THE EFFECTS OF INTERAURAL CROSSTALK
ON STEREO REPRODUCTION
AND
MINIMIZING INTERAURAL CROSSTALK IN NEARFIELD
MONITORING BY THE USE OF A PHYSICAL BARRIER:
PART 1

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The Effects of Interaural Crosstalk on Stereo Reproduction

and

Minimizing Interaural Crosstalk in Nearfield Monitoring by the Use of a Physical Barrier: PART 1

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ABSTRACT:
A study of the effects of interaural crosstalk on normal spaced-speaker stereo listening environments is presented. Interaural crosstalk detrimentally affects both imaging and frequency response. Imaging is affected by restriction of the sound stage to between the speakers and by the loss of realism and preciseness of the sonic images. Interaural crosstalk also creates very severe comb filtering in the frequency response of the direct sound field in which the listener's ears are placed. Furthermore, the amplitude and frequency characteristics of the response comb filtering are found to depend heavily on the positions of the panned images, and are at their worst for a centered image. The interaural crosstalk signal can be thought of as a high-level early reflection coming from the direction of the opposite speaker, but whose timing and amplitude depend on the signal in the opposite channel. Current studio monitoring design techniques tend to accentuate the problems of interaural crosstalk.

Preliminary psychoacoustic test results of a simple method to minimize the effects of interaural crosstalk in a nearfield stereo/binaural loudspeaker monitoring setup are described. The results show accurate horizontal imaging and localization over a 120° frontal angle for both intensity-difference and delay-difference stereo program material. The method depends on the use of a flat vertical boundary erected between two front-positioned, side-by-side nearfield monitor loudspeakers. The listener is situated facing the monitors with his/her ears on opposite sides of the boundary. Advantages include: independent control of amplitude, phase, and delay at each ear; solid frontal out-of-head imaging for side-to-side head shifts and head rotations; extremely good center image; creation of realistic lateral beyond-the-speaker acoustic images; minimization of crosstalk frequency-response comb-filtering effects; and excellent results with both stereo and binaural program material.

Ø. INTRODUCTION

During the past two decades, much attention has been given to the subject of sound localization and, in particular, the interaural crosstalk generated by loudspeakers in stereophonic reproduction systems. Under ideal conditions, your left ear should hear only sounds from the left speaker, and your right ear should hear only sounds from the right speaker. Unfortunately, your left ear also hears sounds from the right speaker and vice versa. This mixing of acoustic signals is called interaural crosstalk.

Most of the attention given to the effects of interaural crosstalk has considered only its detrimental effects on stereo imaging. This paper extends the analysis to the detrimental effects of crosstalk on frequency response and, in particular, its effects on comb filtering of the frequency response. This study will show that interaural crosstalk can be considered as a detrimental type of high-amplitude early reflection with particularly obnoxious characteristics, because its amplitude, phase, and delay depend on signals in the **opposite channel** rather than on signals from the channel that originally generated the sound!

Atal and Schroeder minimized the problem with crosstalk compensation filters; however, as Schroeder later wrote [1], "head turning destroys the acoustic illusion" and "there is always the oddball nonstandard head for whose bearer the experiment will not work." Damaske [2] had success with 9Ø° filters, Cohen [3] with a "stereo image expander," Mori, et.al. [4] with the "Q-Biphonic" system, and Polk [5] with a specially designed loudspeaker system. Unfortunately, these methods also depend on the head remaining in a fixed position in order that the illusion be maintained. Described here is a simple method of minimizing interaural crosstalk while retaining relative freedom of head movement. The method depends on the use of a physical barrier to directly block the acoustic crosstalk signals.

1. EFFECTS OF INTERAURAL CROSSTALK

1.1 Concepts

To provide background of the phenomenon, a brief summary discussing interaural crosstalk follows.

We localize the sources of sound through binaural hearing which, because our ears are on opposite sides of our heads, accomplishes this by comparing the amplitude,phase, and arrival time of the acoustic signal received by one ear with that of the signal received by the other (see Fig. 1).

If the sound source in Fig. 1 is moved to a position directly in front of, or behind, the listener, both ears receive essentially the same sound and this makes it difficult to discern whether the source is fore or aft. The listener must then move his/her head slightly to create a differential amplitude/delay condition to localize the sound source.

When one listens to a normal stereo system, each loudspeaker sends a direct signal to the ear closest to that loudspeaker and a delayed signal to the farther ear (see Fig. 2) which, instead of localizing each loudspeaker separately, the listener perceives together as emanating from a "phantom source" between the two loudspeakers. The two delayed signals, R_l and L_r of Fig. 2, comprise the subject at hand: interaural crosstalk. This phenomenon can be analyzed through the use of phasors [6]: The signals received at the left ear, L_l (direct) and L_r (delayed), can be represented by the phasor diagram in Fig. 3. The signals received at the right ear, R_r (direct) and R_l (delayed) are represented in the diagram of Fig. 4.

Assuming that the signals are identical and that the loudspeakers are equivalently spaced from the listener, the addition of phasors L_l/L_r and R_r/R_l yields the phasors L and R, respectively, which have the same magnitude and phase angle. The effect, then, is as already stated: the perception of a center phantom sound source. Changes in amplitude and delay (Note: delay in this context refers to the time delay introduced in one channel with respect to the other) may shift the phantom image from left to right, but the image will always be within the boundaries of the loudspeakers.

1.2 Effects of Interaural Crosstalk on Stereo Reproduction

Interaural crosstalk detrimentally affects normal spaced-speaker stereo reproduction primarily in two ways: 1) its effect on sonic imagery and 2) its effect on frequency response.

As noted above, the image will always be within the boundaries of the loudspeakers in normal stereo reproduction. This is an effect which most listeners of stereophonic recordings are familiar with, although they may not know the reasons why it is so. Less obvious, but more detrimental, are the effects of frequency response comb filtering.

Imagery is affected by interaural crosstalk primarily by the restriction of the sound stage width to the angular separation of the loudspeakers, and secondarily by the detrimental effect crosstalk has on the realism and preciseness of the created sonic images.

Interaural crosstalk also creates severe comb filtering effects in the frequency response of the direct sound field in front of the loudspeakers. Furthermore, the amplitude and frequency characteristics of the response comb filtering are found to depend heavily on the positions of the panned images and are at their worst for a centered image.

1.2.1 Effect of Crosstalk on Imagery

The primary effect of interaural crosstalk on imaging is the restriction of the perceived sound stage width to the physical width (angular spacing) of the two stereo speakers. For delay panned images way off to the side, this restriction on positioning is a direct result of the crosstalk signal from the opposite speaker reaching the ear before the correct signal from the speaker on the same side as the listening ear. For more information, see the timing and frequency response simulation for delay panned signals in Appendix 4.

If interaural crosstalk is eliminated, the theoretical lateral sound stage width can expand to the full width of 360° (plus or minus 180° from straight ahead)[Fig. 5]. Listening studies done in anechoic chambers using spaced speakers with careful minimization of acoustic crosstalk signals and frequency response compensation (with the head clamped in one position) confirm this widening of the sound field [2].

The secondary effect of crosstalk on imaging is the detrimental effect on the realism of the created sonic illusion. Stereo is an essentially psychoacoustic phenomenon that depends on the listener's ears and mind to create a realistic, believable sound stage illusion. As Polk [5] has noted:

> Experimenters in directional hearing were the first to be troubled by interaural crosstalk since its existence prevents the independent control of phase and arrival time at each ear. Interaural crosstalk was also thought to be the primary cause for the limitations on stereo imaging. The obvious solution was, of course, to use headphones, thereby eliminating the interaural crosstalk paths. .... Although the elimination of interaural crosstalk seemed to give significant advantages to headphones, the phones still failed to produce a convincing sonic illusion [presumably on non-binaural recorded program material such as normal stereo recordings (author Keele comment)].

Most program material listened to with headphones sounds as though it is coming from inside your head. Very few convincing frontal out-of-head images are produced with typical stereo program material reproduced with headphones.

Normal two speaker stereo reproduction produces out-of-head frontal images because the speakers are placed physically in front of the listener. For two-speaker stereo, the best images usually are the right, left, and phantom center images. Images between these points, in most cases, are not as well defined, a bit more diffuse, and more difficult to locate laterally. Only in the best listening situations, where all the early reflections have been properly controlled and reduced, does normal stereo reproduction with spaced-speakers approach ideal imaging performance [7],[8].

As will be shown later, crosstalk can be thought of as a high-level early reflection coming from the direction of the opposite speaker (or from the direction of a true reflection from an imaginary reflective center barrier). The timing of this "reflection", however, is unfortunately based on the path length of the opposite speaker to the listener's ear and on what is received from the **opposite channel**. From an imaging standpoint, this crosstalk "reflection" comes from the worst possible direction--that of the opposite channel. Furthermore, this "reflection" is not coherent with the speaker on the same side as the ear but is **coherent with the opposite channel's signal**. All of these factors contribute to the very detrimental effect crosstalk has on imaging in a normal spaced-speaker stereo listening setup.

To hear how good two-channel stereo imaging can be without the detrimental effects of interaural crosstalk, set up one of the barrier listening setups that are described later in this paper.

1.2.2 Effect of Crosstalk on Frequency Response

The second major affect of interaural crosstalk is the detrimental effect that it has on frequency response. The strong crosstalk signal causes severe comb filtering in the sound field where the listener's head is placed. However, the existence of the listener's head in the sound field and the listener's psychoacoustic processing somewhat decreases the effect of this comb filtering due to diffraction and forward masking effects, etc. These effects will be investigated later in this paper.

1.2.2.1 Ideal Conditions

For stereo reproduction, under ideal conditions without interaural crosstalk, the right ear would hear only the right speaker and the left ear would hear only the left speaker (Fig. 6). If a standard stereo listening setup, based on an equilateral triangle, is assumed (Fig. 7), the energy-time arrival and frequency response at each ear's position, for this ideal condition, is illustrated in Fig. 8. Also shown in Fig. 8 are the resultant ear's responses for a specific interchannel level and delay difference. Use these figures of ideal responses to compare the theoretical and measured responses shown later in this paper.

The levels in Fig. 8 are referenced to the one meter sound pressure of the loudspeakers. At the listener's location, which is roughly 3.5 m from the loudspeakers (assumed to be non-directional sources), the relative level is Ø.28 or about 1Ø.9 dB down from the loudspeaker's SPL at one meter.

1.2.2.2 Real-World Conditions

For the stereo playback setup of Fig. 7, under real-world conditions, the crosstalk signal for a centrally placed image is only Ø.3 dB down and delayed 25Ø uSecs after the direct sound from the loudspeaker on the correct side of the head [see Appendix 2]. This means that each ear is immersed in a direct-sound acoustic field that has some 36 dB peak-to-dip comb filtering with strong dips in the response at 2kHz, 6 kHz, 1Ø kHz, etc. See Fig. 9 for a plot of the theoretical time arrivals and resultant frequency response curves for the sound field at each ear.

Both the depth and frequency characteristics of the resultant comb-filter responses are found to depend heavily on the positions of the panned stereo images. Thus, after-the-fact equalization of the comb-filter responses is very difficult because the equalization depends on the position of the image which may not be known at playback time. Only direct action to reduce the crosstalk signal itself will improve the situation.

