Virtual Acoustic Technology: Its Role in the Development of an Auditory Navigation Beacon for Building Evacuation

Peter Rutherford

University of Strathclyde
Department of Architecture and Building Science
131 Rottenrow,
Glasgow G4 ONG

Tel: *(0141) 552 4400 extension 3017*
Fax: *(0141) 552 3997*
e-mail: *P.Rutherford@strath.ac.uk*

This paper addresses the issue of escape from unfamiliar, smoke filled buildings such as department stores or hotels where being blinded by smoke may result in death to its occupants. It proposes that we may be able to apply concise auditory information to the escape procedure. In order to achieve this, predictive *virtual acoustic* techniques have been employed to assess its feasibility.

Keywords: navigation, localization, binaural room simulation

INTRODUCTION

The application of sound as an aid and safeguard for navigation has a long and varied history. From the days when whistles and bells served their purpose as warning signals to the wary mariner, the auditory mechanism has been used to resolve the deficiencies imposed by the visual system. Indeed, it may be stated that the ability to localize sound in enclosed environments is a very important function of the auditory system of humans. If, for example, one is sharing a dark cave with a sabre-toothed tiger, the ability to obtain the location of the tiger by listening to its growl is of considerable value!

However, because our brains and whole way of life are built around light and vision, we fear the prospect of blindness; of being trapped in darkness, debilitated and as a result in a helpless state. One such example of complete visual deprivation is being trapped in an unfamiliar building which is on fire and smoke filled. The victim is not familiar with the escape exits or indeed the location of the fire itself, thus not able to form any kind of escape plan.

Aim

The aim of this paper therefore is to address this issue of escape from such buildings, proposing that it is possible to apply concise auditory information to the escape procedure, guiding the building's occupants to safety. Underlying the whole paper is a description of predictive virtual acoustic techniques which were used to evaluate the feasibility of such a proposal. Using psychoacoustic modelling and acoustically 'rendering' the escape routes, a series of experiments were created which proved the success of the navigation beacon. As can be understood, exposing subjects to the dangers of a fire situation in order to achieve an optimised navigation beacon is not necessarily the best way to undertake research. Virtual acoustic technology therefore allowed such research to be conducted in the safety of the office, allowing for a far greater range of proposals than would normally have been available.

1. Building Egress and Wayfinding Conditions

In order to develop an auditory navigation beacon, it is necessary to look at several factors which influence successful evacuation from buildings. The following therefore briefly outlines these factors.

As Passini states (1992, p.22), "Buildings are often difficult for wayfinding under normal conditions, but very particular and often critical wayfinding problems occur when buildings have to be urgently evacuated as in the case of fires." Therefore, being familiar with ones surroundings is greatly needed when a sudden exit has to be made (Malhotra, 1987, p.57). If the routes to the various exits are known and if any exits are blocked by smoke then the alternative exits are not so difficult to find. However, where the occupants are not familiar with their surroundings, movement will be slow and wayfinding will prove difficult. It must be kept in mind that, unlike a drawing, no overall view of complete escape is available when a person walks along a corridor. Signs may be available to aid sighted navigation, but if the corridor is completely smoke filled then they are in themselves useless.

In addition, within a smoke filled corridor, the choice of escape action is restricted, resulting in hysteria or panic. Various authors agree (Sime, 1985, pp.697-724; Canter, 1980) that the "association of panic and fires does not hold as long as an escape route appears feasible to the victim." However, panic may be induced if 'there is a limited number of escape routes…..some of these routes are affected by fire and smoke…some of these routes are as a result blocked' (Marchant, 1973). So, how does anyone stand any chance of escape under such a situation? They have very limited wayfinding cues and along with many precipitating factors, such as delayed warning and ambiguous messages, really do not stand any chance of escape. Consider for example the conventional fire alarm. It has been shown to be among the most inefficient means to get people to leave a building (Proulx, 1991). It is too loud, over alarming, unlocalizable, and worst of all effectively cuts out peoples ability to verbally communicate with each other.

