# Auditory Evacuation Beacons*

**SANDER J. VAN WIJNGAARDEN,** *AES Member,* **ADELBERT W. BRONKHORST, AND LOUIS C. BOER**

*TNO Human Factors, 3769 ZG Soesterberg, The Netherlands*

Auditory evacuation beacons can be used to guide people to safe exits, even when vision is totally obscured by smoke. Conventional beacons make use of modulated noise signals. Controlled evacuation experiments show that such signals require explicit instructions and are often misunderstood. A new signal was designed that combines a chime sound with a spoken message ("exit here"). In a tunnel environment the evacuation success rate without prior instructions to the participants was 16% for conventional beacons and 87% for the newly designed beacons. Also, a novel way for coding the relative distance to the exit was used. By exploiting the precedence effect through the application of time delays, subjects were induced to naturally "follow" the sound. During an experiment in the mockup of a ship's interior 88% of participants followed the intended route compared to 38% with the conventional approach. The optimum time delay between beacons was found to be approximately 20 ms.

## 0 INTRODUCTION

In many emergencies a quick and efficient evacuation of endangered people is vital. Methods to help improve the evacuation process, such as clear indications of emergency exits, often save lives. One of the complications arising during the evacuation of people is that vision may be obscured by smoke. This may prevent fleeing people from localizing safe exits. A possible solution is to mark the locations of these exits by auditory evacuation beacons, or sound beacons. A sound beacon is a sound source placed near an exit, audible to people in the immediate surroundings of this exit. Humans are capable, within limits, of directional hearing [1]. By finding the direction from which the sound is coming, they can find out where to run in order to find a safe exit. The sound beacon technology was pioneered by Sound Alert Technology, based on research done at the University of Leeds [2]. They promote the use of pulsated noise as an evacuation signal. In this report the type of signal used by Sound Alert will be called "conventional" beacon signal. Alternative signals will be described, which were specifically designed to perform well when used with auditory evacuation beacons.

In Section 1 design criteria for auditory evacuation signals are proposed, and a specific set of signals is derived from these criteria. Section 2 describes experiences with these signals (and the conventional pulsated noise signals), obtained during simulated evacuations from a traffic tunnel. These experiments were carried out under carefully controlled conditions. They indicate human performance during an evacuation from a tunnel filled with smoke, with and without the aid of auditory beacons. Similar experiments, but in a ship's interior instead of a tunnel, are described in Section 3. Section 4 explores the robustness of a proposed way to indicate routes along multiple sound beacons by making use of the so-called precedence effect.

## 1 DESIGN OF AUDITORY EVACUATION BEACONS

### 1.1 Using Design Criteria to Obtain Suitable Signals

To optimize any design process, it helps to compile an explicit list of design criteria. This was done for the design of optimal sound beacons, resulting in the following list:

1) The sound beacons must be audible (despite background noise).

2) The sounds produced must be sufficiently salient.

3) The sounds must be sufficiently localizable.

4) If possible, the sounds must be self-explaining.

5) The sounds should interfere as little as possible with other useful sounds, such as public-address systems and interperson speech communication.

6) When multiple sound beacons are used together, the route along these beacons (toward the exit) must be coded unambiguously.

Audibility of the sound beacon, the first design criterion, can be met by adjusting the sound level to be sufficiently high. (ISO 7731 [3] recommends a signal-to-noise ratio of 15–25 dB for danger and warning signals.) Of course, in very high noise levels this leads to a required

---

*Manuscript received 2004 April 7; revised 2004 December 2.

sound level of the evacuation beacon that is even higher. Even if it is technically feasible to generate such sound levels in a beacon of limited dimensions, it may not be wise to do so. Such extremely loud warning signals may only add to the confusion, and may even promote a sense of panic. This means that in high-noise environments (such as industrial plants and track vehicles), auditory beacons are probably not the best solution.

The second criterion (saliency) can be addressed by the field of expertise known as sound design. Signals can be optimized in terms of objective acoustic measures that predict saliency, such as tonality, roughness, and loudness. Saliency can be measured (or verified) through subjective experiments, using listener panels.

The third criterion (localizability) can be met by choosing the spectral and temporal structure of the signal to make localization easy, utilizing knowledge of the human auditory system. Humans use three different types of cues for the localization of sound: interaural time differences, interaural level differences, and spectral cues. Because the latter cues in particular are mostly present at high frequencies (>2 kHz), the sounds need to cover a wide frequency range (up to 16 kHz or higher) and show a sufficiently close spacing of frequency components. Pulses, clicks, or sharp onsets also enhance localizability. There is a wealth of scientific literature on spatial hearing that helps in constructing signals that can be localized accurately (such as [1],[4]–[6]). The noise-based signals used for conventional sound beacons consist of square-wave modulated thermal noise, with a modulation frequency of 5–10 Hz, and a spectrum that is (approximately) flat on a logarithmic scale after reproduction through a loudspeaker. This is one good way to create a signal that is easy to localize. However, other signals may be constructed that are localized with the same accuracy, but which perform better in terms of the other design criteria.

The fourth criterion (self-explaining) may be at odds with saliency and localizability. Certain sounds that are noticed easily (very harsh and dissonant sounds) are probably not the ones that are most easily associated with a safe exit. Similarly, reinforcing high-frequency components in signals to improve localizability is likely to reduce the attractiveness, again disassociating it from the suggestion of a safe exit.

