By **Daniel J. O'Connor, P.E., FSFPE**

directional sound

DIRECTIONAL SOUND is a new technology that holds promise in improving the use of exits and helping people find their way to an exit, a refuge area, or some other means of egress during emergency evacuation of a building, particularly under such adverse conditions as smoke or darkness. It works by introducing short bursts of broadband sound in a frequency range that's distinct from simultaneously operating fire alarm sounders, such as bells, horns, or voice communication systems. These pulses of sound, which make use of our ability to localize sound sources, are produced by electronic signaling devices installed as part of a building's fire alarm system to provide additional sound cues that don't conflict with the traditional fire alarm system notification appliances. >>

Since sound can penetrate in many directions, even around corners, using directional sound to indicate exits is inherently more flexible and efficient than using line-of-sight methods.

Illustration By **Brad Yeo**

Figure 1

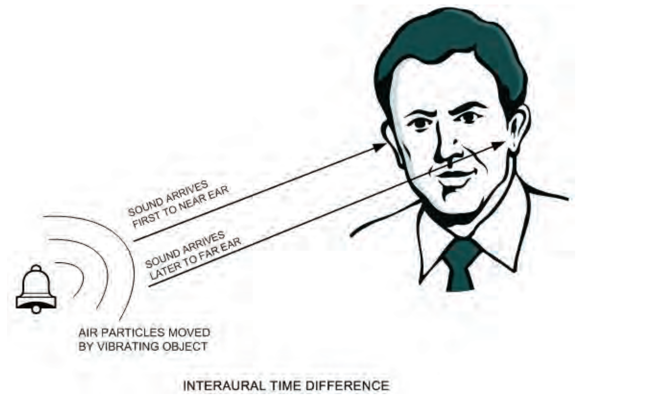
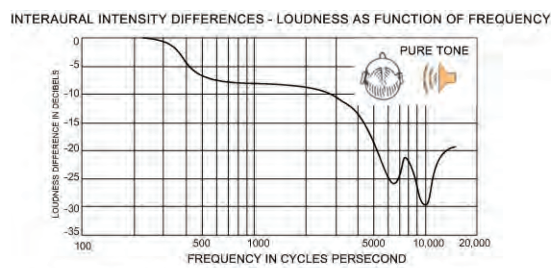


Figure 2



DIFFERENCE IN LOUDNESS-LEVELS AT THE TWO EARS WHEN PURE TONES OF VARIOUS FREQUENCIES COME DIRECTLY FROM THE SIDE. THE CURVE ILLUSTRATES HOW SOUND-SHADOW OF THE HEAD CHANGES INTENSITY AT VARIOUS FREQUENCIES. (SOURCE: HEARING ITS PSYCHOLOGY AND PHYSIOLOGY, AMERICAN INSTITUTE OF PHYSICS)

The technology and initial applications of directional sound were developed at the University of Leeds in the United Kingdom in partnership with SoundAlert Technology Plc under the supervision of Deborah Withington, professor of auditory neuroscience. Directional sound's introduction into North America is being led by System Sensor, a major manufacturer of fire detection and notification products.

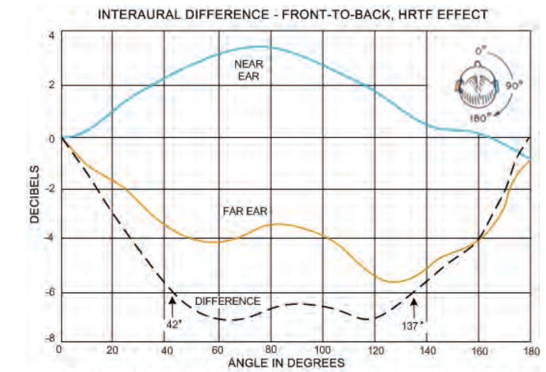
The concept of using directional sound differs from that used for bell, horn or voice speaker installations. Generally these notification devices require placement at numerous locations in order to achieve the sound levels that can be heard and understood by occupants throughout all building areas. In a basic installation of directional sounders, the concern is not for establishing a minimum audible signal in all occupied building spaces. Rather, the focus is to provide sound cues to assist occupants in more easily locating the direction to a nearby exit or area of refuge when occupants are moving through the means of egress during an evacuation (Figure 4). Since sound can penetrate in many directions, even around corners, using directional sound to indicate exits is inherently more flexible and efficient than using line-of-sight methods.

