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Determining physiological reaction probabilities to noise events during sleep

General considerations

The determination of reaction probabilities to noise events during sleep is an integral part in the process of establishing exposure-effect relationships for noise impact assessment during the night. The functions that describe such relationships are typically used as part of the planning process of new facilities or their extension, such as roads, railroads, or airports, or to define exposure limits in legislation. In such a context, one or more acoustical characteristics of *noise events* (e.g., a train passing or an airplane overflight) are related to the occurrence of reactions of the sleeper. Such reactions are identified either as changes in the EEG pattern (as part of a sleep recording), as the occurrence of instantaneous body movements, or as behaviorally confirmed awakenings, and their relative frequency is regarded as an indicator of the severity of the noise effect. A range of laboratory [7, 8] and field studies [5, 6, 9, 10, 12, 17, 18, 20] reflect this tradition. Awakenings from single noise events, defined as the transition from any stage of sleep to the wake stage, measured by means of polysomnography (PSG), are considered the strongest form of reaction to environmental stimuli during sleep and are one of the most often adopted criteria in night time noise protection concepts.

The current article has been stimulated by a pending lawsuit at the German administrative court pertaining to the night noise protection concept of the Leipzig-Halle airport, whose night curfew was to be suspended in order to allow the airport to be used as main freight hub for a large international logistics company. The controversy pertaining to the introduction of night flights revealed that obviously no commonly accepted scientific standard for the calculation of "noise caused" awakening probability exists. Guidelines for how to estimate so called "behaviorally confirmed" (e.g., by pressing a button) awakening probability associated with outdoor noise events were published by ANSI [1], but this norm does – denying the possible existence of spontaneous behaviorally confirmed awakenings – not contain any information on how to differentiate between noise-caused and spontaneous awakenings, a differentiation that is relevant, as will be shown later.

Owing to the fact that awakening reactions have become a well-established noise effect indicator for the night time [5, 11, 14, 16], adopted both by policy and the public, this article aims at resolving some of the most problematic issues pertaining to the correct derivation of awakening reaction probability – as defined by means of EEG – to noise events during sleep.

Although the calculations discussed in the following paragraphs basically apply to all *binary* reaction types (including EEG awakenings, EEG arousals, cardiac arousals, onset of motility and behavioral/signaled awakenings) and most kinds of stimuli, the further disquisition will be restricted to *noise caused awakening reactions* that are defined, according to Rechtschaffen and Kales [19], as a transition from a stage of *sleep* (S1-S4, REM) to the *wake* (W) stage.

Differentiation between spontaneous awakenings and awakening reactions caused by noise events

Exposure-effect relationships between an acoustical measure and a binary outcome variable (e.g., awakening reactions) are established in studies where the impact of noise events with particular acoustical characteristics (e.g., maximum sound pressure level, slope of rise, sound exposure level) on the probability of the occurrence of a reaction within an associated *time window* is investigated. A time window is defined as a period of time of particular duration – usually in the range of a few seconds to a few minutes – in which the sleeper is screened for reactions.

Awakenings during sleep do not only occur as reactions to noise events, but also due to many other reasons. In the current context, these kinds of awakenings are generally termed *spontaneous*. Since spontaneous awakenings can occur at any time, e.g., also during the presence of noise events, it remains unknown in principle, whether an observed awakening in a corresponding time window was induced by noise or happened spontaneously. Therefore, one needs to distinguish between spontaneous awakening probability and awakening probability caused by noise events. The probability of spontaneous awakening can basically be determined in noise-free time intervals or, as they shall be called, *noise-free time windows*. As any observed awakening in the absence of a noise event is considered spontaneous, the relative frequency of such awakenings is an estimate of the spontaneous probability in question.

For time windows with noise exposure, naturally occurring or experimentally administered, the underlying cause of an observed awakening is not determinable, and awakening reactions will simply be called "observed". In the existing noise effects literature, the probability for spontaneous awakenings is generally subtracted from the probability of observed awakenings, and the result of this calculation is most often referred to as "induced" probability [5, 18] and is regarded as the relevant noise effect indicator. As shown later, careful investigation of the sets of possible reactions reveals that there are in fact two different, but perfectly adequate ways to define induced probability, both implying different magnitudes of the noise effect, and that the probability just described should be called "additional" rather than "induced". One of the main goals of this article is to emphasize the distinction in the interpretation and use of the two notions.