There are methods available for aiding navigation, such as speech based evacuation systems, emergency lighting and luminous escape systems placed on floors and skirting boards (Krokeide, 1988), but they in themselves may be useless. Firstly, it is a misconception that people drop to the floor in a fire situation, as has been consistently proven in aircraft evacuation. Secondly, in the presence of irritant gases, such as ammonia based combustion products, people cannot open their eyes.

2. Criteria Imposed on the Design of the Navigation Beacon

Having established a series of influencing factors which govern the need for a navigation beacon, it was necessary to draw up a shortlist of criteria which were to be the basis for its development. The following outlines these criteria:

- it must be highly localizable. From this, the nature of the signal to be presented is extremely important. Most importantly is the way in which the sound itself propagates through space. In addition, it must offer some kind of meaning as to the nature of its presence.
- it must remove possible cognitive overload conditions which would occur due to the extreme amount of decisions needed when wayfinding (Bridges, Charitos, Rutherford, 1997). There is no point in the navigation beacon offering a holistic, survey representation of the escape procedure (as would be gained from a map). It must be used for giving directional information at a local level. Essentially, all that we want to do is make the victim follow the sounds until they reach their destination, as is the case with signs in buildings.
- The beacon must also be consistently placed in the environment and have the same signal presented in all beacons throughout the building. Any inconsistencies would result in ambiguous meaning.
- It must draw attention to itself without being too striking. From this, it must also offer a clear frequency channel for conventional fire alarms, which in all eventualities will not be phased out.
- Finally, it must offer a clear frequency channel for the victims of fire situations to communicate with each other. It is thought that by allowing for interpersonal communication, the risk of panic is substantially reduced.

3. Basic Theory of 3-D Sound Localization

Before describing the experiments which were conducted for this research, a brief introduction to the theories associated with three-dimensional sound localization will be given. As the victim of a fire situation must make wayfinding decisions in all directions (front, back, left, right), this section explains the processes involved. Although vertical (or elevational) localization will be discussed, this is not a property which was considered to be important for the navigation beacon. This arises due to the fact that in Great Britain, and most of Europe, people escape to the ground floor, unlike the USA where many buildings involve roof-top evacuation.

Auditory localization is in itself a relatively simple concept to explain. However, in order to describe it, some differentiation must be made between localization in the azimuthal (left / right) plane, and localization in the vertical (front / overhead / back) plane.

3.1 Localization in the Horizontal Plane

Much of the research on human sound localization has derived from the classic *duplex theory* by Lord Rayleigh, which emphasised the role of two primary cues; interaural differences in time of arrival (ITDs) and interaural differences in intensity (IIDs). As will be described, these *lateralization* cues are highly frequency dependent. Figure 1 clearly indicates this theory.

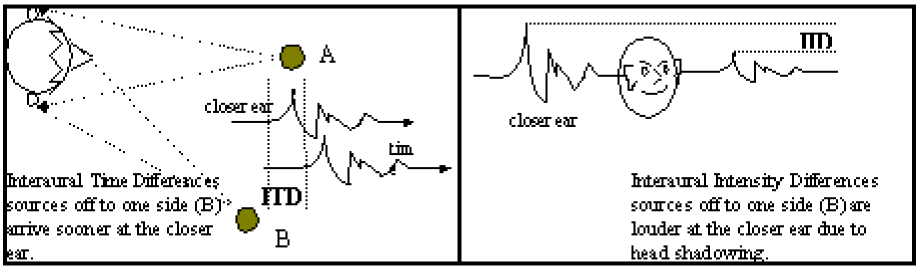

Figure 1. The localization cues of interaural time and intensity differences.

The most important property of a bundle of sound waves propagating from source to receiver is the arrival of the first sound waves at the two ears. For example, source A is straight in front of the listener, therefore both the arrival time and intensity are equal due to the path lengths being the same. However, source B is at 30^{o} azimuth (to the right) of the listener, thus the paths are now unequal, the sound at the left ear arriving not only later, but also quieter than the right. It is this path difference which is the basis for both the ITD and IID. As mentioned, these cues are highly frequency dependent. For example, the ITD cue relates to the hearing system's ability to detect interaural phase differences below approximately 1 kHz. However, IIDs do not work at this low frequency as sound diffracts quite easily around the head at this range, thus no significant attenuation. For IIDs to come into play, they must have waveform components which have wavelengths smaller than the diameter of the head. Essentially, frequencies greater than 1.5 kHz will be attenuated at the left ear as the head is acting as an obstacle. This creates a *shadow* effect on the ear furthest away from the source. As frequency gets higher (wavelength getting smaller), the shadow gets greater (Middlebrooks and Green, 1991). Work done by Wightman and Kistler (1992) concluded that the interaural time difference cue was the dominant cue for lateralization, overriding interaural intensity differences if necessary.