In fact, the exit signs above doors and along egress routes required by building and life safety codes do not always seem to help people find their way out during an emergency. This behavior has been explained in terms of an established psychological concept known as "learned irrelevance," which occurs when someone is continually exposed to a stimulus but rarely needs to respond.[1]

To demonstrate this concept of learned irrelevance, 500 people chosen randomly as they left a large, busy store with 14 emergency exits were asked by experimenters from the University of Ulster at Jordanstown, Northern Ireland[2] (UUJNI) if they noticed any emergency exits in the store and, if they did, how many. After answering the questions, they were asked to identify the exits on a floor plan of the store. Significantly, 75.2 percent did not notice or identify any of the emergency exits.

Several human behavior studies have also demonstrated that occupants evacuating a building during an emergency will leave by a route they know. These studies, which were conducted with fire survivors and through observation of evacuation drills, consistently showed that other emergency exits are largely ignored or underused.[2,3,4] Although it could be argued that this phenomenon is more likely to take place in buildings where most occupants are unfamiliar with the premises, such as a

Figure 3



THE CURVES SHOW THE VARYING LOUDNESS-LEVELS AS A SPEECH SOURCE IS ROTATED AROUND THE HEAD. ALTHOUGH THE DIFFERENCE AT 42 AND 137 DEGREES IS IDENTICAL, THE SOUND QUALITY DIFFERS BECAUSE THE HEAD AND OUTER EAR DISTORTS THE SOUND DIFFERENTLY WHEN COMING FROM THE FRONT OR BACK. (SOURCE: HEARING ITS PSYCHOLOGY AND PHYSIOLOGY, AMERICAN INSTITUTE OF PHYSICS)

HOW WE HEAR

TO BETTER APPRECIATE how directional sound works requires a basic understanding of how human hearing works and how sound processing allows a listener to locate with surprising accuracy the source of a sound.

The human ear is essentially a mechanical system that is extremely sensitive to very small changes in sound waves passing through air. Sound waves are changes in air pressure resulting from the vibration of some other object, such as a musical instrument, operating machinery, or person's vocal cords.

Our ears have three primary parts: the outer ear, the middle ear, and the inner ear. The outer ear is pointed forward with curves and shapes that catch sound and direct it along the ear canal to the tympanic membrane, or eardrum. The eardrum is a thin, rigid piece of skin separating the outer ear from the middle ear. When sound reaches the eardrum, it vibrates, moving rapidly back and forth for higher frequency sound waves while moving back and forth larger distances for louder sounds.

The middle ear is an air-filled cavity that houses three tiny bones, the ossicles, whose primary function is to amplify by a factor of approximately 20 the pressure received from the eardrum. The first bone, the malleus, is connected to the center of the eardrum and transfers vibrations from the eardrum to the other two bones. The last bone, the stapes, connects to the cochlea, a fluid-filled channel in the inner ear. As the eardrum vibrates, so do the ossicles, which allow the stapes to act as piston creating fluid waves in the cochlea that represent the sound waves sensed by the eardrum.

The cochlea, a snail-shaped structure of three fluid-filled tubes separated by membranes, converts or translates these physical vibrations into nerve impulses that the brain recognizes as sound. Fluid waves moving along the cochlea's basilar membrane stimulate the thousands of tiny hair cells in the organ of Corti, which lies on the surface of the basilar membrane and extends across the cochlea.

When a fluid wave excites a particular resonant frequency, the membrane releases a burst of energy that moves the hair cells at that point. This, in turn, sends an electrical impulse through the cochlear nerve to the brain. Thus, the cochlea sends the raw data that the brain must process, analyze and interpret. This neural processing is incredibly fast and accounts for our ability to detect the source of a sound.

