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## Preferred Levels of Auditory Danger Signals

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An important issue at the design stage of the auditory danger signal for a safety system is the signal audibility under various conditions of background noise. The auditory danger signal should be clearly audible but it should not be too loud to avoid fright, startling effects, and nuisance complaints. Criteria for designing auditory danger signals are the subject of the ISO 7731 (International Organization for Standardization [ISO], 1986) international standard and the EN 457 European standard (European Committee for Standardization [CEN], 1992). It is required that the A-weighted sound pressure level of the auditory danger signal is higher in level than the background noise by 15 dB. In this paper, the results of an experiment are reported, in which listeners adjusted most preferred levels of 3 danger signals (tone, sweep, complex sound) in the presence of a noise background (pink noise and industrial noise). The measurements were done for 60-, 70-, 80- and 90-dB A-weighted levels of noise. Results show that for 60-dB level of noise the most preferred level of the danger signal is 10 to 20 dB above the noise level. However, for 90-dB level of noise, listeners selected a level of the danger signal that was equal to the noise level. Results imply that the criterion in the existing standards is conservative as it requires the level of the danger signal to be higher than the level of noise regardless of the noise level.

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## 1. INTRODUCTION

Auditory danger signals are used in many industries. Safety systems usually make use of visual and auditory warning signals. Owing to omnidirectional propagation of sound, auditory signals have proved to be reliable means for alerting of danger, especially in conditions of limited visibility.

In factories, audibility of warning signals is almost always affected by background noise, and also depends on workers' hearing ability, as well as on the use of hearing protectors (Coleman & Simpson, 1994). An auditory danger signal should be clearly audible but it should not be too loud, to avoid fright, startling effects, and annoyance. A signal, which is too loud, may cause nuisance complaints. A proper level of a danger signal may be difficult to obtain at all places in the signal reception area, especially when the characteristics of background noise are variable. For those reasons, audibility of danger signals must be the greatest concern at the design stage of any safety system. Criteria for designing auditory danger signals are the subject of the ISO 7731 international standard (ISO, 1986) and the EN 457 European standard (CEN, 1992). The purpose of the experiment described in this paper was to measure whether the levels of danger signals preferred by listeners are consistent with the requirements of these standards.

### 1.1. Requirements of Standards

Acoustical design criteria stated in the ISO 7731 (ISO, 1986) and EN 457 (CEN, 1992) standards are practically identical. Both standards describe basic requirements for the spectral characteristics, temporal pattern, and levels of auditory danger signals. According to these standards, the danger signal should include spectral components in a frequency range from 300 to 3 kHz, and its spectrum shape and temporal pattern should be different from the spectrum and temporal envelope of background noise.

The standards introduce two methods for determining the level of auditory danger signals. The first method is simple and relies on A-weighted sound pressure levels of the signal and noise measured in the reception area. The level of the danger signal should exceed by at least 15 dB the level of background noise.

The second method is more complex and makes use of an octave-band or 1/3-octave-band analysis of the signal and noise spectra. In

addition, the signal level is increased in certain frequency bands to account for the spread of masking from adjacent bands. The spectrum corrected in this way is called the effective masked threshold. The effective masked threshold is used to calculate the minimum spectrum level of the danger signal. It is required that at least in one band, the spectrum level of the danger signal is greater than the effective masked threshold by 10 dB when levels are measured in octave bands, and by 13 dB when 1/3-octave bands are employed. In both cases, the A-weighted signal level should not be less than 65 dB(A), regardless of the background noise level.

## 1.2. Considerations Leading to the Present Experiment

In our previous work an adaptive danger signal generator was developed, tested, and implemented (Podgórski, Żera, & Kosowski, 1998; Żera, Kotarbińska, & Puto, 1998). This device generates auditory danger signals maintaining a constant signal-to-noise level difference, to provide the required audibility of the danger signal. This is achieved by monitoring the background noise and measuring its spectrum in octave bands, in a frequency range from 63 to 4 kHz. This measurement is used to adjust the level and spectrum of the danger signal.