The previous example can be assimilated to a person coming to an junction in a corridor, having to make a left or right decision as to where they are going. However, the question arises as to the possibility of the sound originating from behind them. In this case, both the ITD and IID are the same as they would be from the front, so what does the ear do to disambiguate front from back?

3.2 Localization in the Vertical Plane and from Behind

The ears ability to disambiguate sources from front to back or from above and below in cases where ITDs and IIDs cannot support this information is described by the role of *spectral* cues in localization. These spectral cues are provided by the way in which sound is absorbed and diffracted by the outer ear (or pinna) and torso. More specifically, the helix of the pinna (or folds) induce minute timing (phase) delays within a range of 0-300 micro seconds, causing the spectral content of the sound at the eardrum to be slightly different to that of the source. Once again, these phase delays are highly frequency dependent. Having established this concept, these microtime delays, resonances and diffractions can be translated into a mathematical model of the ear known as a Head Related Transfer Function, HRTF (Wenzel et. al., 1993; Begault, 1994, pp.51-82). This HRTF is different for each position of the sound source in relation to the listener, and also varies from listener to listener. From this, the remaining sections will discuss the experiments undertaken which are based upon these theories.

4. Experiment 1: An Investigation into 3-D Localization

This first experiment concentrated on the subject's ability to localize sound in free-field conditions for the following purposes:

- to evaluate each individual's ability to localize sound coming from all dimensions under anechoic conditions,
- to evaluate the effect of which signal type had on localization ability, and
- to determine the effectiveness of the virtual acoustic system for presenting and evaluating these criteria.

It was thought that this first experiment would prove to be an important stepping stone in the development of the navigation beacon by giving a good idea as to what types of signals would prove to be the best for localization.

4.1 Subjects and Apparatus

Thirteen subjects (nine males and four females), all from the ABACUS unit of the department participated in the experiment. All reported normal hearing. These subjects were experimented on in a normal reverberant room (10 x 5 meters) which was partitioned off using cloth covered fibreboard into a working area of 2 x 2 meters.

A Pentium PC was used for the experiment, the spatializer board (Beachtron) coming from Crystal River Engineering. Various signals were created using Syntrillium Software's Cool Edit for spatialization into three-dimensions by the Beachtron card. The card was programmed in C, its output sound files dumped to Digital Compact Cassette which gives a very high quality digital recording. This was necessary as, due to the DOS based nature of the Beachtron, there was no way in which it could be used for both simultaneous play and record. These waveforms were then dumped back into Cool Edit and trimmed to their desired lengths, making sure that the onset portion of the wave was not truncated in any way.

The main interface for the experiment was created in Visual Basic which replayed the wavefiles previously spatialized over headphones (figure 2). The experiment was therefore non-real time and had no tracking abilities. Essentially, the subjects played a wavefile from the right hand menu and tried to judge its location on the hemisphere. Their response was then logged by the program for further analysis. The whole experiment presentation was as follows:

- Experiment Set 1: Sine waves with frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz.
- Experiment Set 2: BandPassed Broadband waves with frequencies from 20-125 Hz, 125-250 Hz, 250-500 Hz, 500-1000 Hz, 1000-2000 Hz, 2000-4000 Hz, 4000-8000 Hz.
- Experiment Set 3: LowPassed Broadband waves with frequencies from 20-125 Hz, 20-250 Hz, 20-500 Hz, 20-1000 Hz, 20-2000 Hz, 20-4000 Hz, 20-8000 Hz.
- Experiment Set 4: HighPassed Broadband waves with frequencies from 125-22050 Hz, 250-22050 Hz, 500-22050 Hz, 1000-22050 Hz, 2000-22050 Hz, 4000-22050 Hz, 8000-22050 Hz.

