confidence intervals of the re-analysis are somewhat smaller due to the better explained variance. Figure 13 shows both curves in one graph (for better visibility without confidence intervals). Deviations can be recognized first and foremost in the low and high maximum sound level areas. For the mid-region, where most of the maximum levels are, curves are quite close together.

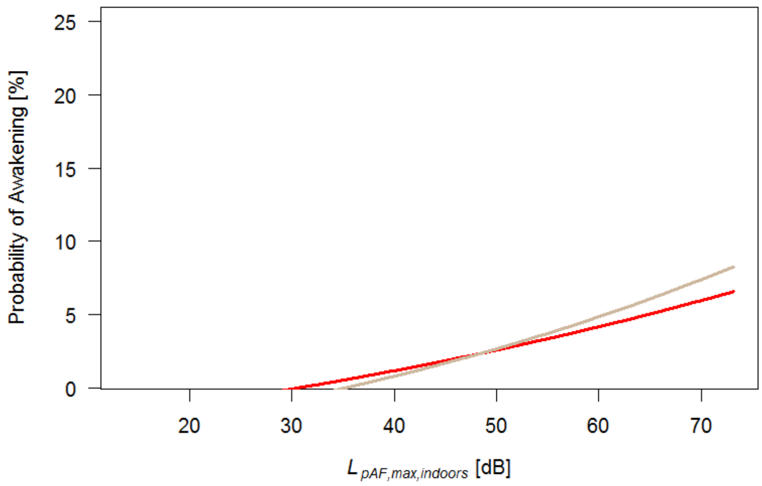

Figure 13: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight (STRAIN study, optimal (red) and published (beige) model). Parameters see Table 2.

It must be mentioned here that both curves could be illustrated with other parameters than those in Table 2 as well, as long as the parameters are in line with the values measured in the study.

4.2 NORAH study

The NORAH study (NOise Related Annoyance, cognition and Health) was carried out in 2011-2015 around Frankfurt airport before and after the beginning of the operation of the 4th runway in October 2011 and the associated night flight ban between 11 pm and 5 am. The aim was to obtain a highly representative and scientifically substantiated description of the effects of noise from air, rail and road traffic on the health and quality of life of the affected residents. The NORAH study was the so far most expensive noise effects' study in Germany and commissioned by the Umwelthaus GmbH, which is part of the Forum Flughafen & Region, and financed by:

- German Federal State of Hessia: 80 %
- Frankfurt Airport: 10 %
- Adjoining Municipalities: 8 %
- Lufthansa: 2 %

9 partners under the lead of the University of Bochum (Prof. Guski) worked on the 5 research modules “Quality of Life factors”, “Health Risks”, “Blood pressure Monitoring”, “Sleep Study” and “Cognitive development of school children”.

In this chapter the acoustic and polysomnography data of the Sleep Study in 2012 will be newly analysed with additional acoustic parameters compared to the final report (Müller et al., 2015; Müller et al., 2016). The Sleep Study was conducted by the German Aerospace Center DLR with support from the Medical Department of the University of Gießen.

4.2.1 Data set

In 2012 all in all 83 subjects (49 female) from age 18 to 77 (mean age = 43 +- 15 STD) years at 75 different measuring points were investigated for 3 nights each (In 8 cases, 2 persons were examined simultaneously at a measuring point). Measurement campaigns always started on Monday evening and finished Thursday morning and were conducted from May to November 2012. There have been two bed time groups subjects could chose to be in:

- bed time group 1: going to bed between 10-10.30 pm and getting up between 6 – 6.30 am
- bed time group 2: going to bed between 11-11.30 pm and getting up between 7 – 7.30 am

The long-term aircraft noise annoyance of these subjects was measured by means of the ICBEN scale (Fields et al, 2001). 38.2% of the subjects were “not at all”, 46.5% “slightly”, 9.7 % “moderately”, 2.8 % “very” and 2.8 % “extremely” annoyed. So this NORAH study sample was significantly less aircraft noise annoyed than the STRAIN sample. It must be mentioned at this point that in the STRAIN study the aircraft noise annoyance was surveyed after the 9 measurement nights, in the NORAH study before the measurement campaign. So it is not totally clear if the 9 measurement nights themselves might have had an impact on the aircraft noise annoyance and if the annoyance measures of the two studies are comparable as they are.

Due to the fact that the DLR Aeromedical Centre Cologne was too far away from Frankfurt to invite the candidates for a medical check-up, they had to fill out an extensive medical history questionnaire combined with a telephone call if necessary in order to guarantee that they correspond to the inclusion criteria.

