Auditory Navigation and the Escape from Smoke Filled Buildings

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This paper addresses the issue of escape from unfamiliar, smoke filled buildings such as hotels or airports where the scenario of complete visual deprivation may result in occupant death. It proposes that we may be able to apply concise auditory information to the escape procedure, using predictive 'virtual acoustic' techniques in order to assess its feasibility.

Keywords: wayfinding, signal presentation, localization

1 Introduction

As visually orienting creatures, we as humans primarily perceive, explore and navigate our environment through the use of our eyes. The human visual system is therefore often cited as being our primary mode of direct perception. This dependency on visual stimuli has consequently resulted in an innate fear of blindness. We fear, either consciously or subconsciously the prospect of blindness; of being trapped in darkness, debilitated and as a result in a helpless state.

One such scenario of complete visual deprivation is being trapped in an unfamiliar built environment which is on fire and smoke filled, such as a hotel or airport. The occupier is not familiar with the escape exits or indeed the location of the fire itself and is thus exposed to a life threatening situation. In response to this problem, this paper addresses the issue of escape from such buildings, proposing that we might be able to apply concise auditory information to the escape procedure which would guide its occupants to safety. Underlying the whole paper is a description of predictive 'virtual acoustic' models which are being used to evaluate the feasibility of such a proposal. Using psychoacoustic modelling and acoustically 'rendering' the escape routes it is possible to accurately predict occupier ability to navigate solely using the auditory system without exposing them to the dangers of a real fire situation.

2 Building egress and wayfinding conditions

Being familiar with the surroundings is greatly needed when a sudden exit has to be made in an emergency situation [1]. 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 wayflnding 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. Not only is it impossible to see if the fire is on the other side of a wall or around a corner, but the conditions are repeated on other visually inaccessible levels. Signs to exits may be available, but if the corridor is completely smoke filled then they are in themselves useless.

Additionally, within a smoke filled corridor, the choice of escape action is restricted, resulting in hysteria or panic. Various authors agree [2] 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'. So how do these people escape? They have limited wayfinding cues, and along with many precipitating factors such as delayed warning and ambiguous messages from co-occupants really do not stand much of a chance of successful escape. In addition, the conventional alarm in and by itself has been shown to be among the most inefficient means to get people to leave a building [3].

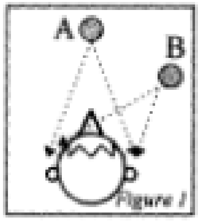
There are methods available for aiding navigation such as emergency lighting and luminous escape systems placed on floors and skirting boards, but in the presence of irritant gases such as ammonia based combustion products, their effectiveness is seriously reduced. It is from this, and from psychoacoustic research that this paper originates and argues that our auditory system is sufficiently developed to compensate for severe visual deprivation in order to guide us to a safe exit.

3 Blind navigation and localization ability

There has been much research into people's ability to localize sound in three-dimensional space, some of the earliest of which was in blind navigation where it was found that blind people navigate in space using sound originating from their footsteps, breathing or cane tapping on the ground [4]. The reflected wavefronts informed the subjects of wall proximity, surface materials etc., not unlike that as used by Bat sonar. From this research, it was found that certain signals cannot easily be localized and the purpose of this section is to describe the nature of these signals for presentation within the system.

3.1 *Localization in the horizontal plane*

The most important cues for localizing a sound source's angular position involves the relative difference of the wavefront at the two ears on the horizontal plane. Most importantly the cues for such lateralization are interaural time differences (ITDs) and Interaural Intensity Differences (IIDs) (figure 1). These cues are highly frequency dependent. Consider the following example. Source A is straight in front of the listener therefore both the ITD and LID are equal, with path lengths being the same.



Source B is 60 degrees azimuth to the right of the listener thus the paths are now unequal causing the sound source to arrive later at the left ear than the right. This path difference is the basis for the interaural time difference (ITD) cue, relating to the hearing system's ability to detect interaural phase difference below approximately 1 kHz. There will also be a significant interaural intensity difference (IID) from source B, but only for those waveform components that are smaller than the diameter of the head (i.e. for frequencies greater than about 1.5kHz which are not diffracted). Higher frequencies will be attenuated at the left ear because the head acts as an obstacle, creating a 'shadow' effect on the opposite side. The smaller the wavelength, (i.e. frequency gets higher) the greater the shadow [5].