Formal derivation of probabilities

Awakening reactions can be understood as *events* in the sense of probability the-

Abstract · Zusammenfassung

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Abstract

Some of the activations that occur during sleep, e.g. awakening reactions, can be considered adverse effects of noise events (e.g., airplane overflights or train passings) during the night. The occurrence of such reactions is an important indicator of the sleep disturbing potential of the particular noise stimulus and it is often desired to exactly quantify that potential in terms of a probability. Awakenings are considered the strongest form of reaction to noise stimuli during sleep and are one of the most often adopted criteria in night time noise protection concepts. However, the correct determination of noise induced awakening probability has given rise to debate in the scientific community in recent years. Because during every night's sleep, spontaneous awakenings can occur at any time, it remains unknown in principle, whether a particular awakening observed during the presence of a noise stimulus was induced by that stimulus or emerged spontaneously. Nevertheless, correctly determining the awakening probability in question is key when it comes to forecasting noise effects during the night. This article introduces two definitions of reaction probability, discusses their advantages and disadvantages, and develops a model of the influence of the time window duration in which reactions of sleepers are screened on the calculated reaction probability.

Keywords

Event-related activations · Noise effects · Reaction probability · Probability calculation · Awakening reaction · Sleep disturbances

Bestimmung physiologischer Reaktionswahrscheinlichkeiten auf Lärmereignisse im Schlaf

Zusammenfassung

Einige im Schlaf auftretende Aktivierungen, z. B. Aufwachreaktionen, können als schlafbeeinträchtigende Effekte von nächtlichen Lärmstimuli (z. B. Flugzeugüberflüge oder Zugvorbeifahrten) aufgefasst werden. Die Auftretenswahrscheinlichkeit solcher Reaktionen ist ein wichtiger Hinweis auf das schlafstörende Potenzial des entsprechenden Lärmstimulus und soll oft so genau wie möglich ermittelt werden. Aufwachreaktionen gelten als stärkste Form der Reaktion auf Lärmstimuli in der Nacht und sind eines der am häufigsten verwendeten Kriterien für den Nachtlärmschutz. Die wissenschaftlich korrekte Ermittlung der lärminduzierten Aufwachwahrscheinlichkeit wurde jüngst unter Lärmwirkungsforschern kontrovers diskutiert. Weil man in jeder Nacht jederzeit auch spontan erwachen kann, ist einem während eines Lärmstimulus beobachteten Aufwachen prinzipiell nicht anzusehen, ob dieses ursächlich auf den Lärmstimulus zurückzuführen war oder spontan auftrat. Dennoch ist die korrekte Bestimmung der entsprechenden Wahrscheinlichkeit für die Prognose von nächtlichen Lärmwirkungen entscheidend. In diesem Artikel werden zwei Definitionen der Reaktionswahrscheinlichkeit eingeführt und deren Vor- und Nachteile besprochen. Ferner wird ein Modell zum Einfluss der Dauer des Zeitfensters, in dem Reaktionen des Schläfers geprüft werden, auf die berechnete Reaktionswahrscheinlichkeit entwickelt.

Schlüsselwörter

Ereignisbezogene Reaktionen · Lärmwirkungen · Reaktionswahrscheinlichkeit · Wahrscheinlichkeitsrechnung · Aufwachreaktionen · Schlafstörungen

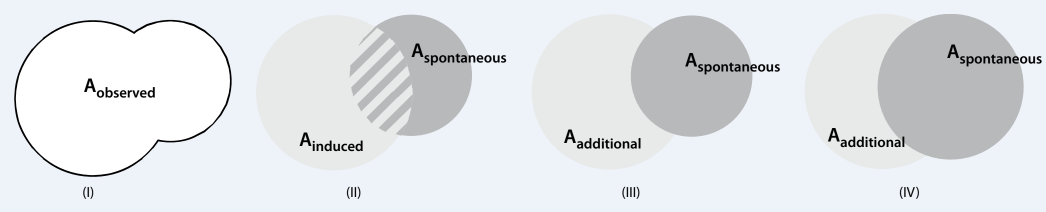

Fig. 1 ◀ Venn diagrams of the sets $A_{observed}$, $A_{spontaneous}$, $A_{induced}$, and $A_{additional}$

ory. Such events are sets (of so-called elementary events). When it comes to awakenings, the relevant sets of events within a time window are the following:

- $A_{observed}$: awakening within the time window;
- $A_{spontaneous}$: spontaneous awakening within the time window; it takes place independently of any noise event that might be present in the same time window;
- $A_{induced}$: awakening within the time window which is caused by a noise event.

More precisely, one can define $A_{spontaneous}$ as the "event" that *at least one* spontaneous awakening takes place in the time window, and similarly for the other two events. For short time windows, two spontaneous awakenings are not plausible, but for longer windows, the specification "at least one" is important.