Pinpointing the location of sound

Several basic factors account for our ability to pinpoint a given sound with surprising accuracy, particularly if it is broadband sound.[1,2,3,4,5]

The anatomy of the outer ear and the fact that there is an ear on each side of the head allow us to capture subtle differences in sound that provide the cues for locating a sound source. These cues are interaural time differences (ITD), interaural intensity differences (IID), and head-related transfer function (HRTF)

The concept of ITD can be explained in terms of sound waves traveling to your ears. The crest of each sound wave will reach the nearer ear before it reaches the ear on the far side of the head (see Figure 1). Thus, a subject listening for the sound will tend to place the sound source toward the side of the first wave crest to arrive at the ear.

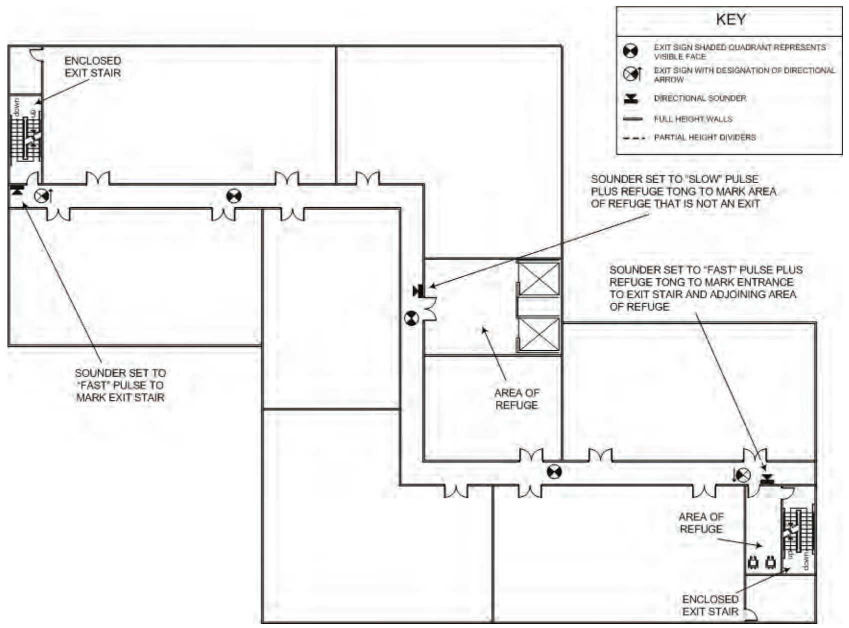
In IID, a difference in intensity occurs at both ears of a stationary listener presented with pure tones of sound to one side, as one ear is shadowed by the head (see Figure 2). As a result, the two ears perceive a significant difference in loudness. At very low frequencies, the shadow of the head has no impact, and there is no perceptible difference in sound. At frequencies above 5000 Hz, however, the difference in perception of loudness between the two ears is as great as 30 dB. With complex sounds such as speech, music, and broadband sound, there is not only the difference in loudness and intensity but also a change in the sound spectrum, as high frequency components are lost to the ear on the far side of the head.

Withington[1] and other sources[4,5] note that intensity and timing differences can result in errors in localization for the listener when narrow band or single frequencies sounds are used. However, confusion of this sort almost never occurs with broadband sources and sound durations that are long enough to allow listeners to move their heads.[5]

The external ear is key to the head-related transfer function (HRTF). The shape of the ear attenuates some frequencies and amplifies others, filtering the sound field as depicted in Figure 3. The HRTF changes depending on sound source location, providing an additional localization cue that is particularly important in determining whether the source is in front of or behind us. HRTF operates over a range of frequencies, but seems to be most effective in the 5,000 Hz to 10,000 Hz range. Combined with the listener's head motion, HRTF provides an independent localization method that complements and reinforces ITD and IID capabilities.

While these three cues provide complementary and redundant means for locating sound, a fourth psychoacoustic phenomenon ensures that too many sound waves resulting from highly reverberant spaces do not cause confusion. This is attributable to the "precedence effect." The ear can discern and fixate on the first sound it receives and disregard later signals, or reflected sound. The signal arriving first suppresses the ear's ability to hear other signals, including reverberation, that arrive up to about 40 milliseconds after the initial signal. A pulsing broadband directional signal makes good use of the precedence effect and can compensate for less-than-optimum listening conditions. Even in highly reverberant spaces, in which every surface was sound reflective, test subjects have had no problem determining the location of directional sounders.