From a directional standpoint, the hearing process determines the direction of the various sounds based on the arrival of the first sound at each ear. This is thewell-known precedence effect in operation [9]. The hearing mechanism of forward masking also somewhat reduces the psychoacoustic effect of the response comb filtering.

1.2.2.3 Comprehensive Theoretical Modeling

See Appendices 3 to 7 for the results of a comprehensive, theoretical modeling of the time-frequency behavior of the spaced-speaker stereo setup under several different conditions including: pure amplitude panning, pure delay panning, and lateral head shifts.

1.2.2.4 Amplitude Panned Signals

Analysis shows that for pure amplitude panning, the comb filtering peak-to-dip ratio is maximum for a centrally located image. This is because a central image is created by equal in-phase signals in both speakers which, coincidentally, also makes the crosstalk signals the highest. For the condition of full-right or full-left amplitude panning there is, of course, no comb filtering because only one speaker is on at a time.

Fig. 10 shows the left and right ear frequency response curves of the sound field for a center-positioned listener under the condition of amplitude panning (see also Appendix 3 for more detailed information on amplitude panning). Note that the created comb filtering at each ear is identical for each value of level differential but that the amount of comb filtering is heavily dependent on the level of channel imbalance. Note also that the frequency characteristics of the comb filtering for amplitude panning are independent of panned angle; i.e., the frequencies of the peaks and dips do not depend on where the image is panned.

Fig. 11 shows the comb filtering peak-to-dip amplitude as a function of the channel imbalance for in-phase signals in each loudspeaker. The plot clearly shows that the peak-to-dip comb filtering is maximum for a center-located image.

1.2.2.5 Delay Panned Signals

Fig. 12 shows the effect on the ear's responses of pure delay panning. Note that this type of panning does not change the peak-to-dip ratio of the comb filtering but does severely change the frequency characteristic of the combing and is different in each ear! Refer to Appendix 4 for more detailed information on the time and response effects at each ear for delay panned signals.

Because delay panning does not change the amplitude of the crosstalk comb filtering but does severely change the frequency response characteristics of the combing is one explanation why amplitude panning is usually used for normal spaced speaker stereo listening. Another explanation can be found in a paper by Lipshitz [10].

1.2.3 Crosstalk Mechanism Similar to Reflection Process

The severe comb filtering that occurs for a centrally panned image can be thought of as a reflection process created from a hypothetical perfectly reflective center barrier erected between the loudspeakers. Thought of in this manner, the true effect of the response effects of the interaural crosstalk are easier to comprehend. The argument sequence is as follows:

Assertion:

Assuming a centered image (equal in-phase signals going to each speaker) in a spaced speaker stereo setup, the interaural crosstalk is identical to the reflections from a centrally located, perfectly reflective barrier.

Proof:

Assumptions (see Fig. 13):

1. Typical two-speaker stereo playback setup.
2. Room is perfectly symmetrical about a center plane (or medial plane going from floor to ceiling).
3. Speakers are symmetrically placed on each side of the center plane.
4. Listener is centered between, and facing, the loudspeakers (medial plane bisects his head).
5. Equal in-phase signals in both channels.
6. Loudspeakers are identical and mirror images of each other.

Argument Sequence:

1. Due to symmetry, the sound pressure at equivalent mirror-imaged points on either side of the center plane is identical.
2. If 1. is true, there is no lateral energy flow from side to side across the room. (Note: For a flow of energy in a particular direction, there has to be a gradient or pressure differential in that direction.)
3. If 2. is true, a perfectly reflective, very thin, perfectly rigid boundary of arbitrary length and height can be erected anywhere along the center line (or line of symmetry: barrier is in the plane of the center plane) without changing the sound field in the room in any manner.
4. Now erect the barrier of 3. running between the center line of the loudspeakers and the listener with a height reaching from floor to ceiling (see Fig. 14).

Observations and Conclusions:

1. In the presence of the barrier, what is the effect of the reflection from the surface of the barrier?
2. Reflection precisely replaces the crosstalk signal.
3. Therefore, the crosstalk can be thought of as a reflection from an imaginary reflective barrier.
4. Strong reflections cause severe comb filtering in the frequency response of the pressure at a point in a sound field.
5. Therefore, interaural crosstalk causes severe comb filtering in the sound field at the listener's ears.

This argument sequence clearly shows that interaural crosstalk can be thought of as a reflection from an imaginary reflective barrier that is placed midpoint between the speakers and the listener. Looked at in this manner, the destructive effects of the crosstalk on the frequency response of the direct sound field at the listener's ears is made clearer.

The next section will show, however, that the eal physical barrier has some strong advantages in eliminating the cross-coupling effect of the crosstalk signals, even though the frequency response problems still exist for a center-placed image. It will be shown that it is the cross-coupling effects of the interaural crosstalk that causes most of the problems.

1.2.4 Characteristics of Reflections from Center Boundary

With a central reflective barrier in place along the medial line between the speakers, the effects of the reflections are much more well-behaved than the equivalent crosstalk signals. This is because the delayed response signal is a delayed replica of the signal on the same side of the barrier, not on a delayed replica of the opposite channel's signal!

The cross-coupling effect of the interaural crosstalk is the main cause for the response aberrations being a function of the panned angle of the image. In the case of the reflections from the center barrier, it is found that the comb filtering is independent of the position of the panned image because there is no cross-coupling between the channels (both in peak-to-dip amplitude and frequency).

Appendix 6 shows the theoretical effect of both amplitude and delay panning on the signals at each ear with a reflective center barrier in place. Observe that neither amplitude nor delay panning effects the comb filtering depth nor frequency characteristic at either ear.

The absence of cross coupling also implies that the imaging will be minimally affected by the barrier's reflection. The reflection creates only a response aberration that is independent of other factors. The response abberations can, however, interfere with non-lateral (up and down, etc.) imaging because of the similarity of the combed response to the ear's inherent response effects due to the pinna of the ear [11].

Furthermore, any moderate amount of comb filtering that exists (less than +-3 dB for example) can be easily equalized with a minimum-phase equalizer. Kates [12] shows that a single reflection process is minimum phase for all reflection amplitudes less than the original unreflected amplitude. Caution: don't try to equalize out any severe comb filter dips -- find the cause first and correct the problem at the source. For speakers placed close to the boundary (particularly the high-frequency elements), the main effect of the reflection is a reduction of high-frequency response that can easily be compensated for.

1.2.5Effectof Crosstalk Response Comb Filtering onReal Head

As mentioned before, the actual effect of the comb filtering when thelistener's head is in place is somewhat less than the comb filtering in the sound field in the absense of the head. The effects of the listener's head on an incident sound wave can be predicted from simplified theoretical models of the human head, such as the work of Cooper [13].

Kendall and Martens [11] have made measurements of the head-related transfer functions for a large sample of subjects and for angles of sound incidences ranging over the whole sphere. Use of this data for lateral angles of $\pm 30^{\circ}$ could yield the actual frequency response curves at a typical listener's ears both with and without the interaural crosstalk signal. Data taken from actual measurements done at the entrance of the ear canal with a listener in a recording studio control room will later be shown [Appendix 9].

1.3 Impact of Interaural Crosstalk on Studio Monitoring Design

Current studio monitoring design techniques tend to accentuate the detrimental effects of interaural crosstalk. This is particularly true for designs based on Live-end Dead-end (LEDE) and reflection-free-zone techniques [7], [8], [14].

In the traditional stereo playback setup used in the home, generally no attempt is made to control reflections, either early or late. In this type of situation, the rich, early reflection environment tends to mask the comb-filtering effects of interaural crosstalk.

Additionally, home stereos often have loudspeaker systems with a number of drivers spatially spread over the front of the loudspeaker cabinet which tends to smear the energy time arrivals of the system. For typical listening points, this means that good coherent summing of direct field signals does not take place at any of the normal listening locations and thus tends to, again, mask the effects of crosstalk.

On the other hand, the modern studio monitoring playback setup, using the latest reflection-free design techniques, will tend to intensify the detrimental effects of interaural crosstalk. This is because all the effort in the latest monitoring designstends to make the listening environment essentially anechoic for the early reflection time period (out to roughly 10 to 20 mSecs) between the direct signal from the monitors and the onset of the rooms reverberent signature.

It is found that a number of the reflection-free studio monitoring design techniques that result in a uniform, time correct, direct-field acoustic signal with very low early reflections, also accentuate the effects of interaural crosstalk. Several of these design techniques that worsen the effects of crosstalk are listed as follows:

1. The goal of making uniform coverage by both monitors of the whole listening-mixing area. This essentially guarantees that the crosstalk signal will be equal in level to the direct signal.

2. The reduction of all reflections to make the monitor-to-listener transmission path essentially anechoic for the early reflection time period. This means that there will be no early reflections to mask the interaural crosstalk comb-filtering effects in the direct sound.

3. The use of time-coherent monitor loudspeakers which produce a strong time-coincident direct field at all listening positions. This design technique also guarantees that the crosstalk will be very precise and will comb filter the direct sound to the greatest extent.

4. The use of point source (co-axial drivers) or vertical line source monitoring systems that stay coherent with respect to frequency over wide listening areas. This also ensures that the detrimental effects of interaural crosstalk will be at their maximum.

We are not, in any manner, suggesting that these design techniques be abandoned, for they have gone a considerable distance in the direction of improving control room monitoring and acoustics for accurate listening assessment.

We are suggesting, however, that the interaural crosstalk signal be considered, along with all the other early reflections, as being very detrimental and that direct ways be found to reduce the level of interaural crosstalk to free the monitoring system of its effects. The following section oulines a number of ways that have been proposed to do this along with a number of suggested new methods of crosstalk reduction.

2. WAYS TO MINIMIZE INTERAURAL CROSSTALK

To minimize interaural crosstalk, and thus free the sound from audible comb filtering and the boundaries imposed by the loudspeakers, one must minimize the delayed crosstalk signals while retaining the direct signals. As noted in the introduction, this end has been accomplished by several different means, which we have grouped into electronic methods and acoustic methods.

2.1 Electronic Methods

The several methods mentioned in the introduction are just a fraction of the many devices created to expand the stereophonic sound field. Most of these systems employ the same basic principles, and it is thus that we have chosen one particular typical method to illustrate those principles.

In a construction article which appeared in Radio-Electronics, Cohen [3] described a "Stereo Image Expander" which, by minimizing interaural crosstalk, would expand the stereo image. A delayed and frequency-contoured stereo difference signal (R-L) is fed into a phase inverter, whereupon the output, L-R and R-L, is added to the right and left channels, respectively.

One problem that occurs with the electronic methods of cancelling crosstalk is that each delayed signal added to cancel existing crosstalk generates its own crosstalk, with its own added delay. For the above mentioned Cohen article, six signals are actually received at each ear: the original three [R + L(delta T) - R(delta T)] plus their crosstalk equivalents. This cancelling process can go on in this way, ad infinitum. Only direct methods that block the crosstalk at the source can get around this problem.

2.2 Acoustic Methods

Polk [5] has described a loudspeaker system which, in essence, utilizes the same electronic methods as Cohen, but substitutes acoustical delay for electronic delay. This is accomplished by having pairs of speakers (i.e. two high/mid frequency drivers) in each loudspeaker cabinet, with the members of each pair separated by 6.75" (171.4 mm) (the approximate distance between a person's ears). The inner speakers (Note: "inner" when looking at both loudspeaker cabinets in a normal stereo setup) are fed a direct signal from their respective channels, while the inputs to the outer speakers are frequency-contoured stereo difference signals (R-L, L-R), derived from the subtraction of a phase-inverted signal taken from the opposite channel.