One can conclude that the event of *observable* awakening is the set union $A_{observed} = A_{spontaneous} \cup A_{induced}$. Because in *every* time window during a night, a spontaneous awakening *can* occur, both spontaneous *and* induced reactions can occur in the same time window. Thus, the intersection between the two sets – formalized as $A_{spontaneous} \cap A_{induced}$ is not empty. $A_{spontaneous}$ and $A_{induced}$ are not mutually exclusive. The meaning of the intersection as regards the event of awakening can be illustrated as follows: At the beginning of the time window, the sleeper might have a nightmare that *will* lead to an awakening reaction in the middle of the time window, while at the same time a noise event (e.g., a very loud jumbo jet at low altitude) starts to build up that would *also* lead to an awakening reaction in that same time window. The probabilities of the events just introduced shall be referred to as:

- $P_{spontaneous}$: probability of at least one spontaneous awakening reaction within the time window;
- $P_{induced}$: probability of at least one noise induced awakening reaction within the time window;
- $P_{observed}$: probability of at least one awakening reaction within the time window;
- $P_{additional}$: probability of at least one noise induced awakening reaction within the time window, but no concurrent spontaneous awakenings would have occurred in the same time window (in other words: the noise event is the sole and only possible reason for the awakening).

From these definitions, $P_{additional}$ can directly be calculated as

$$P_{additional} = P_{observed} - P_{spontaneous} \quad (1)$$

It is reasonable to ask how these probabilities can be estimated from the frequency of observed awakening reactions. As discussed below, $P_{observed}$ and $P_{spontaneous}$ are obtained empirically, and therefore, $P_{additional}$ is also easy to determine. With the following calculations, it will be clear that $P_{induced}$ is yet another quite simple function of the observable quantities. Let us therefore return to considering events, their probabilities, and their interpretation.

Both $P_{additional}$ and $P_{induced}$ are measures for adverse effects of noise events. While the calculation of $P_{additional}$ is quite straightforward, the derivation of $P_{induced}$ is not immediately obvious. To calculate $P_{induced}$ one needs to consider all four possible cases that can occur within a time window. These cases are:

a) at least one awakening reaction which is induced by noise, but no spontaneous awakenings ($A_{induced} \setminus A_{spontaneous}$)[1];
b) at least one spontaneous awakening but no noise induced awakening reactions ($A_{spontaneous} \setminus A_{induced}$);
c) at least one spontaneous and at least one induced awakening reaction ($A_{spontaneous} \cap A_{induced}$). This means that awakening was caused by noise, but would also have occurred spontaneously, or the awakening occurred spontaneously but would also have occurred because of noise;
d) no awakening.

[1] The backslash "\" denotes the set difference, it can be read as "in $A_{induced}$ but not in $A_{spontaneous}$".

Cases a, b and d are non-ambiguous. In Case c, the observed reaction can either be attributed to noise or be classified as spontaneous. Assuming statistical independence of the two causes, the probabilities for Cases a to d are

$$P_a = P_{induced} \times (1 - P_{spontaneous}) \quad (2a)$$
$$P_b = P_{spontaneous} \times (1 - P_{induced}) \quad (2b)$$
$$P_c = P_{spontaneous} \times P_{induced} \quad (2c)$$
$$P_d = (1 - P_{induced}) \times (1 - P_{spontaneous}) \quad (2d)$$

All probabilities add up to 1, $P_a+P_b+P_c+P_d=1$. The probability of observable awakening reactions ($P_{observed}$) is thus equal to $1\text{-}P_d$, which can be expressed as

$$P_{observed} = P_{spontaneous} + P_{induced} \times (1 - P_{spontaneous}) \quad (3)$$

Solving Equation 3 for $P_{induced}$ leads to

$$P_{induced} = \frac{P_{observed} - P_{spontaneous}}{1 - P_{spontaneous}} \quad (4)$$

The above considerations highlight the fact that the probability of awakening from noise can be defined in two different ways: While $P_{induced}$ (Equation 4) expresses the probability of a noise induced awakening reaction *independently* of any other possible cause that might also lead to an awakening reaction at the same time, $P_{additional}$ (Equation 1) reflects only those awakenings that *solely* happen because of the noise event. As long as $P_{spontaneous}$ is greater than zero, $P_{induced}$ will always be larger than $P_{additional}$, and the difference between both probabilities increases with increasing $P_{spontaneous}$.

The difference between the two probabilities can be visualized using venn diagrams of the sets as displayed in **Fig. 1**.

