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A NOISE METRIC FOR MULTI-SOURCE NOISE ENVIRONMENTS

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ABSTRACT
Many people are exposed not to one but to multiple noise sources. There is, however, no widely accepted noise metric that predicts the noise annoyance for such situations. Here the so-called representational approach to finding such a metric is described. In this approach a qualitative exposure-annoyance model is constructed for a multi-source noise environment, and a metric for the total noise is derived from that model. The model consists of five statements which reflect what we know (or take) to be true about the relationship between exposures caused by the individual noise sources that affect the same person, and the noise annoyance caused by the total, multiple exposure. The metric derived from the model has a consistent relation with the ordering of multiple noise exposures with respect to the annoyance they cause, provided that the five statement are valid.

1 - INTRODUCTION
In many cases people are exposed not to one but to a combination of environmental noise sources. As a consequence, there is a need for noise metrics that predict the adverse effects of combined exposures, in addition to the available noise metrics for individual sources. At present there is no such total noise metric that is widely accepted. An overview of proposals can be found in Schulte-Fortkamp et al. (1996). This paper presents total noise metrics that are found by formulating a model of the annoyance ordering of combined noise exposures, and investigating mathematically which total noise metrics numerically order the combined exposures in the same way. The important requirement that a noise metric must give a consistent indication of the annoyance ordering of the combined exposures is called the representation criterion. With this criterion, restrictions on the form of the total noise metric follow from the properties of the annoyance ordering, which are specified by the model.
The total noise metrics presented in this paper can be used in practice after the values of some parameters are estimated. That is, not one metric but a set of metrics is consistent with the annoyance model, and a single metric must be selected from this set by finding the values of various parameters.

2 - NEED FOR A TOTAL NOISE METRIC
Before investigating the total noise metric, the need for a total noise metric in practice is illustrated with three very different examples.
Land use zones in the surrounding of an industrial site
Complex industrial areas usually encompass a large number of sources which cause distinct environmental strains. If the environmental quality can be quantified, then zones with differing levels of environmental quality can be established in the area. For each zone different restrictions on the land use can be defined, prohibiting the construction of new houses, for example. A measure of the total noise caused by an industrial site and the roads in its surrounding can be used for establishing zones related to the combined noise.

Noise abatement measures
Regulations about environmental noise largely pertain to a specific noise source (e.g., road traffic, trains, aircraft, and industry). However, often there is not a single source, but rather a combination of noise sources. For example, around an airport there are instances of significant noise from both aircraft and road traffic. In such a case noise abatement based on exposure caused by a single source may be not sufficient. When evaluating the need for abatement due to combined exposures, a quantification of the combined exposures is needed.
Environmental impact assessment
In many countries the environmental impact of new activities, specifically large scale activities such as the development of a new railway line or the extension of an airport, must be thoroughly assessed. Often different alternatives are being compared with respect to their impact on the environment. Alternative plans differ in a number of environmental respects. A choice between them requires an integral evaluation. A quantification of the total noise (of new and existing sources) can be used to compare alternatives with respect to noise.

3 - DEFINITION OF A TOTAL NOISE METRIC AND A TOTAL NOISE QUANTIFICATION

The total noise metric that will be presented has been found by the so-called representational approach. In this approach a qualitative exposure-annoyance model is constructed for a multi-source noise environment, and a metric for the total noise is derived from that model. The model consists of five statements which reflect what we know (or take) to be true about the relationship between exposures caused by the individual noise sources that affect the same person, and the noise annoyance caused by the total, multiple exposure. The metric derived from the model has a consistent relation with the ordering of multiple noise exposures with respect to the annoyance they cause, provided that the five statement are valid. These statements can be discussed and tested separately. In this way the decision on a metric for a multi-source noise environment is broken down in the evaluation of five clear and explicit statements. The representational approach, i.e., first formulating a model of the ordering of exposures and then deriving from that model implications for the exposure metrics, is taken from measurement theory (see e.g.: Krantz et al., 1971). The theorem presented here can be found in a more general form in Miedema (1996), which also gives their proofs.

4 - THE THEOREM

The following procedure assigns numbers to multiple exposures so that the numerical ordering of exposures is consistent with the annoyance ordering, provided that the annoyance ordering has the five properties presented in the next section. It is assumed that the exposures from the individual sources are described by a L_{Aeq}-based metrics. Examples with different weightings are L_{Aeq}(24h) (no weights), DNL (10 dB penalty for noise in the period $22 - 7$h), CNEL (5 dB penalty for 19-22h, and 10 dB penalty for 22-7h), and DENL (5 dB penalty for $19 - 23$h, and 10 dB penalty for $23 - 7$h).
First for each source i in a combination, its level is converted into the equally annoying level of a reference source using linear matching functions $h_i(L_i) = a_i\ (L_i - b_i)$. Then, disregarding a multiplication by a positive factor α, these transformed equally annoying levels are combined as though they were all levels caused by the reference source, i.e. by energetic summation. More precisely, the total noise metric is:

$$L = 10.\text{lg}\left(\sum_i 10^{0.1\times\alpha\times a_i(L_i-b_i)}\right)^{1/\alpha}$$