Other acoustical methods of minimizing interaural crosstalk would include: 1) headphones [15] (if anyone ever successfully discovers a method of making the sound appear to come from outside the head), 2) "constant directivity ear trumpets" (potential Author Keele invention, see Fig.15) that would channel the sound directly from the loudspeakers to a person's ears, 3) highly directional loudspeakers that would direct the speakers' output to the proper ear [Fig. 16], and 4) the use of physical barriers.

The use of a barrier to minimize interaural crosstalk has been recognized by several people. Mori, et.al. [4] used this method for an experiment in sound localization accuracy.

The only existing commercial use of a barrier, that we know of, is Monster Cable Products, Inc. "Acoustic Imager" (trade mark) [Fig. 17]. This device is a large absorbent barrier, which is placed centrally between the speakers of a normal stereo listening setup. This device is not intended to block interaural crosstalk but to isolate somewhat one speaker from the other so that "one speaker does not hear the other" [16]. Because the barrier is only 20" (508 mm) deep, and actually placed between the speakers, it cannot block interaural crosstalk because it does not extend all the way from the speakers to the listener's head.

Our involvement with the idea that a barrier placed between two loudspeakers would eliminate interaural crosstalk originates back to 1983 when the second author (DBK) experimented briefly with the method at JBL Inc. A new loudspeaker, which was specifically designed to eliminate interaural crosstalk, had recently been introduced to the audio market. Keele speculated whether or not a simple board would be sufficient to eliminate the delayed signals and, after some experimentation, found that it was.

The first author (TMB) became involved with the concept last year while soliciting the second author (DBK) for audio-related ideas to base a university senior project on. Author Keele had been wanting to do more work with the barrier, and so suggested it.

The majority of our work, thus far, has focused on a reflective barrier oriented perpendicular to a seated listener, with closely spaced speakers (Fig. 18), which will be discussed in subsequent sections. There are, however, many other possible placements for the barrier. One could orient the barrier parallel to the seated listener (lateral) and still eliminate interaural crosstalk (see Fig. 19a). Indeed, multiple listeners could benefit from a "picket fence" setup (see Fig. 19b).

Perpendicular (longitudinal) barriers can also be used in the standard stereo setup. Fig. 20 shows two versions of longitudinal barriers: (a) shows a single listener and (b) shows multiple listeners.

Another possibility is a form of portable barrier that a person could wear on his head. This barrier would extend front to back along the head's medial plane, thus blocking the interaural crosstalk (Fig. 21) (this one could be called the "Personal Portable Barrier"; just try to issue one of these babies to your clients when they walk into your studio!).

3. SUBJECTIVE IMAGING TESTS ON BARRIER SETUP

In order to assess the imaging capabilities of the barrier setup, subjective testing was done to determine the direction of the created image for both interchannel amplitude and delay differences. A wooden testing structure, with self-contained barrier and angle sighting capabilities, was constructed for these tests.

Due to time constraints, however, we were not able to do testing with a large number of subjects. Data was gathered using only two subjects, namely the authors of this paper. At this time , the results should only be considered as a pilot study of the imaging effects of the barrier steup.

3.1 Test Setup

The setup that was used for the subjective imaging tests is described in the following sections.

3.1.1 Physical Setup

During preliminary testing for this project, we quickly discovered that a more substantial setup than "a simple board between two loudspeakers" was necessary. The need to have the loudspeakers at ear level dictated that small loudspeakers be used. A move to the outdoors was necessary to escape the reflections and absorptions associated with room acoustics. A rigid barrier was needed due to the tendency of thinner sheets of wood to bow. Considerations for consistency led to the idea of a standard testing station. Lastly, we needed some type of system for identifying the angles at which a listener perceived sound to be coming from. The result is the testing station shown in Fig. 22.

The semi-circular board on which the loudspeakers are placed has divisions marked for degrees. The barrier is 3/4 inch (19 mm) plywood. A pair of Realistic Minimus-7 loudspeakers were chosen as sound sources because of their wide frequency response of 50-20,000 Hz, the ability to obtain a fairly close-matched set, and their smallness of size.

3.1.2 Signal Path

For purposes of amplification, we used the Crown D-150A and IC-150A. A Crown noise generator provided us with a source of pink noise, and delay was accomplished through the use of the ADS 4000 digital delay line, which can be adjusted in one uSec increments.

3.2 Test Procedure

Each test consisted of several trials. The arithmetic mean of each set of trials was then plotted along with its standard deviation (when possible). We used wide-band pink noise for the input signal in all tests discussed in this paper. Because of time considerations, all tests were done without any phase difference. We intend to test for the effect of phase differences during our next round of testing. Also, as noted before, all tests were done outdoors.

The testing was done with one of us taking the role of listener, while the other was the equipment controller and data recorder. The testing station was positioned so that the listener could not see the equipment nor the controller.

The controller varied amplitude or delay (according to the test being performed) and then recorded equipment settings and the response of the listener as to which angle he perceived the sound to be coming from. Roles were exchanged upon completion of each test.

An interesting phenomenon that we observed was the "breakup" of the sound image. Changes in amplitude and delay are effective only at certain frequencies: Up to 700 Hz for delay, and greater than 2,000 Hz for amplitude, with the region between 700 and 2,000 Hz effective for both in combination [17]. Thus, we usually observed all frequencies shifting together but, at times, we would perceive the low frequencies staying at the origin and the high frequencies shifting, or vice-versa.

3.3 Results

As John Eargle has pointed out [17], psychoacoustical testing is essentially a mental judgement or comparison of acoustical events as influenced by the following:

1. The immediate past physical history of the listener.

2. The listener's prior training and acclimation.

3. Certain biases unique to the listener.

The magnitude of this statement was brought home to us a number of times during the testing--especially at those times when results revealed that one of us perceived a sound to be at 90° while the other's perception of the same event would be at 35°. Of course, a quick glance back at data recorded by others for similar testing brings reassurance as they, too, encountered similar discrepancies. Nevertheless, it tends to be disconcerting.

Fig. 23 shows the combined imaging results for amplitude panned signals, while Fig. 24 shows the corresponding data for the delay panned situation.

The results reflect somewhat that which was theorized. The sound field extends much beyond the typical stereo system arrangement of +/- 30°; however, the goal of a +/-180° sound sound field was not met.

The amplitude panned data of Fig. 23 shows that the image shifted in direct proportion to the amplitude differential in dB out to roughly 50° to 60°. The apparent slope was about 0.44 dB per deg of image shift. That is, a level change of 10 dB caused a shift of 22.5° in the apparent image in the direction of the stronger channel.

The delay panned data shown in Fig. 24 indicates a very similar characteristic to the amplitude data in that an image shift limit is found to occur at roughly 50° to 60° off axis. The slope of the graph is about 0.1 ms per 5°. That is, a delay of 0.1 ms introduced into one channel with respect to the other results in a 5° shift of the perceived sound image in the direction of the non-delayed channel.

The image shift limit of about +/-50° to 60°, noted in both the amplitude and delay panned data, could be due to two possible reasons: 1) Imperfect blocking of the crosstalk signal by the barrier, and 2) the effect of the ear's pinna on the frequency response of the received acoustic signal. In the first case, data gathered later in this paper shows that the channel-to-channel separation of the barrier setup is imperfect, roughly 5 dB at low frequencies and then gradually increases to about 15 to 20 dB at high frequencies [fig. 37].

In the second case, the barrier setup generates acoustic signals that always reach the listener coming from directly ahead. If only amplitude or delay panned signals are assumed, the ears are not receiving the correct frequency response cues due to pinna effects, etc., that signals coming in from large off-axis angles would have. This means that additional processing to include these effects may be necessary to swing the signals further around to the side or rear.

4. LISTENING TESTS WITH SPECIAL RECORDING

For the second round of subjective tests, we made special stereo and binaural recordings which we listened tousing three different types of playback setups.

We made cassette recordings, using omnidirectional and directional microphone setups, of automobile traffic sounds on a busy two-lane highway, and of a person walking around the microphones announcing his relative position to the microphones. These recordings were then listened to with three different types of playback setups: 1) standard stereo, 2) headphones, and 3) the barrier setup. Comments and observations by both authors of this paper were then made (shown later).

The use of two different types of microphones resulted in recordings that simulated both delay panning (spaced omnidirectional), amplitude panning (coincident 9Ø° cardiods), and a mixture of both (spaced 9Ø° cardiods).

4.1 Microphone and Recording Setup

We made recordings using omnidirectional and directional microphones with the microphones at several different center-to-center spacings. The microphones used were the new Crown GLM series miniature electret condenser microphones. These microphones have extremely stable directional patterns, over the whole audio range, due to their very small size [Fig. 25].

We used the model GLM-1ØØ omnidirectional microphone and model GLM-2ØØ hyper-cardoid microphone for our measurements. Eumig FL-1ØØØ and Sony cassette decks were used for simultaneous recording with Maxell UDXLII cassette tape. For both series of recordings, we alternated the microphone spacings between 5.Ø, 1Ø.5, and 17.5 inches with an additional coincedent spacing for the cardiod microphone (Fig. 26). The cardiod microphones were pointed in two different directions with a 9Ø° angle between their axis. The recordings were made at a distance of 3Ø feet from a busy highway between the hours of 3:3Ø and 5:ØØ on a weekday afternoon.

The wide spacing of 17.5 inches was chosen so that a sound source at 5Ø° off axis produced a interchannel delay of about 1.Ø msecs. This approximated the delay versus angle slope of the measured barrier data (Fig. 24).

During the production of the recordings, we announced vehicle directions and noteworthy anomolies such as faster moving vehicles. We also, during slack periods, walked around the setup and made announcements from various angles and distances.

4.2 Playback Listening Setups

For this portion of our testing, we each listened to the tapes on our individual home setups.

Author Keele's listening room is a somewhat small, moderately live basement room of about 1200 cu. ft. No special treatment has been done to minimize early reflections. The speakers, JBL model L-96s (a well-executed 10 inch woofer in a three-way bookshelf system with the drivers in a vertical line, were placed about 3 ft. out from the wall at a spacing of about 8 ft. with the tweeters at ear level (for a seated listener). The barrier listening was done with the JBL speakers on either side of a 4 ft x 6 ft x 1/8th inch wall panel barrier (Fig. 27). Acoustical material (high-pile carpet) was applied to the both sides of the barrier to decrease barrier reflections. The speaker-to-ear spacing was about 40 inchs.

Author Bock's listening room is a relatively acoustically-balanced room af about 1800 ft. One set of speakers, Klipsch Cornwalls (a three-way system with the drivers in a vertical line), were spaced at 8 ft., with the nearest room corners being 3 ft away. One corner of each speaker was placed against the wall and the other was set out at 30°. The other set of speakers, Realistic Minimus 7s (described previously), were used with a barrier setup. The tweeters of both sets of speakers were at ear level (for a listener seated). The headphones used were the Koss HV/X.

The special recording was listened to over three different playback setups:

1) Standard spaced-speaker stereo listening configuration.
2) Headphones .
3) Barrier configuration with side-by-side placed speakers.