Any observable awakening reaction lies within the large set shown in Panel I. The full light grey disk in Panel II represents the set of (all) induced awakening reactions, the dark grey disk (Panel III), the set of all spontaneous awakenings. The intersection (shaded) contains all events which can be considered both induced *and* spontaneous according to Case c above. While the full light grey disk in Panel II contains all *induced* awakenings according to our definition, the truncated part (a subset) of the same disk in Panel III contains just the additional awakening reactions. Panel IV demonstrates the dependence of the probability of additional awakening reactions on the probability of spontaneous awakenings.

If spontaneous awakenings became more frequent for any reason, the set of induced awakening reactions would remain the same, but the probability of the set difference ($A_{induced} \setminus A_{spontaneous}$), consisting of the additional awakening reactions, will decrease. Therefore, $P_{induced}$ is not confounded by any variations of $P_{spontaneous}$ or by spontaneous awakening probability which may include awakenings from other external causes, which are not in the focus of a particular study (e.g., noises from other traffic types), or from considering subpopulations of sleepers. However, this advantage basically takes effect only when one adheres to the assumption that noise induced and spontaneous awakenings are physiologically independent from each other. Without this assumption, it remains unclear how the probabilities should be determined. In the next section, whether this assumption should be retained or not is examined. Furthermore, the difference between $P_{induced}$ and $P_{additional}$ will be discussed in the physiological context.

Which indicator is more suitable?

Are stimulus-induced and spontaneous awakenings independent of each other?

The assumption of independence seems plausible at first sight, because for each of the two kinds of awakenings – spontaneous and induced – an appropriate cause can be stated which is obviously not influenced by the respective other cause. On the other hand, there is clear evidence that those sleep states in which spontaneous awakenings occur more frequently are also more prone for noise induced awakenings [2]. It can be postulated that in every state of sleep, some basic sleep regulatory process produces a certain *preparedness to awake*. This preparedness can be regarded as being permanently influenced by endogenous and exogenous processes (e.g., extero- and proprioceptive sensations, dreams, sleep regulating pacemakers). In this view, a noise event just increases the basically endogenous preparedness to awake. Depending on how pronounced this preparedness already was at the beginning of a time window, the noise event will or will not lead to an awakening. In this light, spontaneous and induced causes are not distinguishable anymore. Provided one abandons the independence assumption, $P_{additional}$ remains the only effect indicator that can be quantified without a detailed understanding of the constituents of "preparedness to awake".

Considerations for the choice

Which probability ($P_{additional}$ or $P_{induced}$) is better suited to be used as a noise effect indicator? The following must be considered when judging which indicator to prefer. The time windows within which the screening for awakenings takes place are usually very short (mostly between about 30 s and 1 to 2 min) in relation to the whole night. Then, the probability of both induced and spontaneous awakenings (cp. P_c and Equation 2c) is rather small, at least in healthy persons, and $P_{additional}$ and $P_{induced}$ are quite close to each other.

In terms of physiological significance, noise induced awakenings in Case a and in Case c cannot be compared: In Case c, a spontaneous awakening would have taken place anyway, e.g., as a consequence of a sleep regulating process which normally produces between 20 and 30 spontaneous awakenings per night [15]. In contrast to Case c, in Case a the sleeper might be at the beginning of a new sleep cycle without any endogenous triggering mechanism to awake being 'active'. An awakening reaction because of a noise event out of such a state must be considered the more severe sleep disturbance. Concerning the choice for an effect indicator, this places $P_{additional}$ ahead of $P_{induced}$.

Nevertheless, $P_{induced}$ has some advantages on the conceptual level. The distinction between additional and induced awakenings provides a sound basis for predicting how the probabilities will change if the conditions under which spontaneous and observed reactions are observed, change. Another advantage of calculating and using $P_{induced}$ becomes clear when one looks at the influence of the duration of the *time window* within which sleepers are screened for awakenings.

Choosing optimal time window duration

An important problem which must be addressed in every event related noise effects analysis is the question of how long a particular noise event can reasonably be made responsible for an observed reaction, and therefore, how long a time window should be defined to scan for reactions of sleepers to noise events. The larger such a time window is, the higher the probability will be to observe at least one spontaneous awakening. Therefore, any measure of reactions caused by noise is also dependent on the length of the time window adopted for screening.