After finishing the campaign, in the NORAH study the subjects received an allowance of 70 € / night.

For the event-correlated statistical analysis the data of seven subjects had to be discarded because of apnoea or incomplete data sets. So in the statistical analysis the data of 76 subjects and 157 nights with full dataset were considered (first night always served as an adaption night and was not evaluated, five subjects were investigated for four nights instead of three). 47 of the subjects were female, 29 male, they were 18 – 77 years old (mean age was 43 ± 15).

All in all 3.254 undisturbed aircraft noise events contributed to the calculations whose indoor maximum levels (measured at the sleeper's ear) ranged from 24.0 dB(A) to 73.5 dB(A) with a median maximum level of 45.2 dB(A) (1st Quartile 39.1 dB(A), 3rd Quartile 51.6 dB(A)).

4.2.2 Results

The procedure of the evaluation of the NORAH 2012 data is exact in line like for the STRAIN data as described in Chapter 4.1.2. Here, all in all 30 scientifically plausible different models were analysed by means of a Stepwise Selection Procedure (see Chapter 3.3.2).

Table 4 shows the optimal model for the exposure-response curve, Table 5 the parameters used for calculating Figure 14.

Table 4: NORAH 2012 study, optimal model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ».

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-1.064e+01	1.247e+00	-8.534	< 2e-16	***
L_{pAS_Max} indoors	1.721e-01	2.706e-02	6.361	2.00e-10	***
Event_duration	-8.124e-03	3.606e-03	-2.253	0.02428	*
Background_before_ noise_event indoors	2.165e-01	3.780e-02	5.728	1.02e-08	***
Time_since_Sleepstart	1.894e-03	6.509e-04	2.911	0.00361	**
Sleepstage3_before	-6.245e-02	2.991e-01	-0.209	0.83461	
Sleepstage4_before	-2.834e-01	3.022e-01	-0.938	0.34837	
SleepstageREM_before	2.853e-01	1.473e-01	1.937	0.05275	.
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-4.659e-03	8.059e-04	-5.781	7.41e-09	***
Signif. codes	*0 '***'*	*0.001 '**'*	*0.01 '*'*	*0.05 '.'*	*0.1 ' '*

Table 5: Parameters used for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ». Median parameters were calculated from all undisturbed aircraft noise measurements of the STRAIN study.

Event duration (Median)	65 s
L_{pAS}_steepest_level_rise_time indoors (Median)	2.2 dB(A)/s
Background_before_ noise_event indoors (Median)	30.3 dB(A)
Time_since_sleep_start (Specification)	300 min
Spontaneous Awakening (calculated, optimal model)	4.7 %
Spontaneous Awakening (calculated, published model)	5.1 %

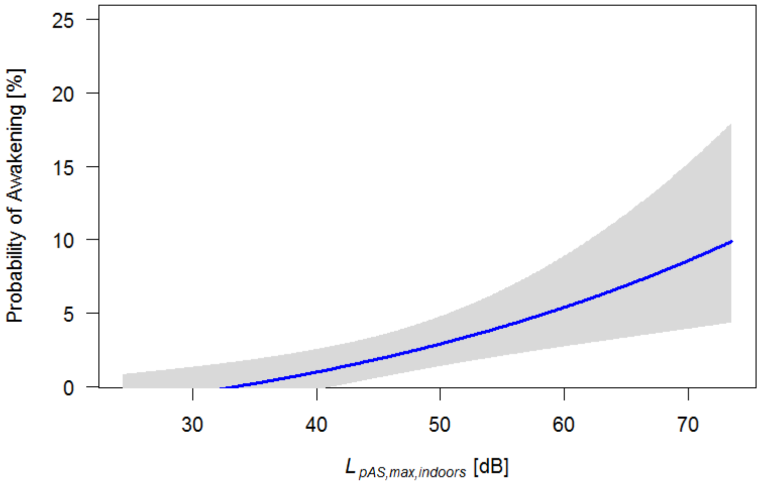

Figure 14: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight + confidence intervals (NORAH 2012 study, optimal model). Parameters see Table 5.

Again, also the NORAH 2012 data were not analysed with the full acoustical parameter set used here in the ANIMA re-analysis. Table 6 respectively Figure 15 show the results of the published model.

Table 6: NORAH 2012 study, published model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight » (Müller et al., 2015).