Our comments on the subjective effects of the recording on each of the three playback situations follows in the next section.

4.3 Subjective Listening Results

4.3.1 Author Tim Bock Comments:

The subsequent listening tests, resulting from the recordings, reinforced our findings from the imaging tests. Beginning with the omnidirectionals, a 17-1/2" spacing yielded a 120° soundfield (approximate) with the barrier in place, a 60° soundfield with the common 60° stereo setup and, as expected, 180° with headphones. In terms of imaging realism, the barrier setup took top honors (even though the Minimus 7's didn't shake the walls like the Cornwalls did when the semitruck seemingly roared through the listening room!) The headphones, which lived up to their reputation as "originating sound within the head", startled me with their "standing in the middle of the highway" imaging.

For a 10-1/2" spacing, the same soundfields were observed as with the 17-1/2" spacing. However, both the barrier and the common stereo setups exhibited a loss of soundfield at what was announced to be 90° on the recording. For the former, 45° was observed and, regarding the latter, 0° (i.e. center image only).

The 5" spacing yielded further reductions of the 45° barrier and common stereo setups while the headphones retained their 180° soundfield. The barrier setup yielded a 90° soundfield; the common stereo setup, 45°. For 90° anouncements on the recordings, the barrier soundfield dropped to 45° and the common stereo setup again exhibited a center image only.

The coincident recordings yielded consistent results regardless of spacing. 120° soundfields with uniformity of levels were exhibited using the barrier; 180° with headphones; and 60° with the common stereo setup.

4.3.2 Author Don Keele Comments:

The widely-spaced cardiod microphone-recorded material (10 and 17.5 inch spacing) provided too much directional emphasis on all three of the playback setups. The traffic sounds seemed to move much too fast laterally when in the center of the sound stage. The widely spaced cardiods provided a combination of both amplitude and delay directional information to the recording.

1. Standard stereo (with 60° speaker angle)
This playback scheme provided good conventional two-speaker images with fairly good lateral directional cues for both the delay and amplitude panned material. The sound stage was limited to the speaker spacing of 60°, however. The person talking at the 45° and 90° directions appeared to come from the speaker direction of 30°. No beyond the speaker images were noted.

I had a preference for the amplitude panned material at the 5 and Ø inch microphone spacing (cardiod pattern). The delay recorded material did better than I expected, particularly for the 1Ø and 17.5 inch mic spacing (omni-directional pattern). For the delay material, there was always some degree of feeling that the sound was coming from two different sources (which it was).

2. Headphones
The phones did the best job of differentiating the different talker positions and the traffic sounds. The directional spread was all inside my head, however. The phones did not create any convincing acoustic images outside of my head. As Tim Bock pointed out, the traffic sounded as though you were standing in the middle of the street, rather than off to the side.

The amplitude and delay-recorded material seemed to work equally well, but I had a preference for the 5 to 1Ø inch spaced omni mics (delay only, no amplitude panning).

3. Bock-Keele Barrier
This setup provided the most realistic "you are there" illusion for all the microphone configurations, with solid frontal out-of-head beyond-the-speaker images. [Editorial note: due to the fact that we recorded the material, we were there to hear the original traffic sounds and thus able to make good recorded versus actual comparisons.] The sound stage, spread over a total angle of about 1ØØ° to 12Ø° degrees (all out-of-speaker images) with no images created at angles beyond.

With respect to directional images created, it worked equally well for both the delay (omni-directional mics) and amplitude (cardiod-directional mics) recorded material. From a realism standpoint, I had a clear preference for the delay recorded material at the 1Ø and 17.5 inch microphone distances, however.

The amplitude panned material, although providing good directional cues (especially for the 5 and Ø inch spaced microphone recorded material), sounded rather dry and sterile. This is presumably due to only one of the ears receiving sound when the source was off to the side.

The person speaking at 45° appeared to be roughly at 45° in playback for the widely spaced omnis and close-spaced cardiods. The 9Ø° talker, however, appeared at an angle only slightly farther than about 5Ø°.

5. RECOMMENDED BARRIER LISTENING SETUP

The following is our recommendations for a close-listening, near-field, barrier listening setup. The loudspeakers are placed on both sides of a 30" (762.0 mm) x 72" (1828.8 mm) x 0.75" (19.1 mm) thick barrier. The listener's ears are 30" (762.0 mm) from the loudspeakers. Longer speaker to ear distances can be used with deeper barriers, if space permits, because the resultant images and sound stage width are found to be independent of speaker to ear distance.

The setup is based on the use of two small loudspeakers, such as the Realistic Minimus-7, or higher-quality small monitor loudspeaker. All measurements done for this paper on the barrier setup were done with the Minimus-7's.

5.1 General Considerations

The high-frequency components of the speakers should be placed as close to the reflective barrier as possible to minimize the effects of barrier reflections. In the case of the Radio Shack speakers, the tops of the speaker boxes were placed against the barrier, which made the center of the dome tweeter only 1.5" (38.1 mm) from the barrier. This spacing allowed extended high-frequency response from the reflective barrier, which was only down a few dB at 20 kHz (the first interference dip from the reflection occurs at about 26 kHz).

If the tweeters can't be placed close to the boundary, then absorption material must be attached to the boundary to absorb the mid high-frequency reflections. The attached absorption material must have high absorption for grazing incidence sound waves. High-pile carpet works well enough in most instances. The material need not be too large; a 24" (610 mm) x 24" (610 mm) piece applied to the point where the bounce occurs is sufficient, in most cases, to reduce the mid high-frequency reflections.

For wide-range critical listening, additional low-frequency augmentation is required in the range below 100 Hz. This can simply be a summed right-plus-left-channel common-bass setup, operating below 100 Hz by using a single woofer from another larger loudspeaker system. If the bass augmentation is used, the frequency of the main barrier speakers should be rolled off below 100 Hz to prevent low-frequency overload.

5.2 Construction Plans

Suggested plans are shown here for two different types of barrier setups: 1) a speaker-stand style setup with a separate barrier board and 2) a self-contained, stand-alone model with attached speakers on a roll-around assembly.

For informal short-term listening, you can just place your small speakers on any available pair of surfaces that will place the high-frequency elements at ear level. Space for the barrier board must be reserved between the speakers and their mounting stands down to floor level.

Because the low-frequency content of most stereo program material is essentially common to both channels, the transmission loss of the barrier must only be good above roughly 200 Hz. This means that rather thin barriers can be used. Thickness can vary from 1/8" (3.2 mm) to 3/4" (19.1 mm). All of the original barrier listening that author Keele did was done with a 4' (1219.2 mm) x 6' (1828.8) x 1/8" sheet of veneered wall paneling [Fig.27]. Any type of rigid material can be used for the barrier, such as plywood or particle board. Even a sheet of clear "Plexi-glass" could be used for good visual effect (at least the barrier would not block your sight lines!).

5.2.1 Split-Style Speaker and Barrier Stand

Fig.28 shows a three-dimensional illustration of a split-style speaker and barrier stand that supports the speakers, with room for the barrier board to be inserted. The height of the stand should be adjusted so that the high-frequency components of the chosen loudspeaker are at ear level for a seated listener. The size of the stand should be adjusted to properly support the speaker you use. Fig. 29 shows a photograph of the setup we used with the split stand.

5.2.2 Self-contained Stand-alone Style

Fig. 30 shows a three-dimensional illustration of the self-contained, stand-alone, movable-style barrier listening setup. This model has the speakers attached to the barrier, with the whole assembly on a roll-around base. Deflectors are attached to both sides of the bottom of the barrier to minimize the reflection from the floor. Compartments on the side are for storage or can contain the low-frequency augmentation speaker(s).

5.3 Maximum Acoustic Output Levels

Use of a reflective barrier with closely spaced loudspeakers increases the sensitivity and maximum acoustic output of the speakers by 6 dB. This is because the acoustic mirror image provided by the barrier essentially doubles the number of speakers and thus increases the on-axis SPL by 6 dB.

The effective sensitivity and maximum output is also increased by the fact that the listener is only 30" (0.76 m) away from the speakers. Both these factors result in a combined increase of roughly 8.5 dB in sensitivity and maximum output over the loudspeakers normal 1 watt/1 m axial SPL sensitivity. This means that the 88 dB 1 watt/1 meter rating of the Minimus-7 is increased to a 96.5 dB 1 watt/0.75 meter rating.

If an average thermal power capacity of 25 watts (+14 dB above one watt) and a sensitivity of 88 dB 1 watt/1 meter is assumed, a maximum continuous SPL rating of roughly 110 dB SPL is calculated (88 + 2.4 + 6 + 14 = 110.4 dB). This maximum level is quite adequate for most monitoring applications. The speakers can easily handle short term peaks some 10 to 15 dB above the continuous level to properly reproduce the peaks of typical program material.

5.4 Advantages of Barrier Method

As shown earlier, the barrier method allows unrestricted rotation of the head. The listener may also move his/her head laterally, up to one-half (1/2) head width, and still have full benefit of the barrier. As long as the listener keeps his/her ears on the correct side of the barrier, s(he) has complete freedom of head movement (Fig. 31).

Unlike headphones, in which the soundfield rotates with head movement, the barrier method soundfield stays referenced to the world system and stays solidly out in front of the listener. Often, the lateral phantom images created by the barrier method are so realistic that the listener wants to turn his/her head to see the source of the sound. The barrier method allows this, although s(he) won't see the phantom source because it's not there!

As the speakers are positioned centrally close together, a very good central image is maintained--definitely not phantom! Strong, out-of-head frontal images, "binaural-like" lateral images, and extremely realistic beyond-the-speaker images are created from normal stereo material. The loudspeakers seem to disappear!

Because the loudspeakers are only 30" (762 mm) away from the ears and mounted next to a reflective boundary, the effective maximum output and sensitivity of the loudspeakers are increased by roughly 8 dB over the standard one watt/one meter sensitivity and maximum output ratings. The closeness of the speakers to the listener's ears also reduces the effect of early room reflections to levels that compete very well with the early reflection levels in the best control rooms [see ETC measurements on the barrier setup in Appendix 10].

Listening experiments with the barrier setup reveal that the apparent angles of the created phantom images, as heard by the listener, does not depend on the ear-to-speaker distance, as long as the barrier extends the full distance between the listener and the speakers. This means that the listener is free to use any distance between his/her head and the loudspeakers without upsetting the created sound stage. This distance change could allow more or less room sound to enter the listening environment.

In the case of the split speaker-stand style barrier listening setup, the listener is encouraged to move the barrier board towards and away from his head (without moving the speakers) to control the amount of crosstalk rejection. With the board pushed all the way to the speakers, the sound stage collapses into the speakers with no apparent angular width! Pulling the barrier back in place restores the wide sound field. An interesting experiment to perform, with equal signals in each speaker (such as wide-band pink noise), is to offset slightly the position of one speaker in the fore-aft direction and listen to the effect with and without the barrier. Audible combfiltering is heard without the barrier, but with the barrier in place, a non-combfiltered laterally shifted image is heard.

5.5 Disadvantages of Barrier Method

The major disadvantage of the barrier setup is, of course, related to the barrier itself. The listener is restricted to listening at a specific location behind the barrier. Only one person can listen at a time. However, the relatively small size of the nearfield barrier setup could mean that possibly several setups could be placed in a room at the same time.