Figure 4



museum or a mall, people who work or live in a building may be just as likely to exhibit this behavior, particularly if they don't use alternative means of egress in their daily routines.

As a result of their work, the team from UUJNI suggested that "any new form of signage must not be susceptible to learned irrelevance, and the only way to ensure this does not happen is to have a secondary signage come into play only when an evacuation is necessary." Directional sound, which offers an "attention-capturing ability" that extends beyond the line of sight by engaging the sense of hearing to help localize exits, is intended to operate only in conjunction with the fire alarm system during an evacuation, thus satisfying the UUJNI scientists' suggestion that secondary cues come into play only when an evacuation is necessary.

Compatibility with traditional systems

Figure 5 compares the spectrum of a typical fire alarm signal at a high setting with that of the directional sounder at a lower power setting. Note that, while the typical alarm signal clearly dominates at 3,000 hertz (Hz) and, to a lesser extent, at upper harmonics, the broadband signal of the directional sounder is 20 to 30 decibels (dB) louder than the fire alarm over most of the range. Nonetheless, both alarms are audible. Directional signals do not actually have to be higher in overall sound pressure level than traditional alarm signals because traditional alarms only mask a narrow range of frequencies near its dominant pure tones.

The situation is different with voice evacuation systems. Directional sounders can reduce the intelligibility of voice evacuation system speakers when they are in close proximity to voice speakers. Until further work is done, it is generally best if the two systems do not operate simultaneously in the same environment. If simultaneous operation of voice evacuation speakers and directional sounders is to be implemented, however, System Sensor's *ExitPoint Directional Sound Application Guide* will help reduce the effects of the directional sounders on the intelligibility of voice speakers.

Influence on human behavior

Research experiments have shown that the psychoacoustic response to directional sounders lessens the time people need to search for and use egress routes and exits. While these experiments were conducted primarily on passenger ships and ferries, the results are broadly applicable to evacuation and relocation scenarios in buildings.[5, 6, 7, 8, 9]

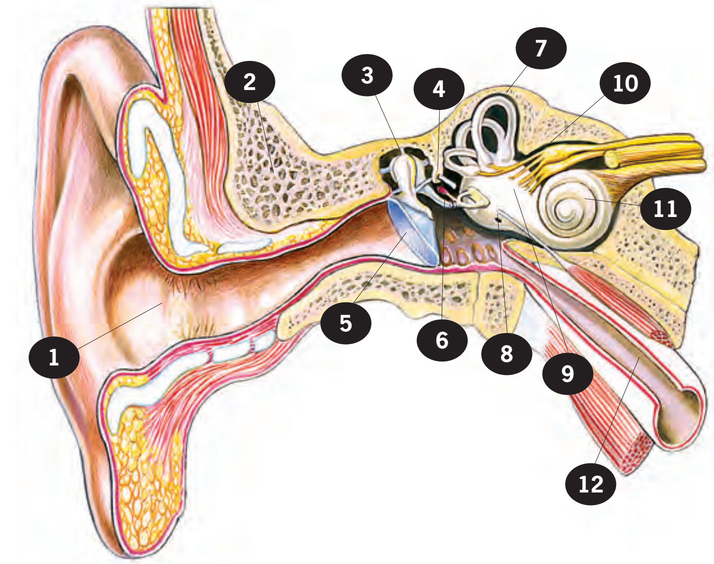
The various trials involved numerous scenarios, such as evacuations with and without directional sound, evacuations with low-visibility conditions created by theatrical smoke, and evacuations in a variety of room and corridor arrangements. In several cases, directional sound was compared to low-location photoluminescent lighting, as well.

In smoke-filled scenarios where exit signs could barely be seen or could not be seen at all, directional sound provided cues that significantly reduced the time subjects needed to find the nearest exit without retracing their steps. The egress behavior of subjects in normal visibility did not show the same extent of improvement in egress times, but subjects indicated that the sound cue acted as a confirming aid in finding the exit.