The previous example can be assimilated to a person facing the exit of a room which is engulfed in smoke with a sound signal being presented over the door. They simply have to maintain the binaural balance of this stimuli in order to reach the door, the reassuring signal getting louder as they reach their destination. However, what if the person is in the same situation, only with their face pointing in the opposite direction? In this instance, 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? The following section describes this ability.

3.2 *Localization in the vertical plane and from behind*

The 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. Most significantly, localization is a spectrum dependent effect caused by the absorption and diffraction of sound by the ears pinnae (or outer ear) and torso. The helix of the pinnae (or folds) induce minute timing 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. These microtime delays, resonances, and diffractions can be translated into a mathematical model of the ear known as the Head Related Transfer Function [6] which is different for each position of the sound source. Table I illustrates the approximate frequency characteristics of sounds which derive a certain location, i.e. if a signal is presented to a subject from about 6 to 10kHz, (center frequency 8khz) the subject is more likely to perceive it as originating overhead.

Perceived location	Center frequency (kHz)	Bandwidth (kHz)
overhead	8	4
forward (band#1)	0.4	0.2
forward (band#2)	4	3
rear (band#1)	1	1
rear (band#2)	12	4

Table 1:Center frequencies and frequency bandwiths for “directional” bands (7)

4 Binaural room simulation and signal presentation

The location of the auditory events in three-dimensional space is only the first step in tackling the navigation problem. The nature of the smoke filled environment itself adversely influences the way sound propagates through it. Elementary filters such as temperature stratification, thermal boundary reflections, smoke absorption and resultant room impulse characteristics such as an acoustically diffuse or focused environment all degrade the occupiers ability to escape, removing vital frequency and temporal information needed to pinpoint the acoustic emitter. In addition, the type of information presented by the system is fundamental to its performance, whether it be pure tones, speech or broadband noise. This section therefore discusses some of these filters through binaural simulation of the sound fields and examines the signals used within its presentation.

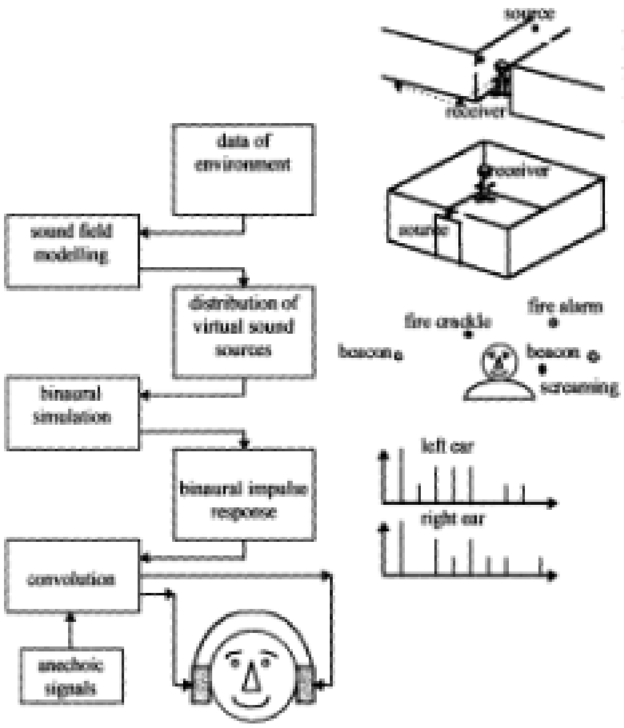
4.1 *Binaural room simulation*

Binaural room simulation allows us to authentically expose a person to a certain acoustic environment in order to evaluate its performance. Within this work, the program EASE (Electroacoustic Simulator for Engineers) [8] 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, HRTFs of the ear and an anechoic signal.