Modeling probabilities and their dependence on the length of time windows

To better understand the implications of the time window duration, one can model the course of $P_{spontaneous}$ and $P_{induced}$ by breaking down the probabilities to the level of 1-second intervals and further extrapolate these probabilities to time windows

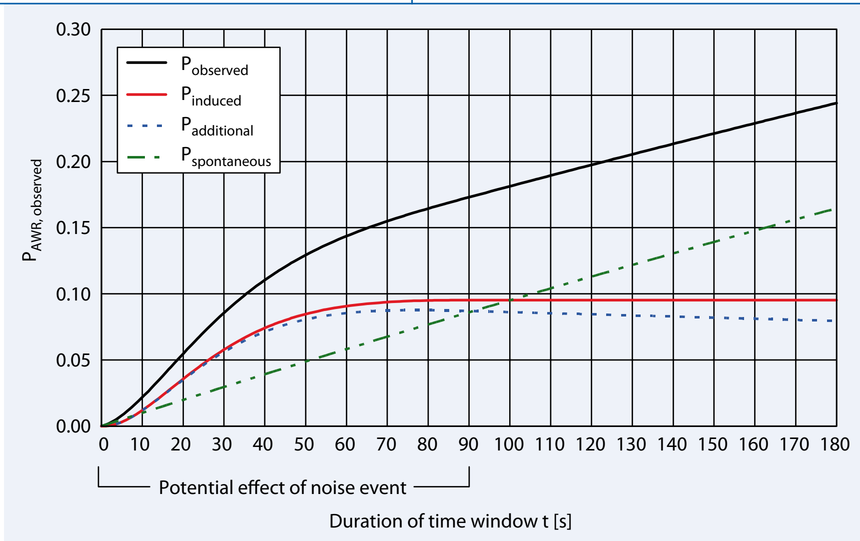

Fig. 2 ▲ Effect of the length of the time window t (s) on the probability of observing at least one awakening reaction of the types $A_{observed}$, $A_{induced}$, $A_{additional}$, and $A_{spontaneous}$

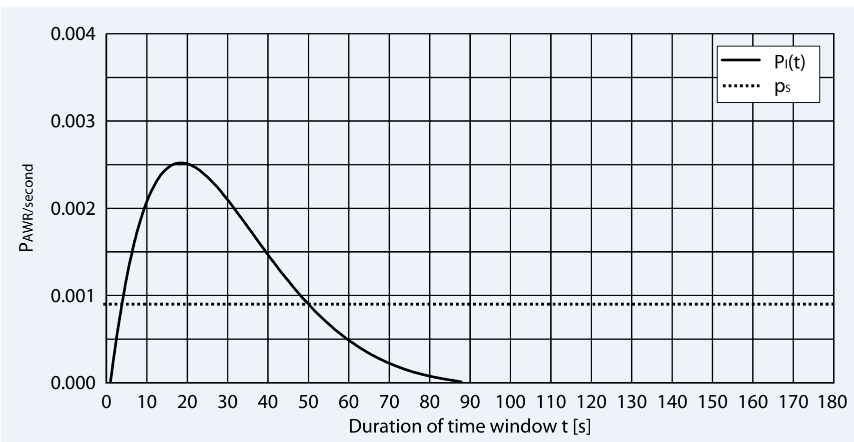

Fig. 3 ▲ Unconditional probabilities p_S (spontaneous) and $p_I(t)$ (induced)

of longer duration. For this modeling, let us assume that at the beginning of the time window, at t=0, the subject is asleep and a noise event starts to build up, which could be a cause for an awakening reaction during the first 90 s of the time window. 90 s is an arbitrary chosen value in this model. **Fig. 2** shows the development of the four probabilities as the time window grows from 1 to 180 s duration.

The calculations to draw the curves are as follows: Let the probability of awaking spontaneously within 1 second be p_S, and denote the probability of not awaking spontaneously until time t by $P_{ns}(t)$. Then,

$$\begin{aligned} P_{ns}(t) &= P_{ns}(t-1)\cdot(1-P_s) \\ &= (1-p_s)^t \cdot P_{spontaneous}(t) \\ &= 1-P_{ns}(t) \end{aligned} \quad (5)$$

where

- p_S : probability of observing a spontaneous awakening reaction in each second within the time window;
- $P_{ns}(t)$: probability of not having observed any spontaneous awakening reaction after t seconds (P_{ns},t=0=1);
- $P_{spontaneous}$ (t) : probability of having observed at least one spontaneous awakening reaction after t seconds.

The probability of spontaneous awakening in a 90-second time window was reported in an earlier field study as 0.086 [5]. This example value can now be used to obtain the one-second awakening probability p_S from 1 - $P_{spontaneous}(90) = (1- p_S)^{90}$, leading to $p_S = 1-(1-0.086)^{1/90} = 0.000999$. In this basic model, the probability for having observed at least one spontaneous awakening within a time window of duration t ($P_{spontaneous}(t)$) increases, while the slope of the curve slowly decreases with time. $P_{spontaneous}$ (t) approaches 1 asymptotically.