Minimization of interference with other useful sounds (the fifth criterion) can be achieved in two ways—by keeping the beacon sound level low (at the expense of audibility) or by allowing periodic lapses of silence (pauses) in the beacon signal. The latter strategy can be very effective. Speech especially is, by its redundant nature, relatively robust against intermittent interruptions through interfering sounds.

Indicating a complex route to an exit by using multiple beacons (the sixth design criterion) can be done by using a "code" to change the beacon sound depending on the distance to the exit. Two ways to achieve this are explained later in this section.

## 1.2 Design Choices for Signal

The six criteria defined in the preceeding section have been used to design an example of a well-chosen sound beacon signal. This newly designed beacon signal will be referred to here as the TNO signal.

### *1.2.1 Audibility*

Audibility is ensured by choosing an appropriate sound level and is of little concern for the choice of the signal structure. It may be necessary to take special precautions to improve audibility when disproportionate numbers of hearing impaired people are expected. In such cases it can be beneficial to invest a higher proportion of the acoustic energy in the lower frequency range (at the expense of localizability), since most hearing impaired are more sensitive at lower frequencies. However, this aspect is not considered in the current design.

### *1.2.2 Temporal and Spectral Structure of Signal*

The newly designed signal is based on a chimelike sequence of two harmonic two-tone complexes. This sequence starts with a C plus E complex (fundamental frequencies 262 and 330 Hz) and a duration of 200 ms. This is followed by a 200-ms silence and then a 200-ms E plus G complex (fundamental frequencies 330 and 392 Hz). After another 200-ms silence this whole pattern is repeated. Between the chime sounds, a spoken message is played (such as "exit here"). The structure of the complete signal is shown in Fig. 1.

The tone pulses have maximally sharp onsets; no tapering is applied. The tone complexes contain each harmonic of both fundamentals, up to a frequency of 20 kHz. Each harmonic is attenuated by 3% compared to the next lower harmonic, to reduce the harshness or unpleasantness of the sound, and is given random phase. Fig. 2 shows the spectrum of the first tone complex in the sequence (C + E).

The speech signals are clipped at 6 dB below the peak level (highest individual sample value in the original signal) to decrease the crest factor and increase the high-frequency energy content. After clipping, the speech spectrum is tilted by means of digital filtering to make the speech spectrum approximately flat on a logarithmic scale. These measures are taken to enhance localizability. Since the effects of peak clipping on speech intelligibility are relatively minor, and the spectral tilting even enhances

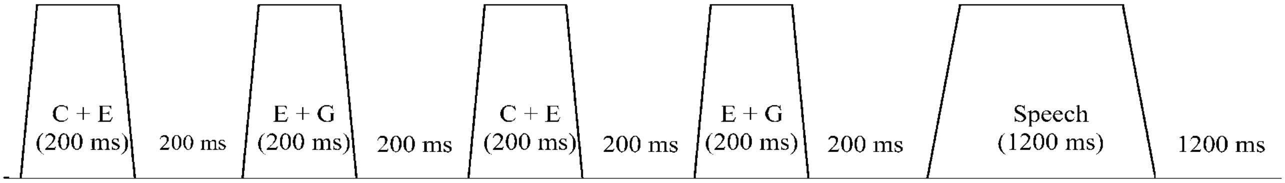

Fig. 1. Structure of beacon signal.

intelligibility slightly by decreasing the effects of auditory masking, the final speech signal suffers only a small decrease in intelligibility.

A tonal signal, instead of the conventional noise-based signal, was mainly chosen for two reasons. First the saliency of tonal signals tends to be relatively high, increasing the probability that the beacon sounds are actually noticed in an emergency situation. Second an important advantage of tonal sounds is that they are generated clearly on purpose and attract attention easily. People are used to responding to chime sounds, as used in public-address systems, by starting to listen, usually expecting a spoken message to follow the chime. Noise-based signals, on the other hand, can be more easily mistaken for mechanical sounds generated as a side effect of something else, especially in chaotic situations such as fires or other large-scale emergencies (such as leaking pipes, pneumatic sounds). This means that noiselike sounds are more likely to be dismissed as irrelevant or associated with some (nonexistent) mechanical threat, and avoided instead of approached.

The relatively simple nature of the tone complex was chosen to avoid computer game associations. At the same time care was taken not to make the signal sound like fire alarms or other existing warnings. This could also make the beacons appear threatening, scaring people away rather than attracting them. For this reason, no frequency sweeps were applied (which would have been useful in terms of saliency and localizability). Localizability was ensured by the dense harmonic structure of the signal, with closely spaced harmonics up to 20 kHz. In addition sharp signal onsets were included to aid the detection of interaural time differences, thus increasing localizability.

The use of short speech signals makes the beacons self-explaining; without speech, the purpose of the sound could remain unclear. By choosing a speaker with suitable voice characteristics (and instructing this speaker to talk in a specific way), the urgency to "follow the sound" is reinforced in a nonverbal way. Speaker selection and instruction are important; a poorly chosen speaker could come across as too threatening, or (on the other extreme) too pleasant and casual to be taken seriously. To ensure adequate intelligibility of the speech signal, the signal level must be sufficiently high in relation to the background noise. For the same reason, the speaking rate and silence periods between utterances should be adjusted to the reverberation characteristics of the environment.

The signal was purposely given relatively long periods of silence (pauses) to improve speech intelligibility for people communicating with each other while the beacons are sounding (the sixth design criterion).

### *1.2.3 Application of Proposed Signal*

It makes sense to tailor the beacon signal as proposed for each specific application. Several adjustments can be made to make the signal more suitable for a specific environment, such as reducing the speaking rate and increasing the interval between stimuli (in reverberant environments) and using multiple languages ("international" environments).