Figure 2 illustrates the general concept behind such a system. 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 (which includes absorption I reflectance characteristics). The sound source(s) are then positioned within the space including their directivity (or dispersion) patterns. An audience area is resultantly mapped onto the space of which several listener positions can be taken. Using geometrical acoustic algorithms, namely ray-tracing, (and if needed, the mirror-image method) the propagation of sound from source to receiver is calculated for linear distortions, such as the spectral modifications from absorption in the atmosphere or by the surface materials. As a result, components of the sound field that impinge upon the listener's head, namely direct sounds and reflections of different orders are simulated with their respect to their direction of incidence and arrival time. It must be noted at this stage that two components of the problem, smoke attenuation and influence of heat cannot be calculated with this software and will not be discussed as they are outwith the scope of this paper.

The next stage in the simulation is the inclusion of the listener's ears in the model. The transfer functions (section 3.2) are convolved with each sound ray's direction of incidence on the ear, the respective components from all sources added (within EARS). This essentially gives the binaural impulse response of the room.

The last step of the process is called auralization, i.e. transferring this data into audible sound. Here, the dry (anechoic) signal such as the alarm sounding, person screaming and ultimately the navigation beacon are convolved with the room impulse response. As a result, the effectiveness of any signal presented can be derived virtually, tested and re-tested in order to optimise its navigation potential. One definite problem with this system is that binaural room simulation usually assumes a static case, i.e. the source or receiver is not moving. In order to assess the viability of any



A block diagram of binaural room simulation [9]

localization system, the head must be allowed to move freely to reduce the possibility of front-back confusions which do arise in static cases (the cone of confusion). Additionally, it is difficult to accommodate multiple sources which are presented simultaneously, especially if there is a temporaldifference between their presentation. These two points will be described in the conclusion.

4.2 *Preliminary ideas on signal type and presentation*

As can be seen, there are several compounding factors which dictate the type of signal to be presented for navigation. At a primary level, the spectral selectivity of the Head Related Transfer Functions dictates that some form of broadband noise must be used in order to engage all portions of the auditory system's localization ability. However, within this broad range of frequencies, there are certain critical bands which are not used and it may be possible to insert additional signals into these spectral locations. There is one definite reason for inserting signals; broadband sound has no real parallels in our everyday life, or in other words it has no real meaning to anyone. A fire alarm sounding, a baby crying and the roar of a lion all have meaning i.e. warning, comforting etc. This meaning must be incorporated into such a navigation system so that people are not confused with many ambiguous messages. Take for example the use of speech in such a navigation system. Speech has a relatively small bandwidth (1-4kHz) yet it is probably the most informative communication medium available. Unfortunately, speech does not have the necessary spectral components needed for localization and more importantly in a multilingual environment such as an airport, the presentation of evacuation directions in many languages would take too long.

This research as a result concentrates on the use of the broadband messages as described previously and suggests two time-variant approaches:

- Presentation of noise which is notch filtered and where pure tones are inserted to form some form of melody. As the person reaches the exit, they are reassured by a raising of pitch within the navigation system. If they are close to the fire, the tones undergo random spectral variations denoting complete danger.
- Presentation of noise which as the person reaches the exits gets closer and closer together, i.e. two pulses are presented for every navigation beacon and as the person approaches the exit, these pulses unite into a continuous stream.

As well as attenuating certain frequencies to insert messages, key localization frequencies must be boosted to accommodate the large spectral modifications from smoke and room impulse conditions. There is also the question of masking within the system whereby external background sounds also affect the signal presentation (such as the fire alarm).

5 Conclusion

This work is currently very much at the final experimental stage whereby the researcher is close to an optimum solution. As can be seen, there are many difficulties within such research, especially using virtual acoustic methods in order to prove them. Firstly, binaural simulation is far from offering real time solutions (taking several hours on a fast Pentium PC for one source) and thus head movement to resolve the cone of confusion cannot be included. Calculating atmospheric attenuation is an additional problem especially when considering that as well as smoke particulates being airborne, they also conglomerate on boundary surfaces thus affecting the absorption characteristics of the materials. The presentation of multiple sources within a corridor also affects the intelligibility of the signal, forming standing waves when pure tones are used within the navigation units. Finally, when using multiple sources, there has to be a time difference between each signal presented utilising another piece of software and many more hours of computation work.

In conclusion, it is the researcher's opinion that we may at some stage in the future see auditory navigation aids being used in the built environment in order to facilitate fire escape. However, the implementation of such systems will be very much technology and legislation driven as the potentially life threatening criticality of building evacuation is not to be taken lightly.

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