Next, we model the probability of having observed an induced awakening reaction within a time window of duration t, $P_{induced}(t)$, in a similar fashion, the difference being that the probability of an induced awakening in the t-th second is not constant over time but follows a curve $p_I(t)$ which is assumed to more or less follow the sound pressure level of the noise event. The probability is basically determined by the shape of the waveform of the noise event. For noise events with steadily rising levels, such as aircraft flyovers, it can basically be assumed to be low at the very beginning of the noise event and rather high at the point where the maximum sound pressure level is reached or shortly thereafter. Here, a slightly skewed bell-shaped curve is assumed (**Fig. 3**; the exact function to draw the curve was chosen arbitrarily but its shape has only very little influence on the final result). The equations for the calculation of $P_{induced}(t)$ are

$$\begin{aligned} P_{ni}(t) &= P_{ni}(t-1)\cdot P_I(t) \\ P_{induced}(t) &= 1-P_{ni}(t) \end{aligned} \quad (6)$$

where

- $P_{ni}(t)$: probability of not having had any induced awakening reaction until the t-th second ($P_{ni}(0) = 1$);
- $p_I(t)$: probability for having an induced awakening reaction within second t;
- $P_{induced}(t)$: probability of at least one induced awakening reaction until the t-th second.

The height of the curve $p_I(t)$ was chosen to obtain a value of $P_{induced}$ of 0.1 after 90 s. This value was chosen because it reflects a realistic probability for awakening due to a noise event and is slightly larger than the spontaneous awakening probability, so the different curves in **Fig. 2** become clearly distinguishable. Both $p_I(t)$ and p_S are plotted alongside each other in **Fig. 3**. After 90 s, as per our definition, the noise event has fully exploited its awakening potential, hence $p_I(t)$ is 0 for all t>90. The spontaneous awakening probability p_S is of course different: its independent potential to awake the sleeper is never exploited and stays at the same level throughout the time window.

Once the course of $p_I(t)$ and p_S in the time window (Fig. 3) are defined, the remaining curves in Fig. 2 can be calculated from Equations 1 and 3 as follows:

$$P_{additional}(t) = P_{observed}(t) - P_{spontaneous}(t)$$
$$P_{observed}(t) = P_{induced}(t) + P_{spontaneous}(t) - P_{induced}(t) \cdot P_{spontaneous}(t) \qquad (7)$$

where

- $P_{observed}(t)$: probability of having observed at least one awakening reaction after t seconds;
- $P_{additional}(t)$: probability of at least one induced awakening reaction until the t-th second, but no spontaneous awakening.

The curves in Fig. 2 show the time course of probabilities for the arbitrary values of p_S and $p_I(t)$ described above. However, the basic *shapes* of these curves are always the same, independent of these values.

Both the $P_{additional}$ and the $P_{induced}$ indicator depend on the length of the time window, with one small difference: As soon as the time window is long enough for the total potential of a noise event to contribute to an awakening reaction to be exploited, $P_{induced}$ does not depend on the window length, but remains constant. For the modeling above, it was assumed the noise event to have a potential effect during the first 90 s; hence $P_{induced}$ reaches its maximum after 90 s and then stays at its maximum value, regardless of the length of the time window. The choice of 90 s for a noise event to exploit its awakening potential in this model was made for several reasons: 90 s is slightly longer than it takes on average for a passing plane (or a distant train) to emit audible noise up to its maximum level and then decline again. It is reasonable to assume that if one awakes because of a noise event, such a reaction should more or less happen within a time span during which the noise source is audible. 90 s is the duration that is covered by three 30-second PSG epochs.