## 1.3 Coding a Route to an Exit Using Multiple Beacons

Conventionally, using modulated noise signals, coding of a route toward an exit is done by increasing the modulation frequency of each successive beacon, with decreas-

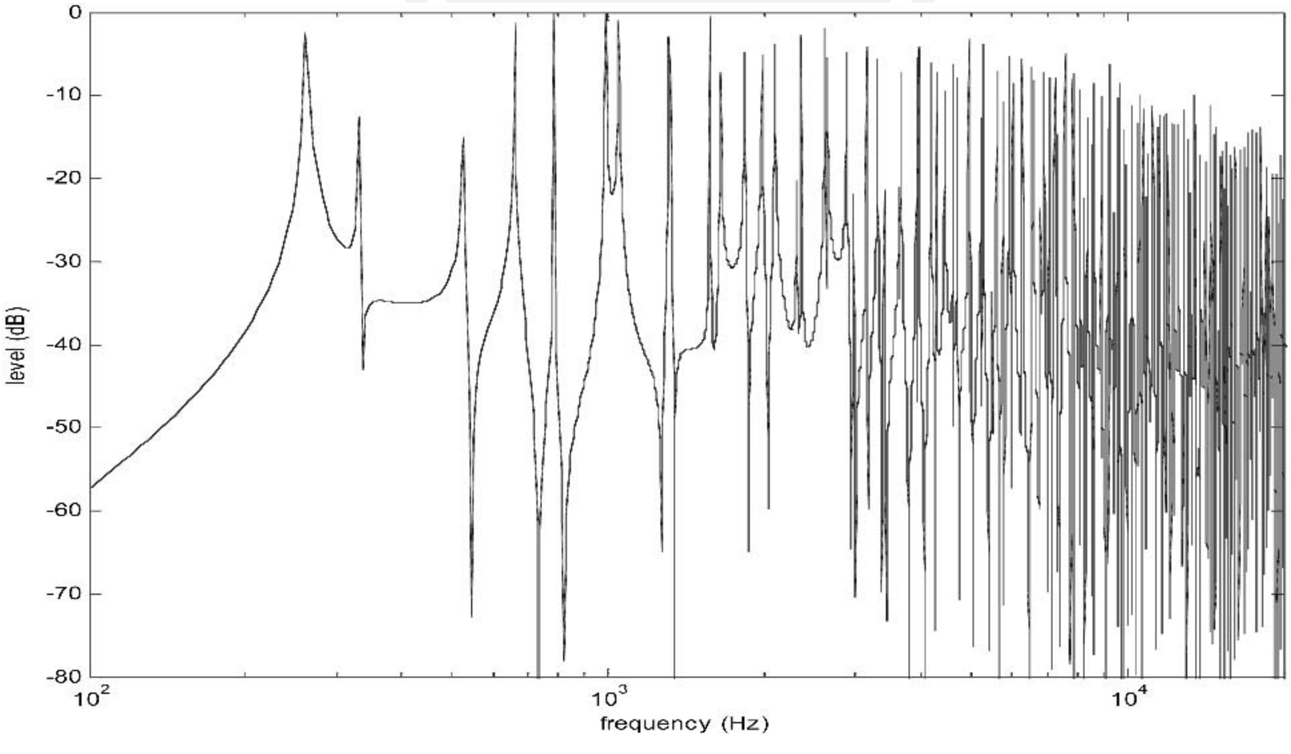

Fig. 2. Line spectrum of first tone complex in sequence (C + E).

ing distance to the exit (the final destination of the route). The designed route is followed by listening for a faster modulated signal, and walking in the corresponding direction. The disadvantage of this modulation frequency code is that it is not self-explaining. It needs to be learned and requires that people have been properly instructed with regard to this code.

With the beacon signals proposed in this section, the direction of the route is coded using time delays. Signals are reproduced by the beacons at different delays. The precedence effect (or the law of the first wavefront) leads us to perceive the sounds emitted by multiple beacons as if they were originating from a single source, the one that reaches us first [7],[8]. This effect, which is useful to determine the location of sound sources in environments with acoustically reflecting surfaces, is utilized by assigning shorter delays to beacons that are closer to the end of the route. This way, once a certain beacon is approached, it is perceptually "taken over" by the next one, because the sound of this beacon is delayed less and reaches the subject first. The delay times need to be designed carefully. The delays perceived by the listeners should be in the range for which the precedence effect is most effective. Also, travel times must be compensated for (calculated using the distance between beacons and the sound velocity).

The greatest advantage of using the precedence effect (compared to the conventional modulation frequency code) is that it does not have to be learned and requires no interpretation by the subjects. They will not even be aware that a code is being used. As long as they keep following the direction from which the sound appears to be coming, they will automatically follow the route in the right direction. The illusion that they are actually following the same, single source moving ahead in front of them can be very powerful.

### 1.4 Design Choices for Beacon Hardware

An auditory evacuation beacon is, in principle, a simple device consisting of only four components: signal storage (an EPROM or even a CD), signal reproduction (digital-to-analog conversion or a CD player), loudspeaker amplifier, and loudspeaker. Requirements on the fidelity of the system in terms of jitter and harmonic distortion can be low. However, the system bandwidth is important and should extend to at least 16 kHz with a reasonably flat response. The bandwidth of the system (or, more generally, the frequency response) will probably be mostly determined by the characteristics of the loudspeaker.