Fixed effects	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
(Intercept)	-1.077e+01	1.217e+00	-8.845	< 2e-16	***
SPL L_{pAS_Max} indoors	1.608e-01	2.612e-02	6.156	7.45e-10	***
Background_before_ noise_event indoors	2.137e-01	3.681e-02	5.806	6.42e-09	***
Time_since_Sleepstart	1.976e-03	6.542e-04	3.020	0.00253	**
Sleepstage3_before	-5.832e-02	2.988e-01	-0.195	0.84523	
Sleepstage4_before	-2.881e-01	3.018e-01	-0.954	0.33988	
SleepstageREM_before	2.692e-01	1.471e-01	1.830	0.06726	.
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-4.536e-03	7.827e-04	-5.795	6.84e-09	***
Signif. codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***

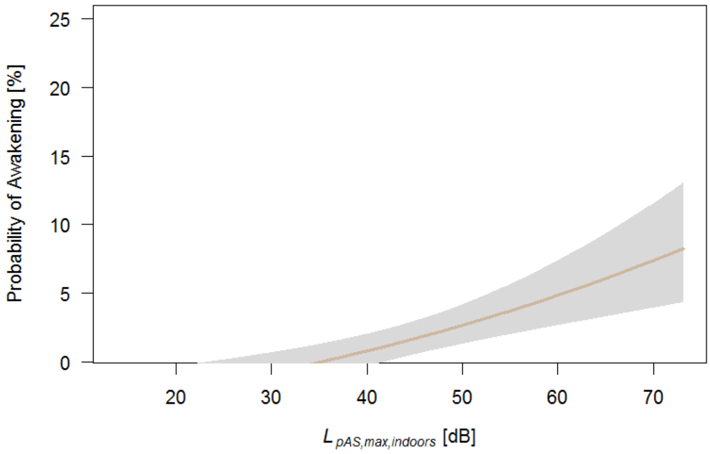

Figure 15: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight + confidence intervals (NORAH 2012 study, published model (Müller et al., 2015). Parameters see Table 5.

In Figure 16 the optimal model from the ANIMA re-analysis and the published NORAH 2012 model are compared with each other using the same parameters as listed in Table 5. Here, in both models first awakening reactions can occur at maximum overflight indoor levels of 32 dB(A) but with increasing maximum levels the curve of the ANIMA re-analysis shows higher awakening probabilities than in the published one. So the awakening probability for an overflight might be somewhat underestimated in the original study publication.

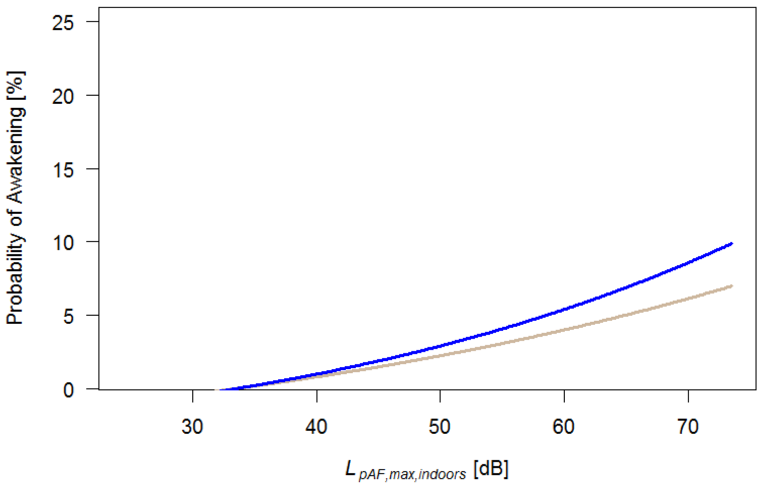

Figure 16: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight (NORAH 2012 study, optimal (blue) and published (beige) model). Parameters see Table 5.

4.3 Pooled evaluation

In Chapters 4.1 and 4.2 it could be shown that the ANIMA re-analysis with additional acoustic parameters available for an optimal model fit led to better results than the originally published models for the STRAIN and the NORAH 2012 study.

So far, these two studies are the worldwide only studies that allow an event-correlated analysis of acoustic data, measured at the sleepers' ear, with sleep data measured with the "gold standard" polysomnography. All used acoustic data reflect deductions from the sound pressure level recordings. Detailed analysis of frequency spectra of every aircraft noise event used in the statistical model would be extremely more complex and time consuming and it cannot be deduced from current field data so far if a stable statistical model for determining the awakening probability including those frequency parameters could be found or if these frequency parameters really had a significant impact on humans' sleep.

The STRAIN data are meanwhile 17 years old which means that they might not totally reflect the current aircraft mix, whereas the NORAH 2012 data are just 7 years old and the aircraft mix shouldn't differ too much from the today's one.