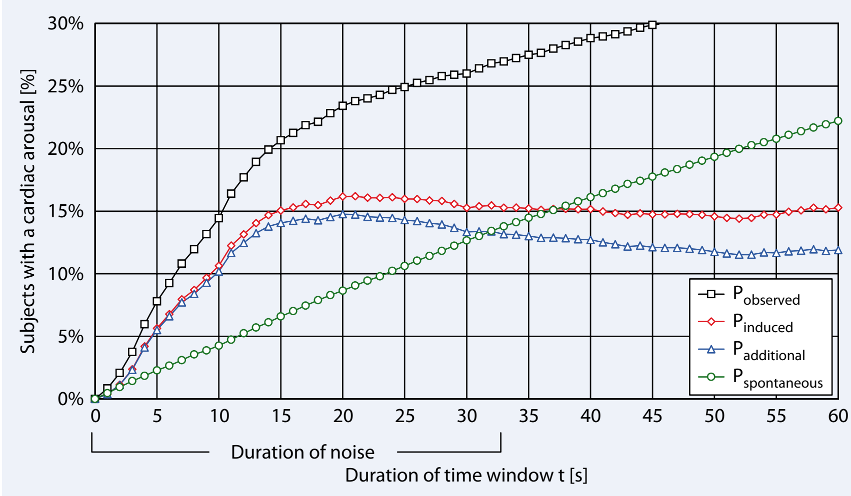

Fig. 4 ▲ Empirically determined course of the relative frequency of subjects having at least one cardiac arousal during and after the occurrence of an aircraft noise event ($L_{AS,max}$≥55 dB) within a time window of 60 s duration. Note: The curves showing $P_{induced}$ and $P_{additional}$ were not directly observed, but calculated from $P_{observed}$ and $P_{spontaneous}$. The data shown were collected by Basner and Samel [4] and analyzed by Basner et al. [3]

In contrast to $P_{induced}$, $P_{additional}$ will, after reaching its maximum value, slowly decrease as the length of the time window increases. This is an effect that can also be observed empirically, since the longer the time window is, the more spontaneous awakenings account for observed awakenings.

Empirical support

As the allocation of EEG awakenings demands epochs of considerably longer duration than 1 second, the effect of time window duration on the four discussed reaction probabilities can better be pinpointed with those kinds of reactions that can – in contrast to EEG awakenings – be related to a more or less discrete point in time, e.g. cardiac arousals which are defined as short-time accelerations of heart rate and occur within just a few seconds. As the theoretically derived behavior of the four curves must be the same for all kinds of binary reactions to external stimuli, we could use a data set from a study by Basner and collaborators who aimed at developing an ECG-based algorithm for the automatic identification of autonomous activations during sleep [3]. For that purpose, they reanalyzed data that were collected in a large polysomnographic study on aircraft noise and sleep carried out by the German Aerospace Center (DLR) between 1999 and 2003 [2, 4, 5]. The original data provide the empirical support for the shape of the curves in Fig. 2. Fig. 4 displays the course of the relative frequencies of subjects in [3] that had at least one cardiac arousal within a 60 second time window in which an aircraft noise event began to build up at t=0, reached an $L_{AS,max}$ of 55 dB after 10.5 s and ended at t=40 s. The course of the relative frequency of spontaneous cardiac arousals ($P_{spontaneous}$) was determined during time windows in nights without noise exposure. Data underlying Fig. 4 are from 95 subjects with 3219 aircraft noise time windows ($L_{AS,max}$=55 dB), and from 112 subjects with 23,937 noise-free time windows, the latter being used to determine $P_{spontaneous}$.

It is evident from Fig. 4 that the behavior of the empirically gained relative frequencies of cardiac arousals is remarkably close to the time course of the probability curves derived from theory and shown in Fig. 2. For drawing the curves in Fig. 4, initially, only the relative frequencies of observed cardiac arousals during noise events, and the frequency of spontaneous cardiac arousals in noise-free time windows were used, and the values for $P_{induced}$ and $P_{additional}$ were calculated according to Equations 1 and 4. Contrary to expectation is the slight decay of $P_{induced}$ after it reaches its maximum at about t=20 s. The most likely explanation for that is that noise evokes cardiac arousals more easily in light sleepers, and these – when having had at least one cardiac arousal within the first 20 s – are removed from the risk set for the rest of the time window: Consequently, the rate of induced cardiac arousals, expressed as $P_{induced}$, drops with each further second. While this cannot be observed directly, it is reflected in a slightly more pronounced decrease of the slope of $P_{observed}$ compared to the slope of $P_{spontaneous}$. This specific behavior of the curves is not accounted for in the system of equations developed so far. Doing so would have raised the complexity of the model without substantially enhancing the predictability of the general shape of the four curves.

How long of a time window should be chosen?

The length of the time window must be a multiple of the epoch duration which defines the smallest unit of time for which a dichotomous reaction variable (e.g., the assignment of the sleep or wake stage) is quantified, and it should practically be as long as required for a noise event to fully exploit its awakening potential.

A common epoch duration for polysomnographic analyses is 30 s [13, 19]. In such a case, the time window length must either be 30 s or a multiple thereof. If one chooses $P_{additional}$ as the relevant indicator, one carefully needs to explore at which length of the time window the additional awakening probability is maximal. Basically, this can only be determined empirically. Basner et al. [5]reported that after three epochs (90 s) the additional awakening probability due to aircraft noise events (which typically have a duration of between 30 and 90 s) was maximized. When planning to carry out polysomnographic noise effects studies, this might therefore be a good value to start with.