5.6 Reference Listening Setup

The relatively small size of the near-field barrier listening setup makes it conducive to portable applications where a reference listening environment might be needed. Because the barrier setup minimizes interaural crosstalk, imaging and localization is very precise and realistic. This makes it very appropriate for critical listening situations where a specific recording or mix is to be evaluated.

Because the barrier setup does so well at reducing the level of room reflections, due to the close spacing between the ears and the speakers, its sound reproduction is essentially independent of room acoustics (even in the worst rooms). This means that the barrier setup can be taken into rooms of unknown acoustics, containing possibly unfamiliar playback facilities, to create a known reference playback environment for a specific listener. Headphones can, of course, be used for the same application but have the well-known problems of not creating realistic out-of-head, in-the-front images.

6. MEASUREMENTS

A number of experimental measurements were run to check some of the effects noted in this paper. This section will show the results of measurements taken on the standard spaced speaker stereo listening setup without an added barrier, and on the recommended barrier listening setup.

Data was gathered in two different environments: 1) a small electronics lab at the Crown facility with poor acoustics and 2) a recording studio control room with very good acoustics for listening.

An AES paper dealing with psychoacoustics, generated by Crown employees, would not be complete without TEF measurements. All data was gathered using the TEF System 10/12 measuring analyzer which uses the techniques of time delay spectrometry [18], [19] to gather and process all data. The analyzer allows in-situ measurements to be made of direct sound signals in any acoustic environment. The microphones used were the AKG model C451E and Bruel & Kjaer type 4007.

In all setups both energy vs. time data (ETC) and energy vs. frequency data (EFC) were gathered.

6.1 Lab Measurements on Standard Stereo Setup

Measurements were made in the lab environment on a standard stereo listening setup using two small two-way, closed-box loudspeaker systems. The Radio Shack Realistic Minimus-7 with a 4.5 in (114.3 mm) diameter woofer and 1.0 in (25.4 mm) diameter dome tweeter, and external dimensions of 4.375 in (111.1 mm) wide, 7.0 in (177.8 mm) high, 4.125 in (104.8 mm) deep, was used.

6.1.1 General Comments

The testing was done on a stereo listening setup based on an equilateral triangle with the speakers separated by 4.Ø ft (1.22 m) center-to-center, and the distance between the center of the listener's head to each loudspeaker also being 4.Ø ft.

Sets of ETC and EFC measurements were taken with the test microphone positioned at a point corresponding to the center of the listener's head and to a point where his/her ear would be. The listener was always assumed to be centered between the loudspeakers. The center of the listener's head was equidistant between the loudspeakers, and the ear position was shifted 3.375 (8.6 cm) to the right or left respectively for the right or left ear (assuming a typical head diameter of 6.75 in (171.5 mm).

Measurements were taken at each position, with one speaker on at a time, then with both operating. As an example, the following conditions at the right ear were observed:

CONDITION	EFFECT
1.Rightspeakerononly	Directsoundfromright speaker
2. Left speaker on only	Crosstalk signal from left speaker
3. Both speakers on	Effect of crosstalk on response at right ear

As mentioned before, for the special case of an equilateral triangle listening setup, the interaural difference in distance between the right ear and the right speaker and the right ear and the left speaker (or symmetrical conditions at the left ear) is essentially equal to one-half the width of the listeners head (see Appendix 2). The interaural time delay (ITD) that corresponds to this distance is 25Ø uSecs.

For a center panned image (both speakers operating in phase) this amount of delay should generate a comb-filter frequency response process in the sound field of either ear that has nulls at 2 kHz, 6 kHz, 1Ø kHz and 14 kHz, etc., and peaks at Ø Hz, 4 kHz, 8 kHz and 12 kHz respectively, etc. Fig. 32 shows a simulation of this process using a digital delay line set to a differential delay of 25Ø uSecs and measured with the TEF analyzer. The measurement clearly shows the response abberations and comb filtering of the delayed signal.

Appendix 8 shows the results of the experimental measurements on the stereo loudspeaker setup. Most of the data was gathered at the center head and right ear locations, but some data was taken at the left ear location. Both ETC and EFC magnitude and phase measurements are shown at most locations.

Fig.33 shows time and frequency responses at the right ear location, assuming a centered head, for the following three on-off combinations of loudspeakers:

1) Left speaker on only (crosstalk signal).
2) Right speaker on only (direct signal).
3) Both speakers on (direct plus crosstalk signals).

The ETC data shows the difference in arrival times of each loudspeaker at the right ear location. When both speakers are operating, the ETC response shows the separate energy contributions of each speaker separated by about 250 uSecs. The predicted comb filtering in the frequency response is very clearly shown when both speakers are operating. Both log and linear spaced frequency scales, of magnitude and phase, are used to clarify the effects.

Fig. 34 shows a three-way comparison of the response curves at both ears and the center head position when both loudspeakers are operating. Note that both ear responses are heavily comb filtered and have essentially the same response shape, but that the response in the center, where both channels add coherently, looks quite good with no comb filtering evident.

6.1.2 Simulated Response Effects of Human Head

The shadowing and diffraction effects of the listener's head was modeled by using a styrofoam wig head. The wig head was placed to the left of the test microphone with the microphone diaphragm located at the right ear position (shifted to the right by 3.375 inches from the center position). The microphone axis was parallel to the floor, aimed straight ahead. Frequency response curves were gathered only at the right ear position for the three on-off conditions of the loudspeakers.

The results are shown in Appendix 8. The amplitude of the comb filtering with both speakers operating was not as bad as the previous tests taken without a head present. The peak-to-dip amplitude of the comb filtering was reduced to about 15 dB from the previous value of about 30 dB. This reduction in comb filtering was due to the shadowing and diffraction effects of the wig head. These effects decrease the level of the crosstalk signal and increase the level of the correct signal, thus decreasing the magnitude of the comb filtering.

6.2 Measurements in Recording Studio Control Room

Measurements of the effects of interaural crosstalk were also made on the loudspeaker monitors in a recently constructed recording studio control room. Sound field measurements were made both with and without the presence of a live human model. A sub-minature Knowles microphone was inserted in the entrance of the ear canal for the live model measurements.

The new control room "A" of Chicago Trax Recording (3347 N. Halstead, Chicago, IL 60657) was the location for the measurements. The room was built by Bob Boland, the acoustician was Doug Jones (EASI), and the studio manager is Reid Hyams. This installation uses the technique of selective application of absorption to control early reflections from the loudspeaker monitors [7],[8]. The resultant room sound is quite live with an essentially anechoic first and early arrival sequence but with a late, very diffuse ambience. RPG mid- and low-frequency diffusers are used across the back wall. The monitors are spaced 10 ft 2 in (3.1 m) apart with the mixer forming an approximate equilateral triangle with the loudspeakers. The monitor loudspeakers are the JBL/UREI model 813's.

As before, sets of measurements were taken with each monitor speaker on individually, and then both operating. The measurements were taken at typical mixing-listening points to the rear of the mixing console. Two sets of measurements were taken: 1) the sound fields at the mixer's ears and center head position without the mixer being present and 2) the sound pressure at the mixer's right ear with the mixer present at five different locations behind the console. The sound pressure was measured at the entrance of the mixer's right ear canal, thus including the effects of head diffraction, head shadowing and pinna transformations [11].

These measurements were taken with the assistance of Doug Jones (ELectro-Acoustic Systems, Inc.), the acoustical designer of the studio; and Gary Kendall, Director of Northwestern University's Computer Music department, Evanston, Illinois. Author Tim Bock was the live model for the ear tests.

6.2.1 Measurements of Sound Field

Fig.35 shows the results of the sound field measurements at the mixer's center-of-console position (with no head present) at both ear positions and center head location. Both ETC and frequency response curves were run for each of the three locations and monitor on-off combinations. The complete measured data set is shown in Appendix 9. The predicted combfiltering is clearly evident when both monitor speakers are on. The amplitude of the comb filtering with both speakers operating was roughly 25 dB.

6.2.2 Measurements of Ear Sound Pressure With Live Model

Only measurements at the right ear were taken. Crosstalk measurements were taken at five different typical mixing positions behind the mixing console:

1. Console left: 2Ø" (5Ø8 mm) to left of center,
2. Console left-center: 1Ø" (254 mm) to the left of center,
3. Console center,
4. Consoleright-center: 1Ø" (5Ø8 mm) to the right ofcenter, and
5. Console right: 2Ø" (5Ø8 mm) to the right of center.

The cited positions are for the center of the mixer's head. The actual ear-microphone position is roughly 3-3/8" (85.7 mm) to the right of the cited position.

Fig. 36 shows the results of the tests with the mixer's head present. Differenced measurements are displayed to indicate the direct effects of the crosstalk, without the confusing frequency response effects of the head and ear. The data shown compares the response with just the right speaker on (no crosstalk) to the response with both speakers on (with crosstalk). The complete set of raw measurements, including ETC data, are shown in Appendix 8.

These graphs again clearly show the detrimental effect of the interaural crosstalk. Rather severe comb-filtering is evident, particularly for points to the left of console center. The left console listening positions increase the level of the crosstalk signal in the right ear of themixer, while decreasing the level of the direct sound coming from the right speaker, thus maximising the crosstalk effects.

6.3 Lab Measurements on Barrier Listening Setup

Measurements were made on the split speaker-stand barrier setup to access the following parameters: the amount of crosstalk rejection (channel separation), frequency response, energy-time response, and reduction of room reflections. The Techron TEF System 10/12 was used for all the measurements. All the raw measurements are displayed in Appendix 10.

In every case, the sound field at the listener's ear was measured, but without the listener present. The microphone was oriented parallel to the barrier and aimed towards the tweeter of the loudspeaker. The microphone was located so that its diaphragm was 3" (76.2 mm) shifted laterally from the barrier and 5" (127.0 mm) to the rear of the barrier. This is the approximate location of a listener's ear if s(he) were there.

6.3.1 Rejection of Crosstalk

Fig. 37 shows the amount of crosstalk rejection (or right-left channel separation) provided by the barrier setup. This curve resulted from comparing the frequency response on one side of the barrier with the response on the opposite side of the barrier with only one speaker operating. The graph shows a rejection of about 4.5 dB for the low frequencies, then gradually increases to about 14 dB at 10 kHz, and then up to roughly 20 dB in the 10 kHz to 20 kHz region. This is to be compared to the standard stereo listening setup separation of roughly 0 dB, which represents essentially no rejection at all!

Fig. 38 illustrates the aberrations in the frequency response, generated by the crosstalk. This was measured by comparing the response on one side of the barrier, with its speaker operating, to the same response with both speakers operating. The curve shows an increase in response of about 4 dB in the 100 to 1 kHz band, gradually changing to a loss in response of about 2 dB from 3 kHz to 7 kHz, and then returning to flat above 10 kHz. This gradually-changing curve should be compared to the standard stereo listening curve, which exhibits severe comb filtering of roughly 36 dB peak-to-dip amplitude over the 1kHz to 20 kHzrange, with deep dips in the response at 2, 6, 10, 14 and 20 kHz!

6.3.2 Frequency Response

Because the frequency response of the Minimus-7's was not paricularly flat, an octave equalizer was used to flatten the response of the loudspeakers. The un-equalized response of the Minimus-7' units exhibited a broad peak in the response of roughly 10 dB between 3 kHz and 10 kHz, with some roll off at higher frequencies.