The STRAIN data measured at Cologne/Bonn airport were measured at residents' places which were exposed to aircraft noise throughout the whole night. The NORAH 2012 data, however, were measured at Frankfurt airport which has a night flight ban between 11 pm and 5 am. So residents there are highly exposed in the "shoulder" hours until 11 pm and especially in the morning from 5 am on (one acoustical example is given in Figure 9). In NORAH 2012 around half of the subjects went to bed before the start of the night time flight ban and were exposed to aircraft noise in the evening as well as in the morning. The other half of the subjects went to bed after 11 pm and was just exposed to aircraft noise in the morning. The time they spent in bed was the same for both groups.

Comparing the exposure-response functions of both optimal models (Figure 11 and Figure 14) shows that although they are different, they still lay within the confidence intervals of each other. This is a good result as it shows that although the aircraft noise scenarios in both studies were clearly unequal, although peoples' sleep differs individually and although, due to the high expenses of such experimental field studies, the number of residents who can be investigated is relatively small, results seem to be relatively stable.

Nevertheless, it makes sense, of course, to pool the data in order to get a medium exposure-response curve that can be either used for communicating aircraft noise issues for the night ("additional aircraft noise induced awakening reactions") as well as for land-use-planning purposes (determining night noise protection zones) at many airports. As field data, we have more or less two extrema. An airport which has a high traffic density throughout all the night (CGN) and one airport (FRA) with a night curfew between 11 pm - 5 am and busy shoulder hours.

The pooling of the data and their analysis will be described in this chapter.

4.3.1 Data set

As in the STRAIN study there were 2.5 more investigation nights and around 3.3 times more undisturbed aircraft noise events and in this pooled analysis it is concentrated on calculating the probability of awakening due to an aircraft noise event, therefore here the number of aircraft noise events from both studies is aligned by adding randomly chosen NORAH aircraft noise events.

So in the statistical analysis the data of 136 subjects and 556 nights with full dataset were considered. 81 of the subjects were female, 55 male, they were 18 – 77 years old (mean age was 40 ± 14).

All in all 21.527 undisturbed aircraft noise events contributed to the calculations whose indoor maximum levels (measured at the sleeper's ear) ranged from 21.8 dB(A) to 73.5 dB(A) with a median maximum level of 44.7 dB(A) (1st Quartile 38.2 dB(A), 3rd Quartile 50.8 dB(A)).

4.3.2 Results

With this dataset and the same procedure like for the individual studies, here 20 scientifically plausible different models were analysed by means of a Stepwise Selection Procedure (see Chapter 3.3.2).

Table 7 shows the optimal model for the exposure-response curve, Table 8 the parameters used for calculating Figure 17.

Table 7: STRAIN/NORAH study, optimal model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ».

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-6.063e+00	2.294e-01	-26.430	< 2e-16	***
L_{pAS_Max} indoors	7.979e-02	4.674e-03	17.073	< 2e-16	***
Event duration	-5.844e-03	1.124e-03	-5.198	2.02e-07	***
L_{pAS}_steepest_level_rise_time indoors	4.003e-02	9.153e-03	4.373	1.23e-05	***
Background_before_ noise_event indoors	7.564e-02	5.804e-03	13.031	< 2e-16	***
Time_since_Sleepstart	1.660e-03	2.335e-04	7.107	1.19e-12	***
Sleepstage3_before	-2.159e-01	1.041e-01	-2.073	0.03815	*
Sleepstage4_before	-4.560e-01	1.389e-01	-3.283	0.00103	**
SleepstageREM_before	3.483e-01	5.573e-02	6.249	4.12e-10	***
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-1.847e-03	9.842e-05	-18.769	< 2e-16	***
Signif. codes	*0 '***'*	*0.001 '**'*	*0.01 '*'*	*0.05 '.'*	*0.1 ' '*

Table 8: Parameters used for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ». Median parameters were calculated from all undisturbed aircraft noise measurements of the STRAIN/NORAH study.

Event duration (Median)	71.1 s
t_{10}_dB_downtime indoors (median)	30.0 s
L_{pAS}_steepest_level_rise_time indoors (Median)	2.4 dB(A)/s
Background_before_ noise_event indoors (Median)	28.6 dB(A)
Time_since_sleep_start (Specification)	300 min
Age	40
Spontaneous Awakening (calculated, optimal model STRAIN/NORAH)	5.4 %
Spontaneous Awakening (calculated, optimal model STRAIN)	8.4 %
Spontaneous Awakening (calculated, optimal model NORAH)	4.0 %