For audibility, the sounds reproduced by the system must be sufficiently loud. If levels up to approximately 90 dB(A) can be reached, this should be sufficient for most applications.

The choice of loudspeaker type is critical, not only because of the overall frequency transfer, but also because of the directivity pattern. Which directivity pattern is most suitable depends on the environment in which the beacon is placed. This directivity pattern, which is frequency dependent, is not only determined by the loudspeaker itself, but also by its casing and its immediate surroundings (for example, mounted on a flat surface, in a small box, behind a horn).

If a single beacon is used in a relatively open space, a loudspeaker that is omnidirectional even at higher frequencies is the best option. Such a loudspeaker will be heard and localized equally well from any direction from which people may be approaching. Highly directional loudspeakers should be avoided especially in highly reverberant environments. When hard reflecting surfaces are present, extremely confusing acoustic mirror images may be heard, leading fleeing people in the exact opposite direction of the exit.

In other cases directional loudspeakers will offer specific advantages. When people need to be led along narrow spaces or corridors, directional loudspeakers will give less reflections from the walls. This is, of course, only true if the loudspeakers are aimed along the length of the corridors, and not directly onto a wall.

When multiple beacons are applied to lead people along a certain route to an exit, directional loudspeakers help prevent people from walking back to a beacon that has already been passed, instead of going forward to the next beacon. This further reinforces the direction coding established using the precedence effect.

## 2 EVALUATION OF AUDITORY EVACUATION BEACONS

### 2.1 Sound Beacons in Traffic Tunnels

With a beacon signal as described here, as well as with conventional, commercially available beacons (based on modulated noise and without speech), two separate evacuation experiments [9],[10] were carried out in a traffic tunnel, the second Benelux tunnel near Rotterdam. The conventional beacons were evaluated in the first experiment, using a total of 97 subjects. Each subject participated only once. All subjects were brought by bus into a tunnel filled with harmless "smoke" produced by smoke machines (Fig. 3). The subjects left the bus individually at 40-s intervals. They were all given general instructions to evacuate from the tunnel, as if the smoke resulted from a

Fig. 3. Tunnel interior while smoke is being produced in preparation for experiment.

real fire and they were in immediate danger. Three doors in a section of tunnel approximately 200 m in length (in the middle of which the subjects were released) were fitted with a sound beacon and designated as “safe exits.” Using thermal cameras, subjects were followed while trying to find these exits. Subjects were considered to have evacuated successfully once they left through one of the exits. Subjects who walked out of the 200-m tunnel section without finding an exit were considered to have failed in evacuating. Hence each subject either left through a door (success) or walked past all doors, out of the tunnel section (failure). There was no time limit.

The subjects in the first experiment (using conventional beacons) were divided into three groups. The first group was not at all informed about the presence of sound beacons. The second group was informed that sound beacons were present. The third group was also told that these beacons were placed above the emergency exits. For all three groups the sound beacons were operated in exactly the same way. The results of this experiment are given in Table 1.

The second experiment was similar to the first, but this time the newly designed TNO signal was used. The number of subjects in this experiment was smaller (75), but this time only one condition (no prior instruction to the participants) was included. Another difference was the beacon hardware used. With the TNO signal, custom-built beacons based on CD players and omnidirectional loudspeakers were used. The results of this experiment are also presented in Table 1.

For the conventional beacons the results are considered inadequate, with the exception of the condition in which subjects were given very explicit instructions about the sound beacons just before the experiments. Without such instructions, the source and purpose of the beacon sounds was unclear to the subjects. Also, some subjects indicated that the beacons sounded unpleasant and “machine-like,” and were not associated with a safe exit at all. The results for the TNO beacons (a success rate of 87% without explicit instructions) are considered satisfactory (Fig. 4).

It should be noted that the interior of a road tunnel is a difficult environment for sound localization. This is due to the highly reverberant character of the tunnel as well as the presence of distinct (and misleading) reflections. Moreover, smoke expulsion fans and moving traffic give rise to fairly high noise levels, which may mask the signals of sound beacons. Such noise was not present during the experiments described here.

Table 1. Results of evacuation experiments.

| Signal | Condition | Number of Subjects | Percentage Leaving through Exit* |
|---|---|---|---|
| Conventional signal | No instruction | 32 | 16% |
| | Beacons present | 33 | 21% |
| | Beacons above exit | 32 | 69% |
| TNO signal | No instruction | 75 | 87% |

* Percentage of people leaving through three designated “safe” exists (above all of which was a sound beacon). All others, who passed these three exists without using them, were considered “not finding an exit.” The percentages presented here can be seen as evacuation rates.

## 2.2 Sound Beacons in a Ship’s Interior

To investigate the feasibility of evacuating ship passengers along specific routes from a ship’s interior to emergency exits, use was made of a mockup. This mockup represents the maze of corridors normally found in the interior of, for instance, a passenger ferry. For this experiment only part of this maze was used—basically only a single T junction of corridors.

Subjects wore safety glasses with lenses made opaque, which deprived them of their visual perception in a way similar to a smoke-filled environment. They were placed inside the mockup, at the starting position marked in Fig. 5, and instructed to head for the exit (without specific reference to the sound beacons). The positions of the sound beacons, integrated in the ceiling (see Fig. 6), are also indicated in Fig. 5.