- Experiment Set 5: Broadband waves with frequencies from 20-22050 Hz.

These frequencies were chosen so that the researcher could identify any possible spectral dependent characteristics for auditory localization.

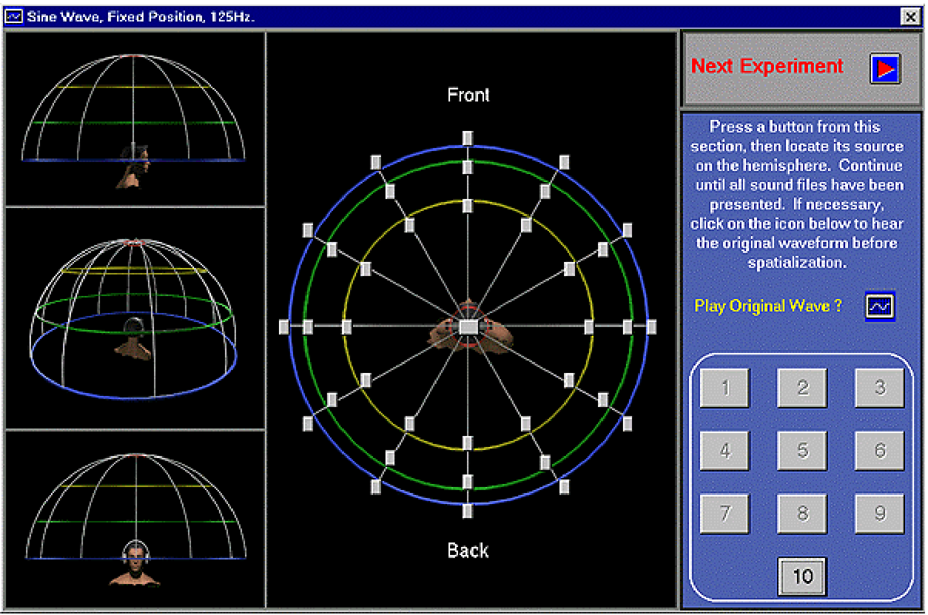

Figure 2. The Visual Basic user interface. On the right are the wavefile play buttons, on the left the hemisphere of possible locations.

4.2 Results and Discussion

The experiment generally did not work as well as expected. However, it did give some interesting points for discussion.

- Localization within the frontal hemisphere was generally very poor, especially for sources which lay directly in front of the listener. In fact, for certain signal types, there were extremely high reversal errors. As the system used static head localization, this was not unexpected. It is difficult to localize sound sources accurately if they lie directly in front of us, or on any plane that is equidistant from the two ears. Generally in real life, if we have to attempt this, we usually do so by moving our heads about, bringing one ear closer to the source. In addition however, the question of evolution arises whereby if we cannot pinpoint an unfamiliar sound visually, we are more likely to perceive it as coming from the rear.
- The bandpassed frequencies from 20 - 125 Hz and 2 - 4 kHz proved to give very little cues as to the location of the sound source (Stevens and Davis, 1983, p.178). This reinforces the knowledge that fire alarms are extremely unlocalizable as their primary frequency band lies between 2200 and 3000 Hz.
- Extreme lateral judgements were virtually always correct (about 85%) however an interesting point arose here. If subjects had difficulty localizing sound from either 0° or 30° elevation, they were highly inclined to push their judgements onto the lateral axis. However, for higher elevations, they were more inclined in pushing their judgements onto the median axis.

As this work was free field and did not take into any consideration the nature of the space which would affect localization, an additional experiment was created of which the optimum signal for the navigation beacon was found. The following section therefore describes this experiment and results gained.

5. Experiment 2: Influence of the Environment on the Navigation Beacon

It is known that the environment through which sound propagates strongly influences the ability to localize a sound source. Infact, the term Precedence Effect(or Law of the First Wavefront) has been used to describe such a phenomenon (Blauert, 1983). In essence, the precedence effect explains an important inhibitory mechanism of the auditory system that allows one to localize sound in the presence of reverberation. The second suite of experiments in this research therefore examined localization within an environmental context using prediction tools called EASE and EARS. These tools are used for *binaural room simulation*.