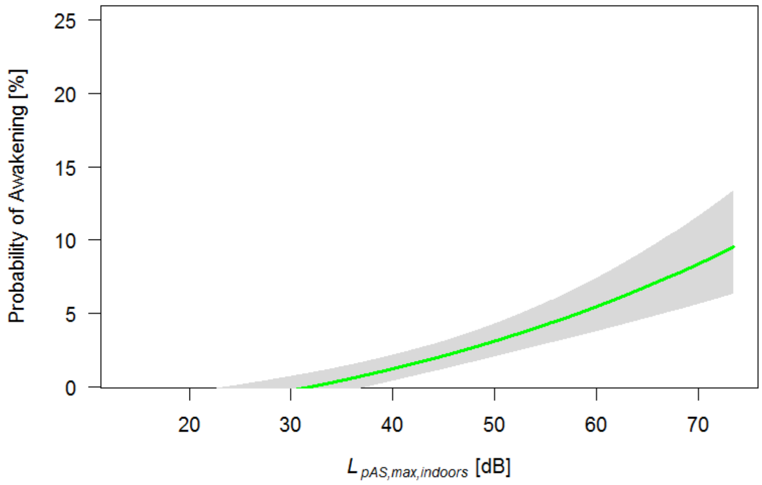

Figure 17: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight + confidence intervals (STRAIN/NORAH study, optimal model). Parameters see Table 8.

Figure 18 shows the exposure-response curves of the optimal models of the individual STRAIN (red) and NORAH (blue) analysis as well as from the pooled evaluation (green), all calculated with parameters listed in Table 8. As it could be expected, in large parts, the pooled curve lies directly in the middle of the individual curves and therefore is undoubtedly a very good approach for the further consistent use for calculations of additional aircraft noise induced awakenings at different airports(Nevertheless, for some airports with many aircraft movements in the early morning, there might be also arguments to use the "worst case" exposure-response curve (NORAH data, night curfew but busy shoulder hours, especially in the morning), instead of the "mean" exposure-response curve). As mentioned for the individual STRAIN analysis, there the "timelength of the noise"-parameters "t10-dB-downtime" and "event duration" led to almost the same optimal model, whereas here for the pooled data the model including the "event duration" is significantly better (see Appendix, Table 11).

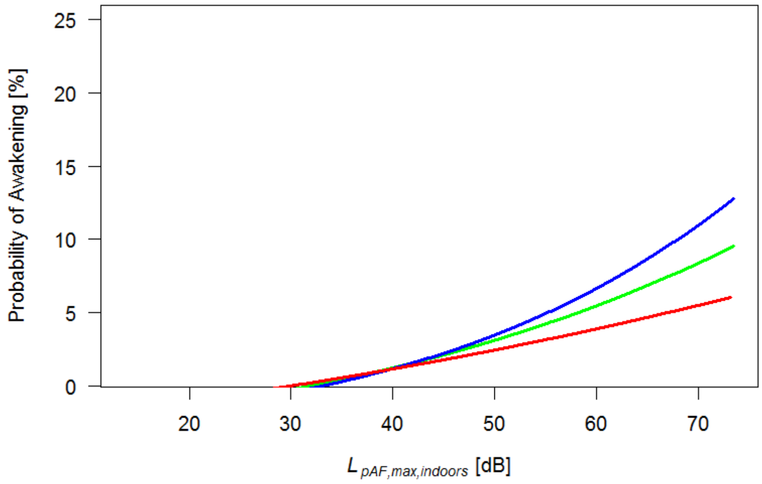

Figure 18: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight. Comparison of all optimized models (STRAIN = red line, NORAH 2012 = blue line, STRAIN/NORAH 2012 = green). Parameters see Table 8.

4.3.3 Introduction of a standard model

In elaborate experimental studies, it is always difficult to hire subjects. Thus, it is usually impossible to achieve a balanced age structure as just relatively small numbers of subjects can be realized. On the other hand, it is undisputed that the sleep structure changes with age and deep sleep phases are partly replaced by light sleep phases when getting older. Therefore elderly people in general have a lighter sleep and should be easier to awake from noise events. This fact is not reflected by the optimal models so far, as in all models the parameter "age" was tested but never led to the optimal model.

Table 9: STRAIN/NORAH study, standardized model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight ».