Each beacon consisted of a loudspeaker, type JBL control 1Xtreme. This loudspeaker was connected to a SONY SRP50 power amplifier. Signals were PC-generated using a Hammerfall DSP multiface audio device. The loudspeaker was placed on top of the mockup, facing down through a hole in the ceiling. A horn-shaped aluminum bracket was used to create a focused directivity pattern for the audio beacon. This bracket was attached to the ceiling inside the mockup, over the loudspeaker hole. Fig. 6 shows the bracket, which has the following dimensions: average width of opening 0.20 m (0.23 m at the base,

Fig. 4. Thermal images of people finding emergency doors.

tapering to 0.18 m), height of opening 0.08 m, and length of horn 0.35 m. A strip of foam was placed in the opening to improve the acoustic characteristics of the beacon. Sounds were reproduced at an A-weighted sound pressure level of 73 dB.

An objective of this experiment was to compare the effectiveness of conventional pulsated-noise beacon signals to the TNO signal described in this engineering report. This was done in the most direct way possible, keeping all parameters equal under different conditions, except for the beacon signal itself.

To mark the evacuation routes with conventional signals, modulated noise signals of different modulation frequencies are used. As the subjects come closer to the end of the route (the safe exit), the modulation frequency increases. In other words, the direction of the evacuation route is coded by means of modulation frequency. Just as the association between the modulation noise and the location of an exit has to be learned first (as was shown in the previous section), it seems likely that the modulation frequency "code" must also be learned. Since actual emergencies normally do not allow time to instruct subjects about the nature of the evacuation aids, this is considered undesirable. Therefore during this experiment the subjects were given no instruction about the beacons at all.

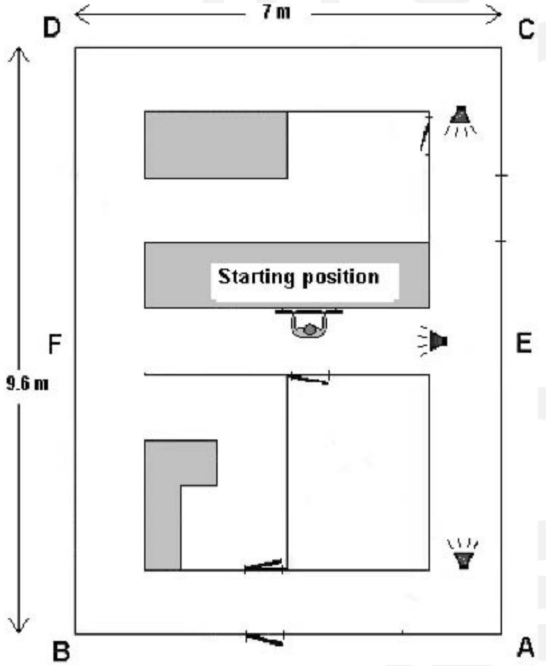

Fig. 5. Layout of ship's interior mockup.

For the TNO signal the direction of the route was coded using time delays, making use of the precedence effect as outlined in Section 1.3. Table 2 lists the four conditions included in this experiment: the conventional and the TNO signal, each used in two different ways (standard route or with a worst-case competing beacon). In each condition 34 subjects participated (17 were directed to the left, 17 to the right). Beacons are indicated by A, C, and E, corresponding to the letters in Fig. 5. For the conventional signals the modulation frequency used with each beacon is indicated; for the TNO signal the delay is given.

The delay times were designed to give 10-ms time differences at the locations where subjects need to "switch over" to the next beacon. For such delay times the precedence effect is known to be effective (see [11]). The delay of beacon E (the first beacon of the route) is also increased to compensate for the travel time of the signals of the other beacons. (Approximately 6 m at a sound velocity of 340 m/s leads to an estimated additional delay of 20 ms.)

The worst-case conditions are labeled this way because the beacons are set up completely symmetrically to the listener at the T junction, in every aspect except the code for the direction of the route (modulation frequency for the conventional signal, delay for the TNO signal). The beacon system would normally be designed to avoid such adverse situations. If the direction code fails, the success rate would be expected to reduce to chance performance. However, this is a good test to evaluate how powerful the direction code can be. The results of the experiment are given in Table 3.

Table 3 shows that some subjects do not even walk in the direction of the first beacon. Apparently they do not understand correctly the meaning of the sound bea-

Fig. 6. Directional beacon mounted on top of ceiling and reproducing sound through holes. Aluminum bracket gives loudspeaker its directional properties.

cons. To walk the entire route correctly, the subject has make two correct choices—first a choice between walking toward the T junction or away from it, then the choice between walking left or right. Using the binomial distribution, it can be calculated that the null hypothesis that both choices are based on pure chance (with 50% a priori probability for each alternative) can be rejected for all conditions, except for the conventional worst-case condition ($p = 0.49$). Essentially this means that in this condition the beacons can be considered completely ineffective.

For the TNO beacons one may assume that the beacons increase the probability of making the right choice at each decision point in the route from 50% to at least 75% ($p = 0.03$ in the worst-case situation). In the standard condition the results are even consistent with an improvement of up to 85% ($p = 0.01$).

## 3 ROBUSTNESS OF PRECEDENCE-EFFECT-BASED DIRECTION CODE

The 10-ms delay mentioned in the previous section was chosen (somewhat arbitrarily) to be well within the range of delay times for which the precedence effect is known to occur (1–30 ms). The value chosen for this delay determines the robustness of the code. Theoretically longer delays imply that the precedence effect works within a larger area around the beacon—the subject can walk further away from the beacon before the “design delay” of the beacons is compensated by travel time distances. On the other hand, if the delays become too long, the effect is lost. The beacons become audible as separate sound sources, and the delayed beacon is perceived as an echo.