5.1 Binaural Room Simulation

Binaural room simulation allows us to authentically expose a person to a certain acoustic environment in order to evaluate its performance. Traditionally, such systems are used for the design of spaces for acoustical performances such as concert halls, simulating the auditory perception of a listener in a specific seat of such a hall. Over the past 5 or 6 years, it has developed to a state of maturity, providing a sound basis for auditory experimentation applications. Within this work, the program EASE (Electroacoustic Simulator for Engineers) has been used to calculate the impulse response of the room, and its sister program EARS (Electronically Auralized Room Simulation) to convolve the room response with HRTFs and an anechoic signal. The following figure illustrates the general concept behind such a system.

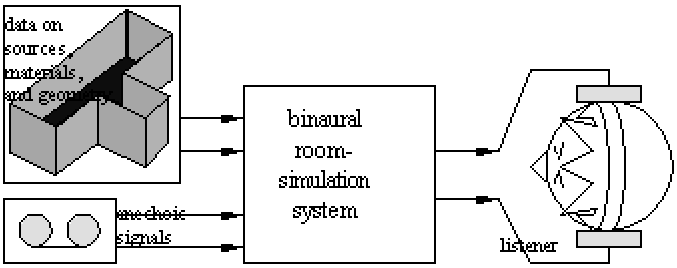

Figure 3. Outline of the architecture behind the binaural room simulation system used for developing the navigation beacon. Adapted from Blauert, 1997 (p.376).

Firstly, the room or corridor is geometrically modelled (in EASE) for positions, dimensions and orientations of surfaces, including the assigning of materials to each surface. Each material has a specific absorption or reflectance characteristic which will determine the resultant frequency dependent reverberation characteristics of the space. The sound sources (or in this case the navigation beacons) are then positioned within the space, including their directivity patterns. The listener (or listeners as may be the case in multiple explorations) is finally positioned in the space. Using geometrical acoustic algorithms, namely ray-tracing (and if needed the mirror-image method), the propagation of sound from source to receiver is calculated. This propagation is affected by elementary filters such as the absorption or reflection from the surfaces, or attenuation through air (although smoke is another important consideration). As a result, components of the sound field which impinge upon the listeners head, namely the ratios between the direct sound and reflections of different orders are simulated with respect to their direction of incidence and arrival times.

The next stage in the simulation is the inclusion of listener's ears in the model (within EARS). Head related transfer functions (measured from a dummy head) are convolved with each sound ray's direction of incidence to the ear. From this, the binaural impulse response of the room is given.

The final stage in the process is called auralization, or in other words, transferring all this binary data into audible sound. Here the dry signal (as would be presented by the navigation beacon) is convolved with the binaural impulse response. As a result, the effectiveness of any signal presented can be presented *virtually*, tested and re-tested in order to achieve its maximum navigation potential. However, as with the previous case, this simulation assumes a static case (i.e. source and receiver are not moving) as this is a computationally very expensive process. As will be discussed, this was once again a problem.

5.2 Subjects and Apparatus

18 subjects were used in this experiment, most of them having been involved with the previous one. Once again, a Visual Basic interface was created to replay wavefiles which had previously been auralized. Although there were 10 experiments in this set, only three criteria were sought to be explored, namely:

- the degree to which signals gave left and right impressions (as in the case of junctions). Each subject had to judge the degree of *leftness* or *rightness* of the source presented.
- to explore the exact signals which gave definite front / back judgements. Three experiments were created for this purpose, one being real (with two loudspeakers instead of headphones situated in front and behind them), the other two using headphones.
- the way in which the position of the navigation beacon in space influenced left and right judgements. For this, the navigation beacon was rendered for several different places in a corridor, the theory being that the placement of such a mechanism is critical for its performance. It was unanimously concluded that a navigation beacon placed on the symmetrical axis of the corridor (i.e. facing along its length) gave the best left / right results. In one of the zones, it was found that the geometry of the space adversely influenced left / right judgements to the extent that they were swapped. This was due to the way in which the sound had to propagate through the space, arriving for example at the left ear before the right even though it was actually located on the right of the zone.

From this, 30 wavefiles were created, ranging from unfiltered broadband noise to pure tones. The following section therefore summarises the results of these experiments.