The adaptive danger signal generator strictly complies with the ISO 7731 (ISO, 1986) and EN 457 (CEN, 1992) standards. However, in many practical situations we observed that the amplification of the signal needed to obtain proper audibility was different from that described in the standards. The present study was carried to verify the levels described by the aforementioned standards in an experiment employing listening tests.

## 2. EXPERIMENT

The purpose of the experiment was to assess the most preferable level of danger signals, generated in the presence of certain background noises. Nine conditions, including three types of danger signals and three types of background noise, were investigated. The listeners adjusted the level of danger signals to obtain proper audibility in the given noise conditions.

## 2.1. Background Noises

The background noises used were pink noise and two samples of noise recorded in a factory. Pink noise was generated using a Brüel&Kjaer 1049 generator. The samples of noises recorded in the factory were high-frequency noise of a milling machine and low-frequency background noise of a machinery shop. The noise samples were played back continuously during the measurement session. Their A-weighted levels were set at 60, 70, 80, and 90 dB.

## 2.2. Danger Signals

The types of danger signals included a 1000-Hz tone, a logarithmic sweep tone (sweep in a frequency range of 500-2000 Hz), and a 10-component harmonic complex with a 300-Hz fundamental frequency. The duration of all signals was 1 s. The sweep tone was used to obtain a signal varying in frequency. In each 1-s segment of the sweep tone, the pattern of increasing frequency was repeated three times.

## 2.3. Apparatus and Measurement Procedure

Listening sessions were carried out in a laboratory room, 140 m<sup>3</sup> in volume, 0.2 s reverberation time. Background noise was played back with the use of four Tonsil Scherzo 350 loudspeakers. The loudspeakers were placed on a trapezoidal foot plane. The distance of the loudspeakers from the median axis of the listening area was 0.4 m (front loudspeakers) and 2 m (rear loudspeakers). The distance between the front and rear loudspeakers was 3.5 m. The listener was seated on the median axis at the distance of 1.8 m from the front loudspeakers. To ensure stable listening conditions the listener was required to lean his head against a special head-rest. The danger signals were played back using two JBL SR4722A loudspeakers standing on the median axis, at the distance of 1.8 m, in front of the participant. All loudspeakers were driven by Crown 460 CSL power amplifiers.

The experiment was controlled using a PC computer equipped with a Tucker-Davis Technologies (TDT) System II DSP processor and an Audiomeia III sound card. The danger signals were played back at

a sampling rate of 44.1 kHz with the use of a TDT DD1 16-bit DA converter. The level of the danger signals was controlled in 1-dB steps with a TDT PA4 programmable attenuator.

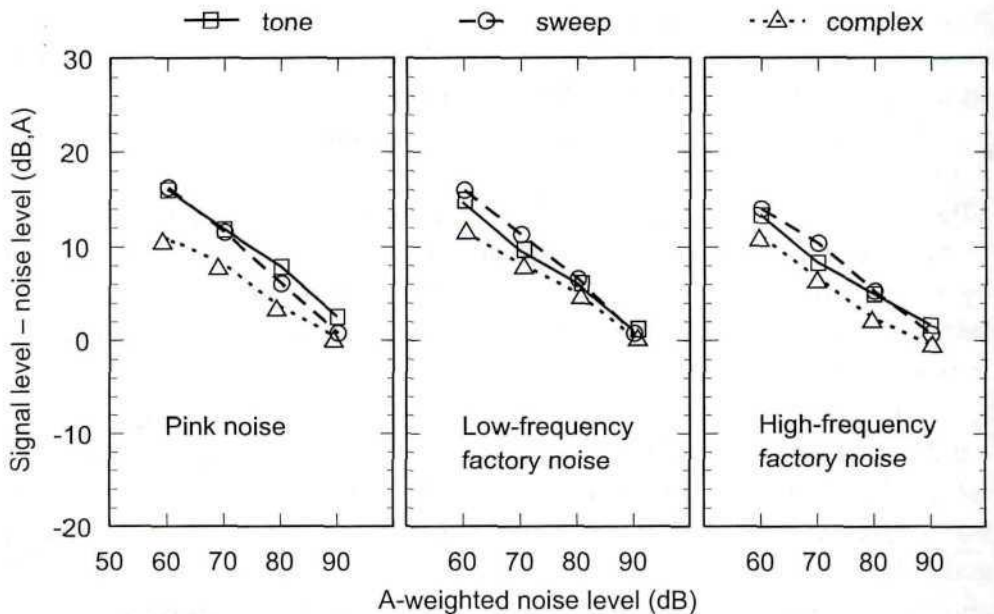
After selecting a background noise sample and setting its level, a block of measurements began. In a block, the listener made five adjustments of the level of three danger signals presented in random order. One block of measurements lasted about 10 m and was followed by a 3-min break. Then the measurements were continued at a different level of background noise. Measurement session with 1 participant lasted for about 2 hrs.