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-6.0043598	0.2779726	-21.601	< 2e-16	***
L_{pAS_Max} indoors	0.0804070	0.0048181	16.689	< 2e-16	***
Event duration	-0.0058474	0.0011256	-5.195	2.05e-07	***
L_{pAS}_steepest_level_rise_time indoors	0.0399624	0.0091569	4.364	1.28e-05	***
Background_before_ noise_event indoors	0.0764112	0.0059805	12.777	< 2e-16	***
Time_since_Sleepstart	0.0016601	0.0002336	7.105	1.20e-12	***
Sleepstage3_before	-0.2145659	0.1041066	-2.061	0.03930	*
Sleepstage4_before	-0.4533692	0.1388330	-3.266	0.00109	**
SleepstageREM_before	0.3482393	0.0557374	6.248	4.16e-10	***
Age	-0.0022583	0.0047294	-0.478	0.63300	
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-0.0018619	0.0001051	-17.715	< 2e-16	***
Signif. Codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***

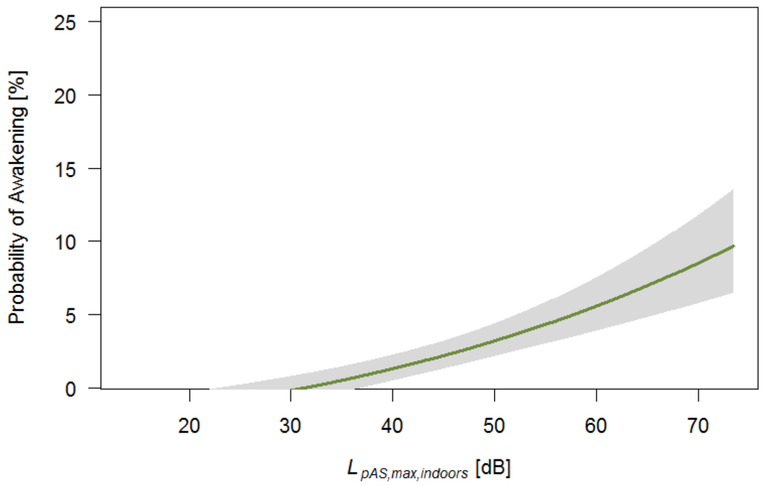

Figure 19: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight. Standardized model for all STRAIN/NORAH 2012 data (Table 9). Parameters see Table 8.

So, in this chapter it shall be tested what effect the additional parameter "age" has compared to the optimal pooled model. This model including the "age" parameter will be called "Standard Model". Table 9 shows the model results and Figure 19 the exposure response function for the parameters in Table 8.

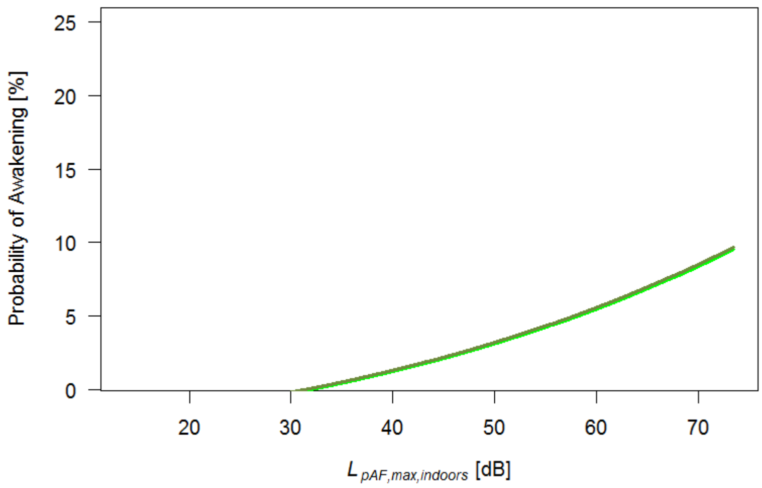

Figure 20 : Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight. Standardized (dark green) and optimal model (green) for all STRAIN/NORAH 2012 data (Table 9). Parameters see Table 8.

Figure 20 then shows the comparison of the optimal model and standard model curve for the same median age 40. It's obvious that for this data set analysis there is no difference between those curves. Calculating the standard curve then for the different ages 20, 40 and 70, as it is done in Figure

21, also does not show any age effect here for this dataset. However, the age effect in sleep research is undisputed, so it is proposed to let this parameter within the standard model so that further studies in the future with special consideration of the age effect might improve the standard model by pooling all then available studies.