Appendix 9 shows the un-equalized and equalized responses of the Minimus-7's, as measured during use in the barrier setup. The microphone was located the same as for the previous measurements, with 30" (762 mm) between the speaker and microphone. The rolloff above 16 kHz is primarily due to the barrier reflection. The receive delay of the TEF TDS analyzer was set to a value of 2.380 mSecs (equivalent acoustic distance of 32.13" (816.1 mm)), which flattened the phase response of the tweeters in the range of 3 to 20 kHz. A time resolution of 2.00 mSec (corresponds to a distance resolution of 27" (685.8 mm), and a frequency resolution of 500 Hz) was used for these measurements.

Appendix 10 shows a pair of frequency-response magnitude, phase, and group delay curves with the receive delay set to the woofer's delay (2.500 mSecs) and the tweeters delay (2.380 msecs). These time values indicate that the signal of the woofer is reaching the listener 120 uSecs after the signal of the tweeter and corresponds to a distance offset of 1.62" (41.1 mm).

Fig. 39 depicts the high-frequency rolloff due to the barrier reflection. The curve is the difference between a response taken with the mic in line with the barrier, and a response with the mic shifted laterally 3" (76.2 mm) to place it at the ear position. The curve is flat +/- 1.5 dB to 12 kHz and rolls off to -10 dB at 18 Khz and -15 dB at 20 Khz. This rolloff could be corrected by placing either the tweeter or the ear of the listener closer to the barrier. A triangular-shaped barrier might work better for this purpose with the wide end either at the speakers or at the listener's end of the barrier.

6.3.3 Energy-time Response

Fig.40 shows the energy-time response measurement of the barrier setup for the left ear, with only the left speaker on, using a 200 Hz to 15 kHz sweep range. All early reflections within 25 mSecs of the direct sound were greater than 37 dB below the direct sound. Refer to Appendix 10 for the complete set of ETC measurements. Note that with the chosen ETC sweep range, the display is heavily weighted towards the high-frequency end of the spectrum, with two-thirds weight being given to the 5 kHz to 15 kHz frequency band.

The left-right separation of the barrier setup was measured by running an ETC on both sides of the barrier, with only one speaker operating. The microphone was located at the listener's ear locations. The measurement yielded a reduction of 15 dB in the direct sound, with the reverberant sound staying at the same level (graphs shown in Appendix 9).

The major early reflections in the barrier setup occurred from the ceiling and floor. To reduce reflections from these surfaces, absorption material was applied above and below the barrier setup [2" (50.8 mm) thick Sonex was used]. Appendix 10 shows ETC's before and after application of absorption. Even without the application of absorption material, the early reflections were greater than 26 dB down from the direct sound.

7. CONCLUSIONS

7.1 Interaural Crosstalk is Very Detrimental to Stereo Reproduction

We have shown that interaural crosstalk is quite detrimental to standard spaced-speaker stereo reproduction, even with the listener's head present. Interaural crosstalk detrimentally effects both imaging and frequency response. Imaging is affected by restriction of the created images to between the speakers and by loss of realism and precisness of the sonic images. Interaural crosstalk also creates severe comb filtering in the frequency response of the direct sound field in which the listener's ears are placed. Measurements with a live human model, with a microphone at the entrance of the ear canel, confirm that the a large portion of the sound field combing is actually relayed to the listener.

Additionally, the amplitude and frequency characteristics of the crosstalk response comb filtering are found to depend heavily on the positions of the panned images and is worse for a centered image. Current studio monitoring design techniques tend to accentuate the problems of interaural crosstalk by emphasizing even coverage, minimization of early reflections, and monitor time coherance. The interaural crosstalk signal should be considered a very detrimental early reflection, and a prime candidate to be minimized, along with all the other early reflections.

7.2 Barrier Listening Setup Minimizes Interaural Crosstalk

A method to minimize the effects of interaural crosstalk in a close-listening stereo/binaural loudspeaker monitoring setup has been presented. The method depends on the use of a flat, vertical, reflective boundary erected between two front-positioned, side-by-side monitor loudspeakers. Subjective localization tests indicate accurate horizontal imaging and localization over an approximate 120° frontal angle for both intensity-difference and delay-difference stereo program material.

Advantages include: independent control of amplitude, phase and delay at each ear; solid frontal out-of-head imaging for side-to-side head shifts and head rotations; extremely good center image; creation of realistic lateral beyond-the-speaker acoustic images; minimization of crosstalk frequency-response comb-filtering effects; and excellent results with both stereo and binaural program material.

The relatively small size of the near-field barrier listening setup makes it quite appropriate for portable applications where a reference critical-listening environment might be needed. Because the barrier setup minimizes interaural crosstalk, the imaging and localization are very precise and realistic. The close-listening barrier setup also reduces the level of room reflections quite dramatically, making sound reproduction essentially independent of room acoustics. This means that the barrier setup can be taken into rooms of unknown acoustics, containing possibly unfamiliar playback facilities, to create a known reference playback environment for a specific listener.

8. ACKNOWLEDGEMENTS

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The first author (TMB) thanks the Physics Department at Indiana University at South Bend for their support, a fine education, and for their flexibility which gave birth to his involvement in this project.

All of the graphics in this paper were done on the Apple Macintosh computer. Software packages that aided in the preparation of this paper include: MacWrite, MacPaint, MacDraw, Excel, and ThinkTank.

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This is What You Want.

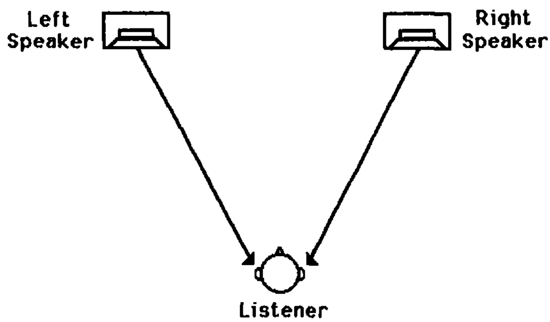


Fig. 1. A standard stereophonic playback system with the primary direct acoustic signals to the ears. The right ear hears the right loudspeaker, and the left ear hears the left loudspeaker.

This is What You Get!

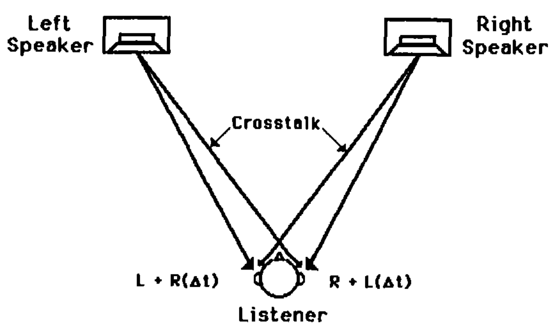


Fig 2. A standard stereophonic playback system including the interaural crosstalk acoustic signals. The right ear, in addition to hearing the right speaker, also hears a slightly delayed acoustic signal, of about the same amplitude, arriving from the left speaker. The left ear likewise hears the right speaker. It is the crosstalk signals that cause problems with imaging and frequency response in a standard stereo setup.

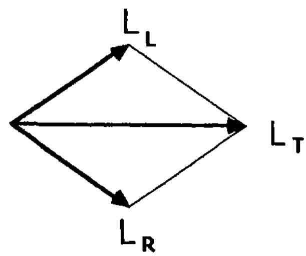


Fig. 3. At left ear; vector addition of primary left signal with crosstalk signal from right speaker yields forward phasor for partial contribution to phantom center image.

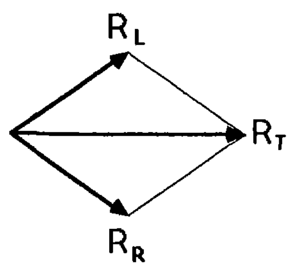


Fig. 4. At right ear; vector addition of primary right signal with crosstalk signal from left speaker yields forward phasor for partial contribution to phantom center image. The effect of the partial forward phasors at each ear, which have the same magnitude and phase angle, yield a perception of center phantom sound source.

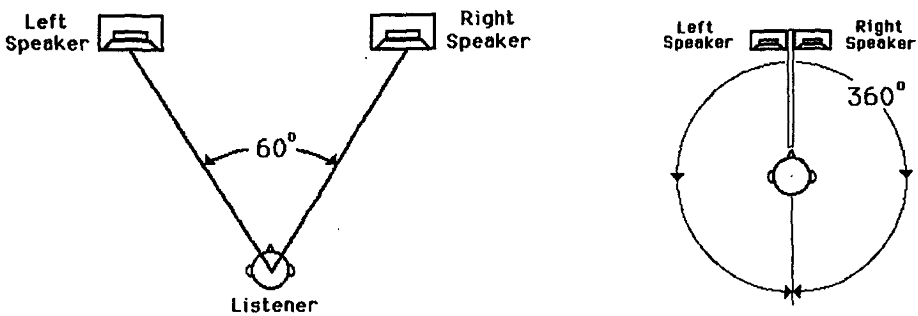


Fig. 5. The potential sound stage angular widths as heard by the listener. (a) Standard spaced-speaker stereophonic system. (b) Barrier imaging system. The sound stage width for the standard stereo setup is limited to the region between the speakers (usually 60 degs) , due to the effects of interaural crosstalk. With crosstalk minimised, on the barrier system (b), the angular width can increase to the full 360 degs, given the proper signal.

Ideal Conditions Without Interaural Crosstalk

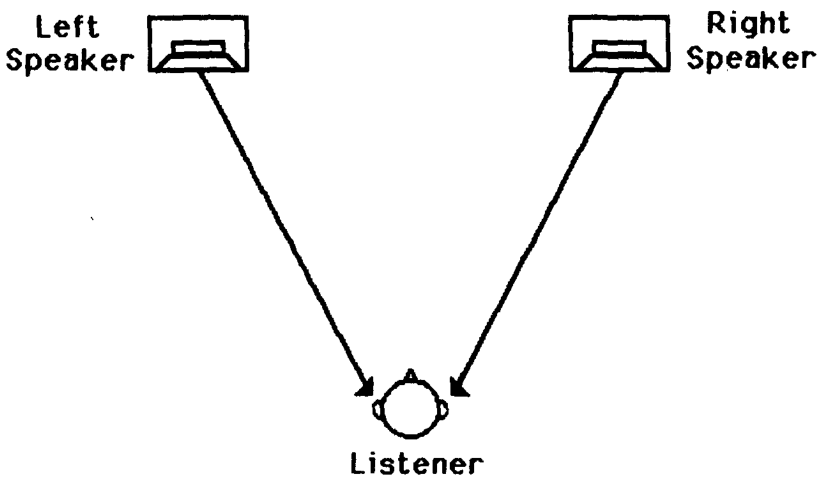


Fig. 6. The standard stereo listening setup would be ideal if no crosstalk signals existed. Imaging would be greatly improved, with strong lateral beyond-the-speaker images and no comb filtering in the frequency response.