To determine the optimal delay (in terms of how far the subject can walk away from a beacon before the effect wears off), a psychoacoustic experiment with six subjects was carried out. Subjects were placed in the middle of corridor A–C. The beacons were switched on with a delay of between 2 and 50 ms. Subjects were instructed to choose a position along A–C at which both beacons were perceived to be equally loud (or at least as equal as possible). Depending on the delay, subjects had to stay close to the middle of the corridor, or they could walk further away from the middle, in the direction of the delayed beacon. Which beacon was delayed (A or C) was a random decision. In a total of 78 trials, 100% of all stimuli were initially perceived to originate (or at least to be louder) from the undelayed beacon. Results of the experiment, in terms of the displacement from the middle of A–C which corresponds to equal loudness, are given in Fig. 7.

A delay of 10 ms implies, according to Fig. 7, that in a worst-case condition, as tested, a subject can walk up to 1 m in the wrong direction before the direction code (due to the precedence effect) is lost. Fig. 7 also indicates that the results for the evacuation experiment could have turned out to be even better at delays of around 20 ms, for which an even larger displacement is allowed.

The displacements in Fig. 7 are the result of two separate mechanisms. First when the subject walks toward the delayed beacon, the delay itself is physically compensated for. Travel times of the sound from both beacons change—the delay of the delayed beacon becomes shorter, the delay of the other beacon becomes longer. Second there is the influence of the sound level. The delayed beacon becomes louder at the position of the subject, the other beacon less loud. Through a mechanism sometimes referred to as time-

Table 2. Conditions for sound beacon experiment in ship’s interior.

| Condition | Route (Left–Right) | Beacon E | Beacon C | Beacon A |
|---|---|---|---|---|
| Conventional signal | EC | Noise, 5 Hz | Noise, 7.5 Hz | |
| Standard route | EA | Noise, 5 Hz | | Noise, 7.5 Hz |
| Conventional signal | EC | Noise, 5 Hz | Noise, 7.5 Hz | Noise, 5 Hz |
| Worst-case route | EA | Noise, 5 Hz | Noise, 5 Hz | Noise, 7.5 Hz |
| TNO signal | EC | “exit here,” 30 ms | “exit here,” 0 ms | |
| Standard route | EA | “exit here,” 30 ms | | “exit here,” 0 ms |
| TNO signal | EC | “exit here,” 30 ms | “exit here,” 0 ms | “exit here,” 10 ms |
| Worst-case route | EA | “exit here,” 30 ms | “exit here,” 10 ms | “exit here,” 0 ms |

Table 3. Percentage of subjects choosing correct direction along evacuation route across T junction.

| | % Correct choices (and $N$) | | |
|---|---|---|---|
| | At Beginning* | After T Junction | Whole Route Correct‡ |
| Conventional signal, standard route | 71% ($N = 34$) | 54% ($N = 24$) | 38% ($N = 34$) |
| Conventional signal, worst-case route | 47% ($N = 34$) | 50% ($N = 16$) | 24% ($N = 34$) |
| TNO signal, standard route | 94% ($N = 34$) | 94% ($N = 32$) | 88% ($N = 34$) |
| TNO signal, worst-case route | 91% ($N = 34$) | 77% ($N = 31$) | 71% ($N = 34$) |

* Percentage of subjects who chose to walk toward beacons from starting position.
† Percentage of subjects who chose correct direction at junction.
‡ Products of two columns at left.

intensity trading (or the Haas effect [11]), subjects can compensate for the level difference by applying a time difference that has the opposite effect.

Ignoring the effect of sound level, subjects would theoretically be expected to compensate a delay of 10 ms by walking 1.7 m in the direction of the delayed beacon. This would decrease the delay of the undelayed beacon by 5 ms and introduce an additional delay for the other beacon, which is also 5 ms. Due to the effects of sound level differences, the subject will walk less than 1.7 m—approximately 1 m according to Fig. 7. Since the delayed beacon will be perceived louder (and the other less loud), the perceptual "middle" between the two beacons is influenced by the Haas effect.

The data presented in Fig. 7 were translated into the magnitude of the Haas effect for this specific setup. The distances in Fig. 7 (vertical axis) were translated into time differences, using the speed of sound. By subtracting these time differences from the actually applied delay (horizontal axis), the amount of time difference traded for each intensity difference was obtained. This intensity difference was then estimated by performing sound pressure level measurements in two environments—the mockup used in the experiment and an anechoic chamber. In both cases the A-weighted sound pressure level of beacon signals was measured as a function of the horizontal distance from the loudspeaker, at a height of 1.6 m (corresponding to the average ear height).

In the case of the anechoic measurements it is assumed that the signal intensity is traded for a time delay completely due to the original source, without contributions of even the lowest order reflections. In the narrow corridors of the mockup, such very early reflections may be perceptually indistinguishable from the original source, and are perceptually "integrated" into the source signal. The in-situ level measurements, on the other hand, presume that all reflections are attributed to the source. In conclusion, the true Haas effect would be expected to lie within the calculated effects based on these two measurement types. As Fig. 8 shows, the original data by Haas [11] fit this expectation.

An important difference between the current results and the results reported by Haas [11] and other classic and textbook publications on the Haas effect (such as [8] and [12]) is the loudspeaker configuration. Traditionally loudspeakers are placed symmetrically in front of the listener, at horizontal angles of ±22–45°. In our setup these angles are ± 90°. The loudspeakers are exactly opposite each other, with the listener in the middle. Also, Haas used speech stimuli, whereas in this case both speech and pulsated chime sounds are used. These factors together may explain the fact that a more pronounced optimum around 10 ms for the time-intensity trading relation was found (instead of a plateau).