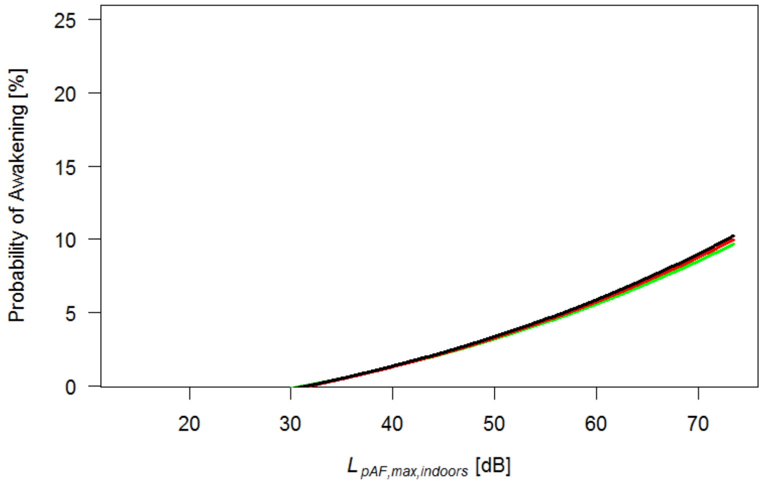

Figure 21: Probability of awakening as a function of the maximum sound pressure level indoors $L_{pAS,max,indoors}$ of one overflight. Standardized model for age 40 (green), age 20 (red), age 70 (black). Parameters see Table 8

5. Considerations for a night noise protection concept

The derived exposure-response function of the standard model from Chapter 4.3.3 can now be used for two purposes:

- Communicating the effect of nocturnal aircraft noise and its development over the past years or, with the help of forecasts, for the future years to airport residents or decision makers in the easy-to-understand metric “additional aircraft noise induced awakenings” for every area around the airport.

- It is now possible to develop a protection concept that can directly prevent physiological acute-effects of nocturnal aircraft noise and therewith most likely also long-term health effects. This is not possible with an average acoustical sound level measure like the Leq (provided that it is not unrealistically low) as it does not reflect the fact that humans during sleep react on the single aircraft noise events and not on an average acoustical measure for the night for which one can get the same value in completely different noise scenarios.

In this chapter some considerations shall be made, how such a night noise protection concept as described in 2) could be developed.

The main idea of a protection concept should be to prevent airport residents from harmful adverse health effects. Although very little is known about the pathways how years of nocturnal aircraft noise exposure lead to possible health consequences, it is most plausible that if a protection concept can prevent primary reactions (here: additional noise-related awakenings), also possible long-term health consequences should be avoided.

In Chapter 3.4 it was illustrated that just “sleep-healthy” subjects could have been investigated in the studies, otherwise it wouldn’t be possible to bi-uniquely differentiate if an awakening reaction was caused by an aircraft noise event, by an internal sleep disorder or possible side-effects of other illnesses.

However, a protection concept has to protect also diseased residents, of course. “Diseased” does not necessarily mean that those people sleep worse, as there are illnesses which increase the sleep pressure or the side effects of medicaments they have to take increase drowsiness. But for those who belong to a “sleep-vulnerable” group some conservative, i.e. protective, assumptions for the residents should be considered both in the calculation process of the exposure-response function as well as in the setting of total limit values.

These protective assumptions in the here presented model are that the "awakening reaction" is not only defined for the transition to the stage "awake", but also for the transition to the light sleep stage "S1" and not just for the whole aircraft noise event duration but within 90 s after the start of the aircraft noise event which is a usually around one third longer. The curves here were calculated for subjects being in the previous light sleep stage 2 before the aircraft noise event. That means it reflects the situation that the resident is already in a light sleep and thus has a higher awakening probability than from deep sleep stages. A similar additional effect was achieved here by calculating the curve for 300 min (5 hrs) after sleep start, which usually corresponds to the last third of the night, in which human sleep is characterized by significantly more light sleep phases due to the decrease in sleep pressure than at the beginning of the night.

As early as in 2006, Airport Leipzig/Halle was planning a significant expansion of night-time traffic, which meant that the competent authorities had to issue a new operating permit for the night. The German Aerospace Centre DLR was asked to develop a night noise protection concept which should be better than that provided in the German Air Traffic Noise Act because of the drastic change of nightly aircraft movements that were planned. The proposal of the DLR was expressly confirmed by the highest German administrative court, the Bundesverwaltungsgericht, in its decision from 9th November 2006 and then implemented around the airport.

Basis for the calculations of the awakening probability for an aircraft noise event were the original analyses of the STRAIN data. Afterwards, a prognosis for the nocturnal flight movements was made for the year 2015, taking into account the mix of aircraft types, and from these data the outdoor maximum level frequency distribution was calculated for all affected residential areas. Assumptions for the window insulation were then made in order to get the aircraft noise maximum level distribution for indoors. With this distribution, for every resident's house and every single aircraft noise event the probabilities to awake were summed up which resulted in the values for the additional aircraft noise induced awakenings.