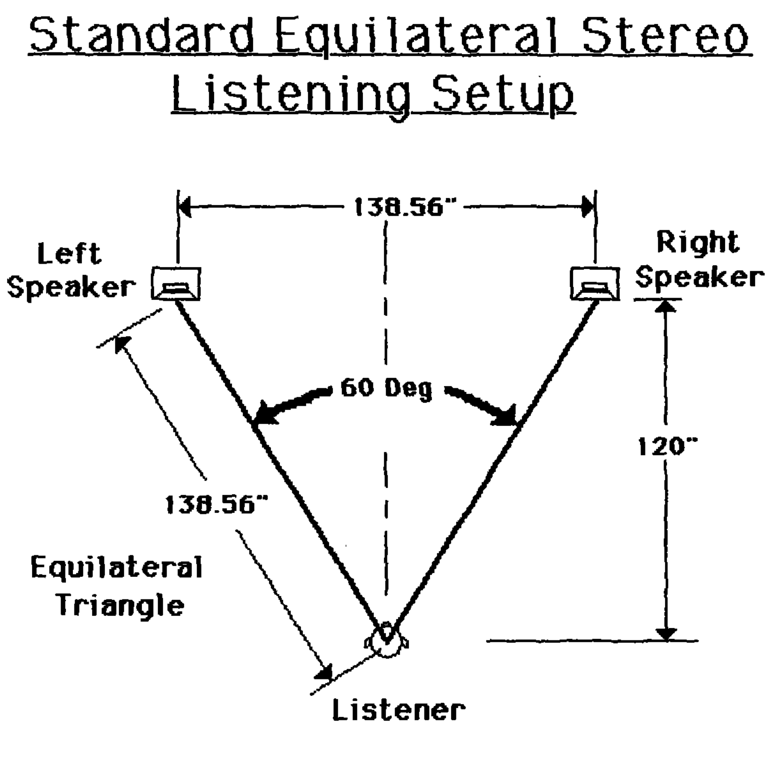
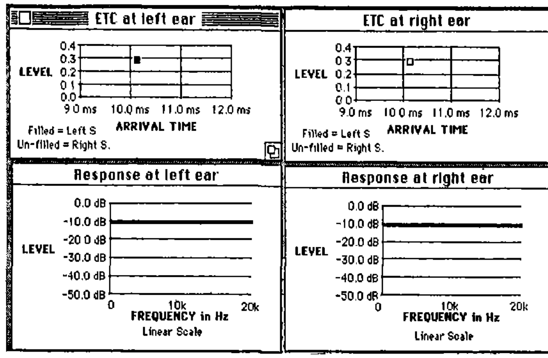


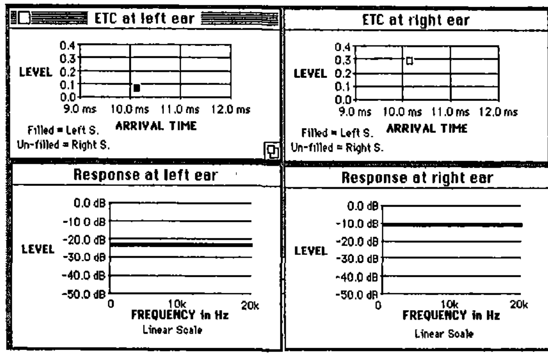
Fig. 7. Standard equilateral stereophonic listening setup with a 60 deg angle between the loudspeakers, as seen by the listener. The distances shown are assumed in most of the theoretical studies in this paper.

Ideal Conditions with No Crosstalk

a. Equal Signals in Both Channels (Center Pan)



b. Left Channel Down by 12 dB (Right Amplitude Pan)



c. Left Channel Delayed by 1.5 msecs (Right Delay Pan)

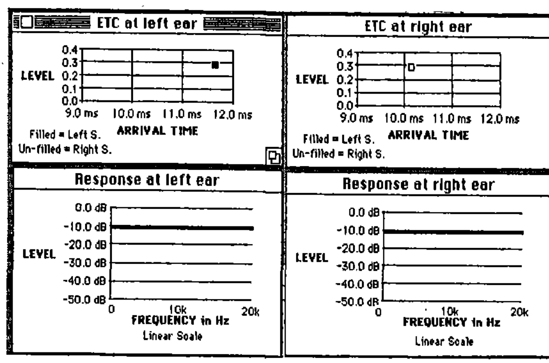
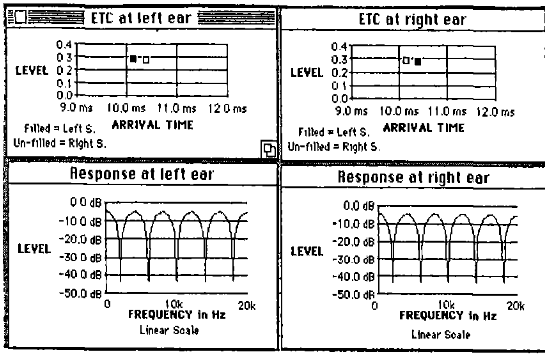


Fig. 8. Set of theoretical time and frequency responses, at both ear positions, for the ideal stereo listening setup of Fig. 7 without interaural crosstalk. Three conditions are shown: (a) Equal signals in both channels (corresponds to a center panned image).(b) Left channel reduced in level by 12 dB (corresponds to amplitude panned to-the-right image). (c) Left channel delayed by 1.5 msec (corresponds to delay panned to-the-right image).

Real World Conditions with Crosstalk

a. Equal Signals in Both Channels (Center Pan)



b. Left Channel Down by 12 dB (Right Amplitude Pan)

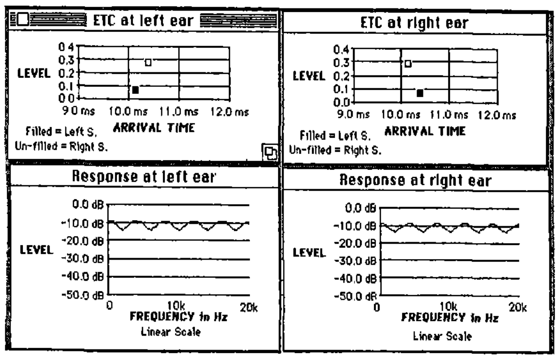


Fig. 9. Set of theoretical time and frequency responses, at both ear positions, for the ideal stereo listening setup of Fig. 7 with interaural crosstalk. Three conditions are shown: (a) Equal signals in both channels (corresponds to a center panned image).(b) Left channel reduced in level by 12 dB (corresponds to amplitude panned to-the-right image). (c) Left channel delayed by 1.5 msec (corresponds to delay panned to-the-right image). Note that there are now two signal arrivals at each ear: the direct signal from the nearest loudspeaker, and a delayed crosstalk signal from the opposite speaker. These two signals cause comb filtering in

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c. Left Channel Delayed by 1.5 msecs (Right Delay Pan)

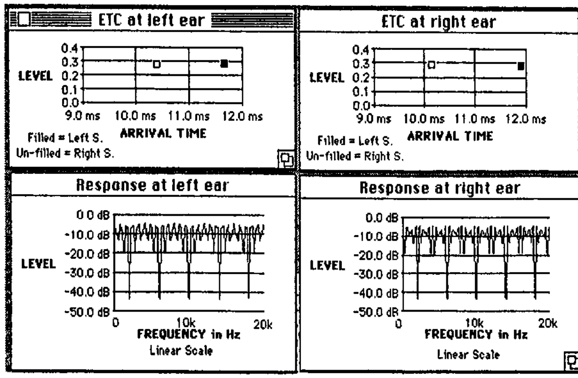

FIG. 9. CONT.

the frequency response at each ear. Note that amplitude panning decreases the comb filtering (b). Note also that in (c), the signal from the right speaker is the first to reach each ear which means the image can go no farther than the right speakers position. Compare these curves to the corresponding no-crosstalk curves in Fig. 8. The apparent change in ripple at different frequencies for (c) is an artifact of the graphing process (samples of the response do not coincide with the exact positions of the dips). The peak-to-peak ripple amplitude does not change for pure delay panning.

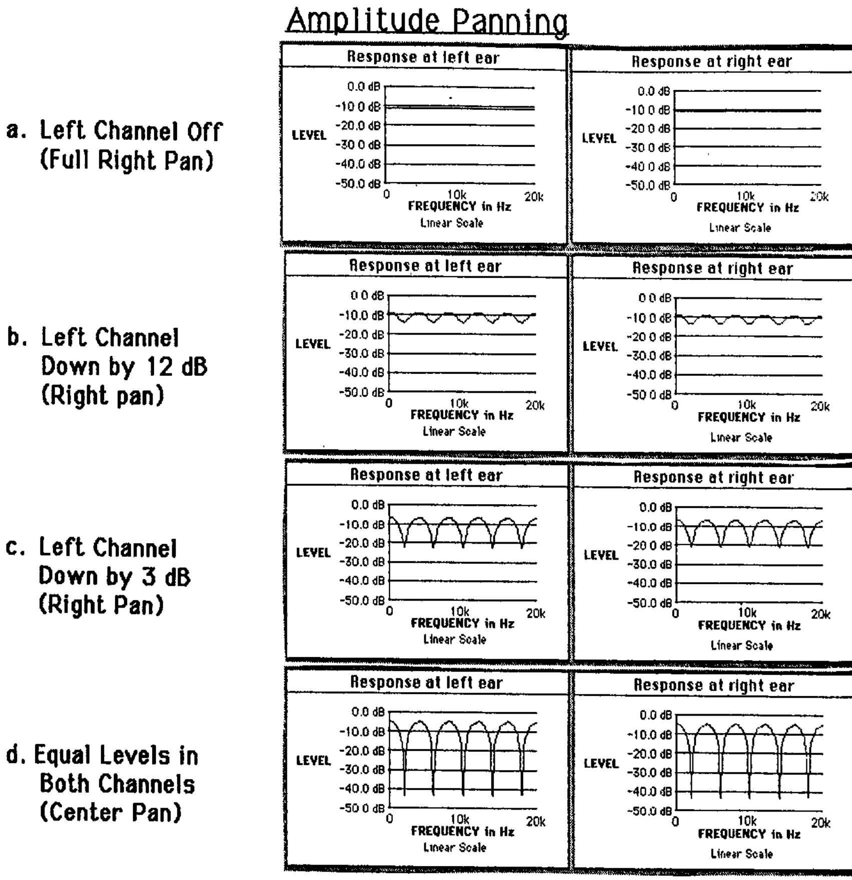

Fig. 10. Set of theoretical frequency response curves, at each ear position, for the condition of an amplitude panned signal, for the stereo setup of Fig. 7 with interaural crosstalk. (a) Left channel off (full right pan). (b) Left channel down 12 dB (right pan). (c) Left channel down 3 dB (right pan). (d) Equal levels, in phase, in both channels (center pan). (e) Right channel down 3 dB (left pan). (f) Right channel down 12 dB (left pan). (g) Right channel off (full left pan). Note that the response comb filtering

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e. Right Channel Down by 3 dB (Left Pan)

f. Right Channel Down by 12 dB (Left Pan)

g. Right Channel Off (Full Left Pan)

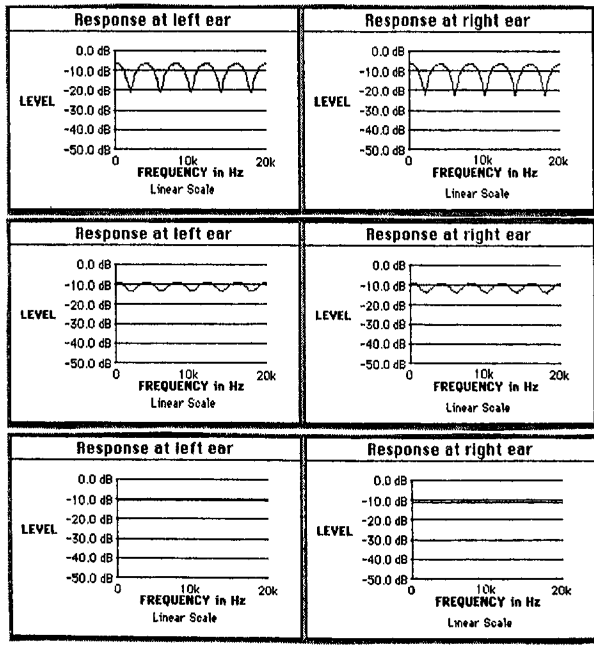


FIG. 10 CONT.

amplitude is a strong function of the position of the panned image. Note also that the comb filtering is highest for a center panned image and goes to zero for a full-right or full-left panned image.