If one decides for $P_{induced}$ as the relevant effect indicator, one must make sure that the total effect of the noise event is fully accounted for within the time window. Therefore, it is advisable to rather opt for a longer than shorter duration. Empirically, the optimal duration can be determined by also systematically varying the time window length until $P_{induced}$ is maximal or stabilizes. Although $P_{induced}$ is (theoretically) stable even if one employs very long time windows, there is in practice still an upper limit of window duration because the occurrence of several noise events within a single time window must be avoided.

Discussion

The purpose of this methodological essay was to investigate to what extent the method of probability calculation and the choice of time window duration determines the calculated awakening probability and hence, exposure-effect relationships linking acoustical properties of noise events to awakening reactions. This article clarifies the probability calculation issues in this domain of research, provides the argumentation pertaining to the choice of the probability indicator, and suggests a theoretical model of the influence of the time window duration on effect probabilities.

It has been shown that, depending on the assumption of dependency/independency acted upon, two different approaches for awakening probability calculation exist.

The calculation of $P_{additional}$ according to Equation 1 neither requires nor excludes independent causes and hence, $P_{additional}$ is the only indicator which is valid under both the independency and the dependency assumption. It expresses the proportion of the probability of awakening that is ascribable to noise events only. It therefore also has the advantage that it is congruent with exactly those awakenings that can be prevented or be avoided with noise protection concepts. As long as the independence assumption is not explicitly retained, that means that awakening in a time window is regarded as possibly being the result of just one basically intrinsic process which is merely altered by external noise events, there is in principle no reason for adhering to a calculation of $P_{induced}$. However, the $P_{additional}$ indicator is clearly dependent on $P_{spontaneous}$, which might differ across studies, groups, or samples.

The main advantage of the $P_{induced}$ indicator is that it is less influenced by the particular circumstances (e.g., presence of other types of stimuli) that prevailed during the empirical determination of $P_{spontaneous}$. With regard to potential future meta-analyses on awakening probability from noise events, $P_{induced}$ would therefore be the indicator to prefer. Furthermore, it is less prone to the effects of a possibly too long time window duration. For these reasons, $P_{induced}$ also qualifies to be used as an effect indicator, provided the conceptual constraints discussed above are known and accepted.

To better understand the significance of time window durations, we modeled the course of the discussed probabilities for time windows of any duration and came to the conclusion that both the $P_{induced}$ and the $P_{additional}$ indicator demand a well-founded choice of time window duration. That duration should in principle be determined systematically by performing several analyses with varying time window lengths until the probability in question stabilizes or is maximal.

Using the proposed calculations and terminology above does of course not solve all methodological problems pertaining to the calculation of reaction probabilities and their significance in night time noise effects assessment at once. An important problem remaining to address are the effects of *interdependencies* of reactions to noise events. For forecasting awakening reactions for a particular night noise scenario, it is important to know whether the total probability of awakenings can be expected to be always the same, independent of a particular distribution of noise events over time in a night. This seems rather unlikely because, on the one hand, proneness to be awaken depends on sleep stage and increases with the time elapsed since sleep onset [5] and, on the other hand, any reaction to a noise event, whether awakening occurred or not, can surely influence the micro- and macrostructure of sleep and therefore also alter the probabilities of awakening at subsequent events.

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Erratum

S3-Leitlinie Nicht erholsamer Schlaf/Schlafstörungen

Somnologie (2009) Band 13, Supplement 1

Die oben genannte Leitlinie enthält einen Fehler auf S. 65, mittlere Spalte, 15. Zeile von unten:

> Der Effekt einer Therapie mit Unterkieferprotrusionsschienen ist i. d. R. geringer als der einer PAP-Therapie (Ferguson et al. 2006). Prädiktoren für einen Therapieerfolg von UPS sind ein niedriger AHI, eine deutliche Lageabhängigkeit der Schlafapnoe mit ~~minimaler~~ Ausprägung in Rückenlage, junges Alter, normaler BMI und geringer Halsumfang sowie weibliches Geschlecht. Bei entsprechender Selektion geeigneter Patienten, insbesondere solchen mit einer leicht-

Das Wort „minimaler“ soll in dem Satz „ […] eine deutliche Lageabhängigkeit der Schlafapnoe mit minimaler Ausprägung in Rückenlage, […]“ entfallen.
Wir bitten, diesen Fehler zu entschuldigen.
Die Online-Version des Originalartikels finden Sie unter:
http://dx.doi.org/10.1007/s11818-009-0430-8