This total noise metric gives a consistent indication regarding the annoyance ordering provided that the annoyance ordering satisfies the five properties that are discussed in the next section.
Miedema (1992, 1996) proposed a procedure that is based on the approach described here. He derived the values of the a_i and b_i from exposure-annoyance relationships for individual sources, and provisionally proposed to set α=1. Unaware of this approach, Vos (1992) proposed a similar procedure which additionally assumes on the basis of data from laboratory experiments that α=0.67. The estimation of the parameter values and the available evidence regarding their values is not discussed here.
The above procedure is an informal description of a theorem that has been mathematically proven to be correct (see: Krantz et al., 1971; Miedema, 1996). This theorem is *not* an empirical theory. It says that if the annoyance ordering has certain empirical properties, then the above procedure gives a total noise metric that represents the annoyance ordering. In principle, verification of these properties requires empirical testing. The properties may be accepted without testing if they are considered to be very plausible, or acceptable simplifications or idealizations.

5 - THE PROPERTIES OF THE ANNOYANCE ORDERING

The numbers assigned to multiple exposures by the metric presented in the previous section give a consistent indication of the annoyance ordering of the exposures, provided that the annoyance ordering has the following five properties. In the formulation of the properties, x_i and y_i are levels of the metric for an individual source, and both $x=(\ldots,x_i,\ldots)$ and $y=(\ldots,y_i,\ldots)$ are combinations of such levels of individual sources.
Transitivity: if x "is at least as annoying as" y, and y "is at least as annoying as" z, then x "is at least as annoying as" z.
Restricted solvability: if x "is at least as annoying as" y, then the exposure of any source in the combination y can be changed so that the combination becomes equally annoying as x.
Independence: if x and y both are combinations of exposures such that

- the exposure level of source i in combination x is at least equal as in combination y (i.e., $x_i \geq y_i$),
- the exposure levels of the other sources are equal (i.e., $x_j=y_j$ for all $j\neq i$), then x "is at least as annoying as" y.

Connected (on n, with n>2): x "is at least as annoying as" y or y "is at least as annoying as" x (or both) for any x and y.
Restricted context independence: given a positive number s that is added to the noise exposure level of the k-th source, then there are positive numbers r_i for all sources, with $r_k=s$, such that $(\ldots,x_i+r_i,\ldots)\check{s}(\ldots,y_i+r_i,\ldots)$ if and only if $(\ldots,x_i,\ldots)\check{s}(\ldots,y_i,\ldots)$.
Here $\check{s}$ must be read as "is at least as annoying as".
The addition of a positive number in the above definition of restricted context independence can be thought of as a change in the unit of the metric underlying the logarithmic noise exposure metric, i.e. a change in the unit of sound intensity. Therefore the above property can be also formulated as follows. If the unit of the underlying noise exposure metric of the k-th source is changed (multiplication by a positive number s), then the units of the underlying metrics of the other sources can be changed (multiplication by a positive number r_i).

6 - INDEPENDENCE

Independence is the most crucial property. It can be illustrated as follows. Consider the two following orderings of exposure situations with respect to the degree of annoyance they cause:

- the annoyance ordering of all situations with only road traffic noise;
- the annoyance ordering of the situations obtained from these 'only road traffic noise' situations by adding to each the same aircraft and railway noise combination.

Then independence holds only if the addition of the aircraft and railway noise does not affect the annoyance ordering.
The following example illustrates the probably most important violation of independence. Consider:

- the annoyance ordering of all situations with only road traffic noise;
- the annoyance ordering of the situations obtained from the 'only road traffic noise' situations by adding to each the same tonal sound.

Then independence is violated if the tonal sound with little or no road traffic noise is more annoying than the tonal sound with a higher level of road traffic noise. This may actually occur if the tonal sound is masked the latter case. A similar phenomenon may be found with very low frequency noise, or impulsive noise instead of tonal noise. In these cases the annoyance reduction caused by the masking of the very irritating sound may outweigh the annoyance increase caused by the higher road traffic noise.
Although such situations do exist, they will be rather scarce because of the following reasons:

- The above-mentioned types of very irritating sounds, for which the described effect may be important, are rather scarce compared to the widespread prevalence of noise from various types of transportation, or industry without these specific aspects.
- In general, if the above-mentioned types of very irritating sounds occur, it is unlikely that masking will occur to an extent that affects the reaction to this sound. The reason for this is that important binaural masking requires, in addition to a sufficiently high level of the masker, overlap in time, overlap in frequency spectrum, and spatial proximity of the source of the irritating sound and the masking noise.

Findings of Fields (1998) demonstrate that the influence of a second noise source on the evaluation of another source in general is not important. This supports that the above discussed violations of independence in general are not important. He found that "residents' reactions to an audible environmental noise (...) are only slightly or not at all reduced by the presence of another noise source (...) in residential environments".

7 - DISCUSSION AND CONCLUSION

In conclusion, the total noise metric

$$L = 10.\lg\left(\sum_i 10^{0.1\times\alpha\times a_i(L_i-b_i)}\right)^{1/\alpha}$$

gives a consistent indication of the annoyance caused by combined exposure levels L_i of individual sources The most important assumption underlying the use of this metric as an indicator of the total annoyance from multiple exposures has been discussed. Limitations to the range of application due to violation of this assumption in specific circumstances have been pointed out.

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