Then the following limits were set for the protection concept (Basner et al., 2006):

- Allow on average less than one additional aircraft noise induced awakening per night (which means less than 365 / year, one additional aircraft noise induced awakening = sum of 100 % probability of awakening)
- Avoid awakenings that are recalled in the morning
  (just allow at most one aircraft noise event with a maximum level of 65 dB(A) per night inside)
- Avoid interference with the process of falling asleep again.
  (1.4 dB(A) malus for the second half of the night)

The limit values of bullet point 2 and 3 result from DLR laboratory studies and are described in detail in the corresponding paper from Basner et al.

Under these assumptions the night noise zones at Airport Leipzig/Halle were not just increased by 28 % compared to the German Air Traffic Law but also the shape of the zones differed at some points which manifests that human physiology does not react on acoustical average levels.

6. Outlook

The development of a night noise protection concept for aircraft in Chapter 5 showed that there have to be made some limit settings which, for lack of further information, do not necessarily have strong scientific evidence (e.g. limit: less than one additional aircraft noise induced awakening on average per night). Therefore, one of the main foci of future epidemiological noise effects' research must be to clarify the question of how many additional noise-induced awakening reactions lead to which increased health risks after a long-term exposure to aircraft noise. Subsequent, in compliance with the conclusion of other works concluded with ANIMA, this must be accompanied by a social debate which determinates the risks that are tolerated by the society in order to facilitate nocturnal flight movements. These agreements then can be better taken to define the limits of such a protection zone than the current fixations.

Apart from this, from a scientific point of view it would be certainly desirable to have further sleep data sets from field studies and maybe also find methodologies that allow to measure sleep of vulnerable groups. Due to the high financial and time expenses required for this type of field studies, though it cannot be expected that in the near future there will be many more experimental studies on this issue with the described methodology. However, as described here in the Deliverable, there are efforts made to get similar results by replacing the polysomnography measurements by electrocardiogram and body movement measurements which would significantly reduce costs.

From the author's point of view, however, these future perspectives should not further delay the urgently required improvement of the airport residents' protection during the night. The existing results are completely sufficient to improve the level of protection for the residents and to shift the aircraft noise calculation system for the night from a purely physical quantity to a measure that takes into account human physiology.

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8. Appendix

Table 10: STRAIN study, model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors LpAS,max,indoors of one overflight » using the « event duration » instead of the « t10-db-downtime » as in the optimal model. AIC differences of both models: 0.9

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-4.0268465	0.3105058	-12.969	< 2e-16	***
L_{pAS_Max} indoors	0.0446670	0.0069414	6.435	1.24e-10	***
Event duration	-0.0052156	0.0013067	-3.991	6.57e-05	***
L_{pAS}_steepest_level_rise_time indoors	0.0335715	0.0093947	3.573	0.000352	***
Background_before_ noise_event indoors	0.0161413	0.0099667	1.620	0.105335	
Time_since_Sleepstart	0.0016525	0.0002929	5.642	1.68e-08	***
Sleepstage3_before	-0.3657812	0.1350321	-2.709	0.006752	**
Sleepstage4_before	-0.6615688	0.2395560	-2.762	0.005751	**
SleepstageREM_before	0.3387617	0.0744370	4.551	5.34e-06	***
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-0.0006235	0.0001814	-3.437	0.000588	***
Signif. codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***

Table 11: Pooled STRAIN/NORAH 2012 data, model for the exposure-response curve «Probability of awakening as a function of the maximum sound pressure level indoors LpAS,max,indoors of one overflight » using the « t10-db-downtime » instead of the «event duration » as in the optimal model. AIC differences of both models: 16

Fixed effects	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-4.0268465	0.3105058	-12.969	< 2e-16	***
L_{pAS_Max} indoors	0.0446670	0.0069414	6.435	1.24e-10	***
Event duration	-0.0052156	0.0013067	-3.991	6.57e-05	***
L_{pAS}_steepest_level_rise_time indoors	0.0335715	0.0093947	3.573	0.000352	***
Background_before_ noise_event indoors	0.0161413	0.0099667	1.620	0.105335	
Time_since_Sleepstart	0.0016525	0.0002929	5.642	1.68e-08	***
Sleepstage3_before	-0.3657812	0.1350321	-2.709	0.006752	**
Sleepstage4_before	-0.6615688	0.2395560	-2.762	0.005751	**
SleepstageREM_before	0.3387617	0.0744370	4.551	5.34e-06	***
SPL L_{pAS_Max} indoors * Background_before_ noise_event indoors	-0.0006235	0.0001814	-3.437	0.000588	***
Signif. codes	***0 '***'***	***0.001 '**'***	***0.01 '*'***	***0.05 '.'***	***0.1 ' '***