A more dramatic result was evident in evacuation trials in which subjects were briefed on the meaning of the directional sound. In these trials, the subjects consistently performed better at finding the closest exit and exhibited faster exit times.

However, directional sound may not be of great use in all occupancy types. For example, hospitals may not benefit significantly from directional sound because hospital evacuation training relies on the staff to implement protect-in-place or relocation procedures before evacuating patients. In addition, required fire drills typically keep hospital staff well acquainted with the locations of exits and refuge areas.

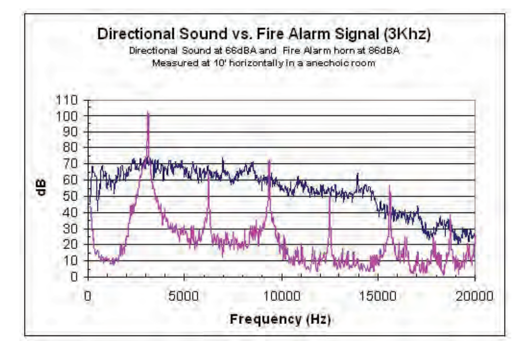
The benefit of directional sound in smoke filled or limited visibility conditions is apparent as a result of the work that has been done in simulated smoke filled conditions. In the case of sprinklered buildings, full-scale fire tests have demonstrated that sprinklers will significantly limit the smoke toxicity and visibility hazard.[10,11] Consequently, for sprinklered buildings an emphasis on smoke filled or smoke obscured egress routes is far less a concern than for buildings without automatic sprinklers. However, given that adding directional sound to a building's fire alarm system is estimated to be only a 4 to 8 percent additional cost, it is worth considering for a variety of occupancies. Directional sound should also be considered for use in evacuations during emergencies other than fire, such as tornadoes, earthquakes, and hazmat spills.



1. Ear Canal
2. Temporal bone
3. Malleus
4. Incus
5. Eardrum
6. Stapes
7. Semicircular canals
8. Round window
9. Vestibule
10. Vestibular nerve
11. Cochlea
12. Eustachian tube

EAR ILLUSTRATION: VINCENT PEREZ

Figure 5



Education and training important factors

Just as we have all learned that red means "stop" and green means "go," people in buildings with directional sounders will have to learn what the signals mean and how to react to them. Although some research appears to show that people will intuitively react to directional sound, we should not assume they will. Building managers, safety directors, and others responsible for emergency evacuation procedures should be aware that training and education increase the effectiveness of directional sound installations.

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Endnotes to sidebar

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ACHIEVING CODES AND STANDARDS RECOGNITION

ALTHOUGH DIRECTIONAL SOUND technology is a recognized and accepted technology in other countries, System Sensor considered it important to obtain independent North American expertise to review the technology and help develop an application guide. To lead this effort, System Sensor chose Schirmer Engineering Corporation because it had the appropriate combination of technical fire-alarm-system design expertise and practical experience in designing and developing life safety concepts for a wide variety of buildings and occupancies.

Currently, ULI, Factory Mutual, and the California State Fire Marshal has listed or approved System Sensor's directional sound product.

When a new fire-safety technology arrives in the marketplace, it can be expected that the NFPA standards-development process will play an important role. In collaboration with the National Electrical Equipment Manufacturers Association (NEMA) and the American Fire Alarm Association (AFAA), System Sensor submitted technical data and proposals to the NFPA 72®, *National Fire Alarm Code®*, technical committee for evaluation. This committee is responsible for developing installation and application rules for fire detection and notification systems. Without review and consideration of the diverse volunteer experts of the NFPA 72 committee, it would be more difficult to gain widespread recognition and acceptance of a new technology such as directional sound technology.

In January 2005, three different technical committees evaluated several of the proposals NEMA and AFAA submitted, concentrating on notification appliances, maintenance, and protected premises systems. The committees' deliberations are available for review in the Report on Proposals, which provides the formal record of their actions.

At this time, the directional sound proposals have been accepted with various technical revisions or additions. Any public comments NFPA receives may result in further refinements during the next phase of committee deliberations, the results of which will then be published in the Report on Comments.