A method of free adjustments was employed. The listener used a multi-turn knob to adjust the level of the danger signal and make the signal clearly audible in the presence of background noise. The listener was instructed to avoid excessively high levels that would cause fright and startling effects. The listener was allowed to adjust the signal at will and pressed a button to signal that the adjustment was completed. Four participants took part in the experiment. All of them had hearing sensitivity within normal range.

### 3. RESULTS

The levels of danger signals averaged across 4 listeners are combined in Figure 1. Data obtained for three types of background noise, that is, pink noise, low-frequency factory noise, and high-frequency factory noise are shown in the left, middle, and right panel, respectively. The abscissa shows the A-weighted level of background noise and the ordinate represents the signal-to-noise ratio in decibels. Results for a 1000-Hz tone are plotted with a solid line and open squares. Dashed line and open circles represent the data obtained for a 0.5-2 kHz sweep tone, and the dotted line and open triangles indicate data obtained for a harmonic complex with a 300-Hz fundamental frequency.

The data show that the signal-to-noise ratio corresponding to the preferred listening level decreases when the level of background noise is increased. This tendency is common to all types of background noise and danger signals. At a 60-dB noise level the signal level is by 10-16 dB higher than the noise level; at a 90-dB noise level, the difference in level between signal and noise ranges from  $-2$  to  $+3$  dB. The adjusted signal-to-noise ratio decreases by 10 to 15 dB when the noise level is



**Figure 1.** Signal-to-noise ratios most-preferred for danger signals presented in three different background noises. Data averaged across 4 listeners, all levels measured as A-weighted sound pressure levels. Controlled variable: danger signal level. Method: method of adjustment. Danger signals: a 1000-Hz tone (solid line, squares), a logarithmic sweep tone from 500 Hz to 2000 Hz (dashed line, circles), a harmonic complex with 300-Hz fundamental frequency (dotted line, triangles). Background noises: pink noise (left panel), low-frequency (middle panel), and high-frequency (right panel) factory noise.

increased from 60 to 90 dB. On average, the decrease is about 0.3 to 0.5 dB per 1-dB increase of noise level. This result is not surprising although it is not taken into account by the ISO and EN standards. As mentioned earlier, the standards require a constant signal-to-noise ratio of 15 dB regardless of the background noise level. The finding that danger signals are audible at a lower signal-to-noise ratio at high noise levels is an effect of the loudness recruitment phenomenon known in psychoacoustics and in audiology (Stevens & Guirao, 1967). Due to loudness recruitment the increase in loudness with level is faster in the presence of high-level background noise than at low levels of noise and in quiet.

The data suggest that the requirement of a 15-dB signal-to-noise ratio set by standards is rather conservative. In this experiment, the level of the danger signal exceeded the noise level by about 15 dB only at

noise level of 60 dB. However, it should be noted that in real work conditions, attention of a person in a danger signal reception area is focussed on work. Thus, a higher level of a danger signal may be required. It should also be noted that the signal-to-noise ratio depends to some extent on the frequency and spectrum of the danger signal.

#### 4. CONCLUSIONS

Results of the present experiment show that the signal-to-noise ratio decreases from about 15 to  $-2$  dB when the A-weighted level of background noise is increased from 60 to 90 dB. This finding is in agreement with the phenomenon of loudness recruitment observed for signals partly masked by noise. The data obtained in this experiment may be used to refine the criteria of auditory danger signals given in the ISO 7731 (ISO, 1986) and EN 457 (CEN, 1992) standards.

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