5.3 Results and Discussion

It was obvious from the very beginning of the experiment that certain signals were yielding far better left / right localization performance than others. Figure 4 outlines the preferences of the subjects for varying signal types. As can be seen, numbers 25, 35 and 38 consistently prove themselves to be far superior to any of the other signals presented.

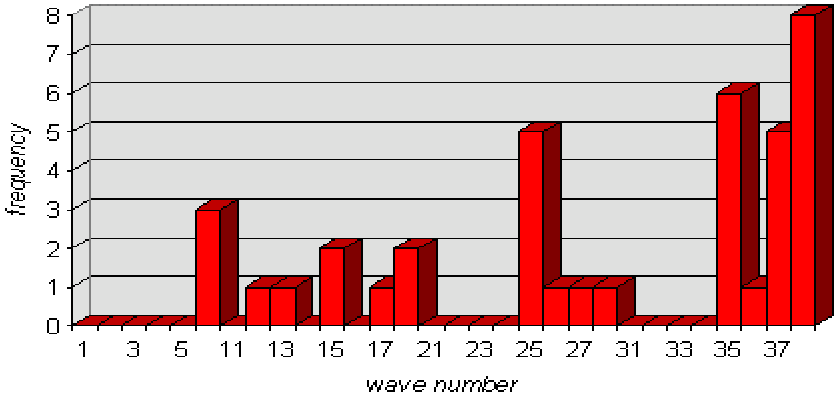

Figure 4. Frequency of occurrence chart illustrating signal preferences

The question arises as to what type of signals were presented in this experiment. Firstly, let us consider that number 1 is pure broadband noise. Theoretically, this should have given excellent directional indication as to its location. However, consistent reports by the subjects indicated that the sound was too 'fuzzy' due to its large spectral content. When viewing these results in accordance with work done by Hartmann (1993), it seems apparent that the corridor with which the sound was propagating through was acting as a strong waveguide. Here, it is probable that the room geometry (long, narrow and low) re-orders the reflections, confusing them with the direct sound. As a result, there is a small breakdown in the precedence effect. Effectively what happened was that due to the vast spectral content of the broadband noise, the reflections from the walls appear as a masker, decreasing localization performance.

On the other hand however, numbers 25 and 35 were tone pulses with a duration of 0.05 seconds, their frequencies at 400 and 4500 Hz. Following from the previous theory (and from subjects response), they were always perceived as being much clearer and more 'to the left (or right)'. Unfortunately, as they were pure tones, all subjects had difficulty in perceiving whether they came from the front or back. The simulated front / back experiments offered absolutely no correct directional judgements, all 30 sounds being perceived as originating from the rear.

Finally, number 38 is broadband noise which had been filtered, containing only frequencies below 1600 Hz, tones at 400, 4500 and 12000 Hz, and bandpassed noise from 10 to 14 kHz. Essentially, number 38 includes all the information necessary for left / right localization (the 1500 Hz barrier as mentioned before for ITDs) and two bands of information which yield front / back responses (the tones and the bandpassed noise). As was also required, this signal has a clear spectral band for conventional fire alarms to operate In addition, there is also the possibility for people to communicate. Since numbers 25 and 35 had poor front / back localization ability, number 38 must be seen as the optimum signal for the beacon. One bonus result was the way in which number 38 was perceived. As the tones only appeared at the first impulse of the noise, they drew the subjects attention to the navigation beacon, acting as an attention cueing aid. In addition, the nature of the pulse also gave some idea as to the distance from source to listener. The experiment was as a result a success and concludes this research.

Conclusions

It can certainly be said that throughout the past 3 years of this research, it would have been almost impossible to conduct these experiments without the use of such virtual acoustic tools. Infact, it would not be untrue to state that to set up real-life experiments as described above would have taken the whole 3 years, nevermind complete the research. Of course, as with any work there is a considerable amount to be done in the future and of interest to the researcher is the way in which smoke adversely influences the propagation of sound in such enclosures (with wider applications in chemical plants etc..). However, it is hoped that this paper has given a sufficient outline of the tools and techniques involved in developing the navigation beacon, hopefully taking an active roll of saving lives in the future.

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