## 4 CONCLUSIONS

Auditory evacuation beacons can be used as effective tools for improving emergency evacuation regimes. The design of the beacons, in particular the design of the beacon signals, is crucial for their performance.

Our tunnel experiments showed that modulated noise signals, without speech, are not very effective unless specific instructions about the beacons have been issued. The ship's interior mockup experiment showed that the noise stimuli may even be completely ineffective (performance at chance level). In all cases much better performance is obtained when a chime-plus-speech signal is used. It has been proposed [10] that the conventional modulated noise signals can be made sufficiently self-explaining by adding a spoken message, as was also done with the TNO signal. This remains to be proven.

Using modulation frequency as a code for indicating progress in approaching the exit (successive beacons using increasing modulation frequencies) is not as effective as using time delays. Due to the precedence effect, time delays can be used effectively to steer subjects along a route

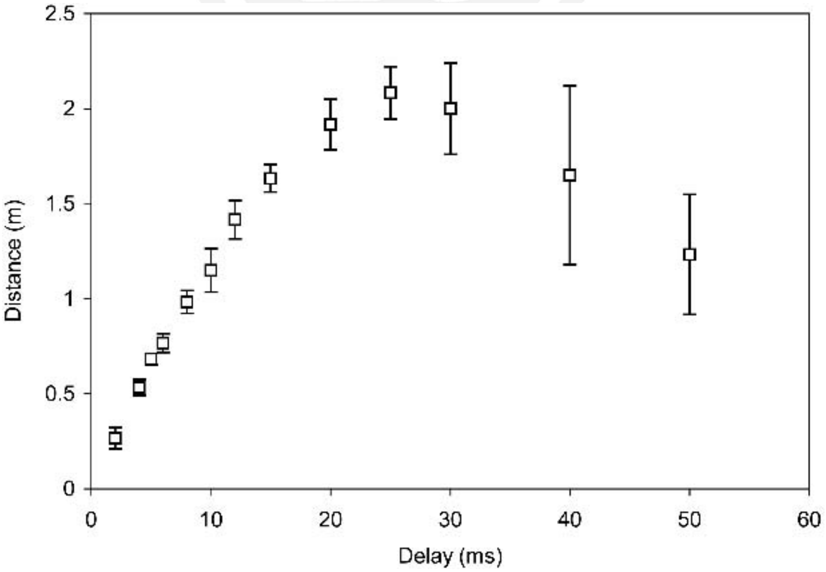

Fig. 7. Distance along which a subject can be displaced from the theoretical optimum position (middle of corridor A–C) before effect of an applied time delay (precedence effect) is compensated for. Error bars represent standard error ($N = 6$).

of beacons. Even at worst-case intersections (where two opposite beacons are audible at the same sound level, differing only in the arrival time of the first wavefront) the time-delay code is effective in indicating the desired direction.

A disadvantage of the precedence-based approach, compared to using different modulation frequencies, is that it is only effective around specific locations. Time delays are calculated to yield the proper arrival times at intersections of corridors exactly. However, once a person starts walking in the wrong direction, the effect starts to disappear. Fortunately for suitably chosen time delays, the tolerance is quite good. In a worst-case setting a subject may walk up to 2 m in the wrong direction before the precedence effect "wears off" and the subject loses preference for one beacon over the other (Fig. 7).

The time-intensity trading effect is greatest if the time difference is approximately 10 ms (Fig. 8), as expected from, among other sources, the original data by Haas [11]. This does not mean that 10 ms is the best design choice for the time delay between successive beacons. In principle, greater time delays are better. One can walk further away from the intersection before the time difference at the listener position becomes too small to induce the precedence effect. This is limited by the time difference at which the delayed beacon starts to be perceived as an echo. In the narrow corridors of the ship's interior, the optimum is approximately 20 ms (Fig. 7).

## 5 REFERENCES

[1] J. Blauert, *Spatial Hearing: The Psychophysics of Human Sound Localization,* rev. ed. (MIT Press, Cambridge, MA, 1997).

[2] D. J. Withington, "Life Saving Applications of Directional Sound," in *Pedestrian and Evacuation Dynamics,* M. Schreckenberg and S. D. Sharma, Eds. (Springer, Berlin, 2002), pp. 277–296.

[3] ISO/DIS Std. 7731, "Ergonomics—Danger Signals for Public Work Areas—Auditory Danger Signals," International Standards Organization, Geneva, Switzerland (2002).

[4] E. H. A. Langendijk and A. W. Bronkhorst, "Contribution of Spectral Cues to Human Sound Localization," *J. Acoust. Soc. Am.,* vol. 112, pp. 1583–1596 (2002).

[5] E. H. A. Langendijk, "Spectral Cues of Spatial Hearing," doctoral dissertation, Delft University of Technology, Delft, The Netherlands (2002).

[6] D. Wesley Grantham, "Spatial Hearing and Related Phenomena," in *Hearing,* B. C. I. Moore, Ed. (Academic Press, San Diego, CA, 1995), pp. 297–345.

[7] M. B. Gardner, "Historical Background of the Haas and/or Precedence Effect," *J. Acoust. Soc. Am.,* vol. 43, pp. 1243–1248 (1968).

[8] P. M. Zurek, "The Precedence Effect," in *Directional Hearing,* W. A. Yost and G. Gourevitch, Eds. (Springer, New York, 1987), pp. 85–105.

[9] L. C. Boer and S. J. van Wijngaarden, "Directional Sound Evacuation from Smoke-Filled Tunnels," in *Proc. Conf. Safe and Reliable Tunnels* (2004).

[10] L. C. Boer and D. Withington, "Auditory Guidance in a Smoke-Filled Tunnel," *Ergonomics,* vol. 10, pp. 1131–1140 (2004).

[11] H. Haas, "Über den Einfluss eines Einfachechos auf die Hörsamkeit von Sprache," *Acustica,* vol. 1, pp. 49–58 (1951).

[12] W. A. Yost and D. R. Soderquist, "The Precedence Effect: Revisited," *J. Acoust. Soc. Am.,* vol. 76. pp. 1377–1383 (1984).

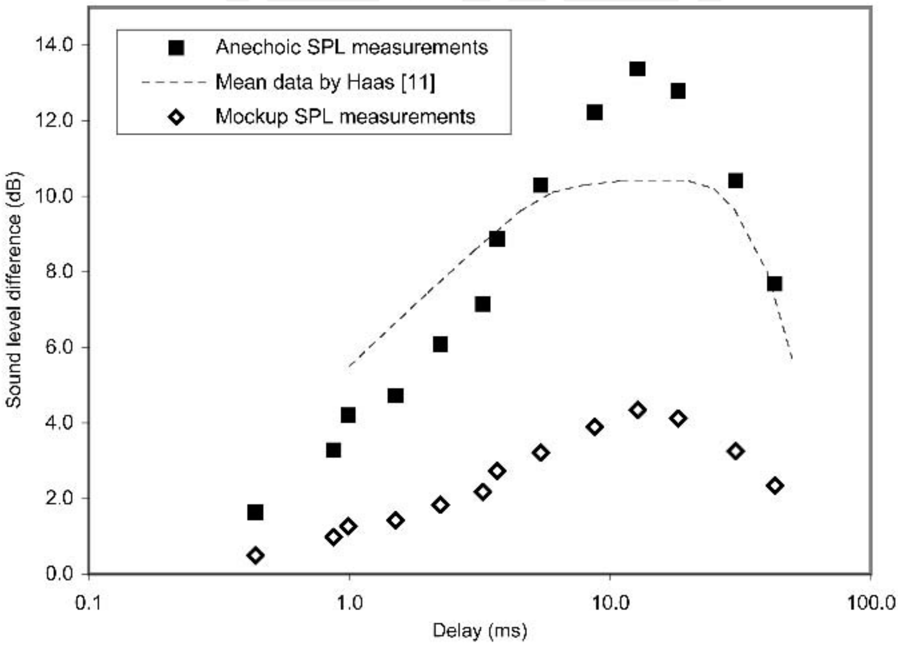

Fig. 8. Derivation of magnitude of Haas effect from data presented in Fig. 7. —— original data by Haas [11], averaged over 15 subjects; ■ calculations of Haas effect if reflections are completely ignored (sound-level measurements in anechoic chamber); ◇ calculations in which effects of reflections are fully included (sound levels measured in situ in mockup).

## THE AUTHORS

S. J. van Wijngaarden

A. W. Bronkhorst

L. C. Boer

Sander J. van Wijngaarden was born in Rotterdam, the Netherlands, in 1971. He studied applied physics and specialized in perceptual acoustics at the Delft University of Technology. He received a Master's degree in 1996.

Dr. van Wijngaarden joined the Speech & Hearing group at TNO Human Factors as a research scientist in 1996. After working in a variety of areas, but mostly focusing on prediction of speech intelligibility and assessment techniques for narrow-band voice coders, he carried out an in-depth study of the intelligibility of nonnative speech. This work led to his Ph.D. thesis while at Free University of Amsterdam in 2003. He is currently group leader of the Speech & Hearing group and has extended his research interests to various other topics, including auditory warning signals.

Dr. van Wijngaarden is the Netherlands codelegate to the NATO technical group on speech technology (RTO(IST/RTG013) and is active in national and international standardization working groups. He is a member of the Audio Engineering Society, The Acoustical Society of the Netherlands, the Acoustical Society of America, the Netherlands Phonetic Sciences Association, and the International Speech Communication Association.

●

Adelbert W. Bronkhorst was born in Horn, the Netherlands, in 1958. He received a Master's degree in experimental physics from the University of Amsterdam in 1982. His thesis describes pilot measurements with the 500-MeV coincidence scattering facility of the Dutch Institute for Nuclear Physics in Amsterdam. He received a Ph.D. degree for his thesis on binaural speech perception in noise from the Medical Faculty of the Free University in Amsterdam in 1990.

Dr. Bronkhorst worked as a clinical audiologist at the University Hospital of the Free University. His activities included audiological testing, hearing aid fitting, and fundamental research. In 1989 he was appointed research scientist at TNO Human Factors, and from 1995 to 2003 he led the Hearing Group and then the Speech & Hearing group. In 2003 he was appointed head of the Perception Department, which consists of approximately 20 researchers and assistants, where he conducts research on visual and auditory perception. His research interests include spatial hearing, auditory attention, and multimodal perception.

Mr. Bronkhorst is member of the Acoustical Society of the Netherlands, the Acoustical Society of America, and the German Acoustical Society.

●

Louis C. Boer was born in 1947. He studied and worked as a psychologist at the Free University in Amsterdam. He started working at TNO in 1981. Since 1993 he has studied human behavior in crowd evacuation including studies on ships and in buildings and tunnels (for example, how motorists react to a burning HGV that unexpectedly blocks the roadway).