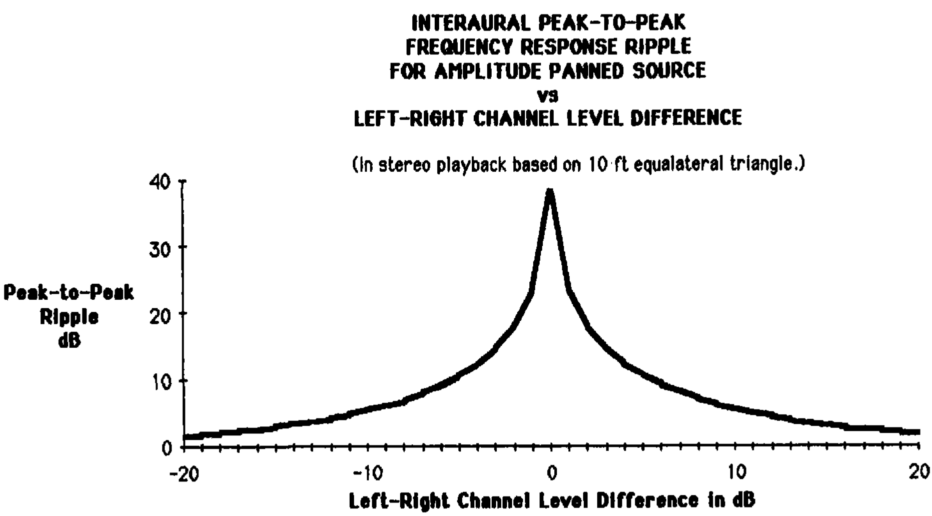


Fig. 11. Frequency response comb-filtering peak-to-peak ripple amplitude, for an amplitude panned signal, versus left-right channel level imbalance for the stereo setup of Fig. 7 with interaural crosstalk. The curve shows a maximum peak-to-peak ripple of about 38 dB for a center panned signal (equal signals in both channels). The ripple amplitude decreases as the signal is panned to either side. At the extremes, full right or full left, the ripple is zero because the opposite channel is off.

Delay Panning

a. Left Channel Delayed by 0.750 msecs (Right Pan)

b. Left Channel Delayed by 0.250 msecs (Right Pan)

c. Left Channel Delayed by 0.1875 msecs (Right Pan)

d. No Delay, Equal Levels (Center Pan)

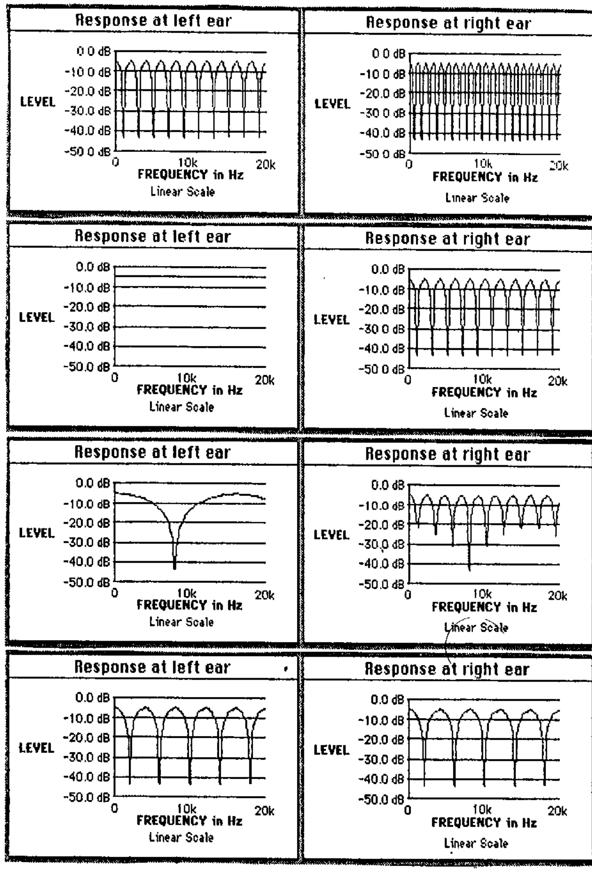


Fig. 12. Set of theoretical frequency response curves, at each ear position, for the condition of a delay panned signal with equal levels in both channels, using the stereo setup of Fig. 7 with interaural crosstalk. (a) Left channel delayed by 0.750 msec (panned to right). (b) Left channel delayed by 0.250 msecs (panned to right). (c) Left channel delayed by 0.1875 msecs (panned to right). (d) No delay (center pan). (e) Right channel delayed by 0.1875 msec (left pan). (f) Right channel delayed by 0.250 msecs (left pan). (g) Right channel delayed by 0.750 msecs (left pan).

CONT. ON NEXT PAGE

e. **Right Channel Delayed by 0.1875 msecs (Left Pan)**

f. **Right Channel Delayed by 0.250 msecs (Left Pan)**

g. **Right Channel Delayed by 0.750 msecs (Left Pan)**

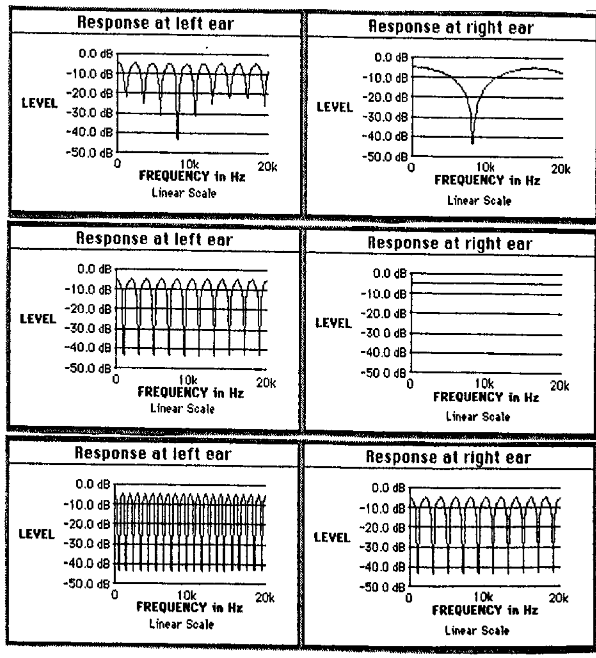


FIG. 12. CONT.

Note that the frequency characteristics of the comb filtering are heavily influenced by the amount of delay. The peak-to-peak ripple amplitude does not change for delay panning. The apparent change in ripple at different frequencies for (c) and (e) is an artifact of the graphing process (samples of the response do not coincide with the exact positions of the dips). The delay for (b) and (f) is just right to make the main signal and the crosstalk signal coincide at one of the ears (no comb filtering!).

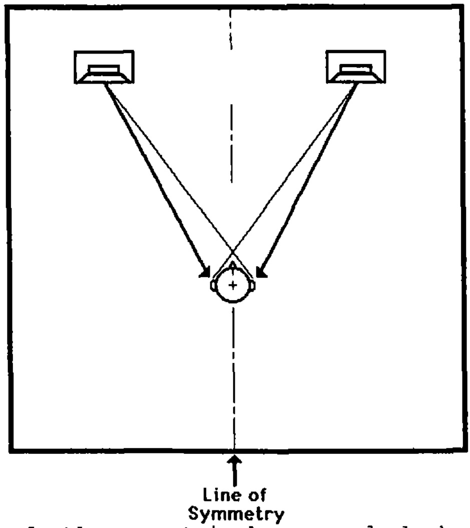


Fig. 13. Perfectly symmetrical room and playback system with equal signals radiating from the speakers (center panned image). If everything is symmmetrical, the sound pressure at corresponding points on either side of the center line is exactly the same.

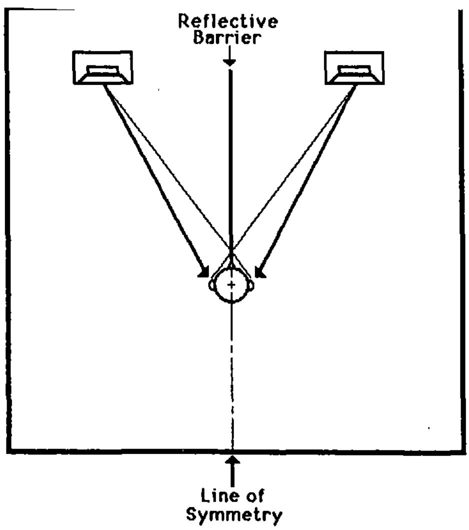
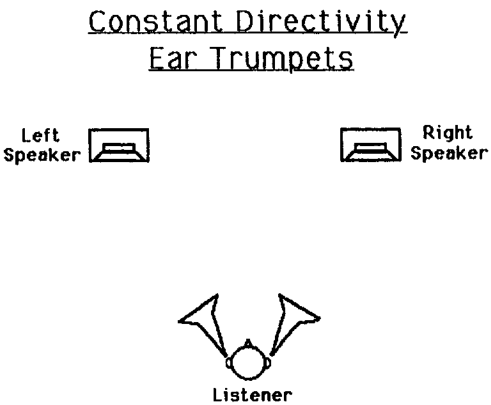
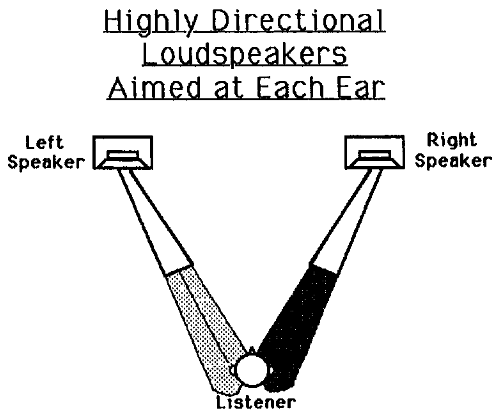


Fig. 14. The perfectly symmeterical room of Fig. 13 with added barrier along center line. The barrier does not change the sound pressure distribution in the room in any way due to the symmetry of the situation. The crosstalk signal of Fig. 13 is exactly replaced with the reflection from the barrier. This shows that the crosstalk, for a centered image, can be considered as a reflection from an imaginary reflective center barrier.





LEFT

Fig. 15. A method of minimizing interaural crosstalk by making the ears more directional.

RIGHT

Fig. 16. A method of minimizing interaural crosstalk by using very directional loudspeakers aimed at the listeners ears.

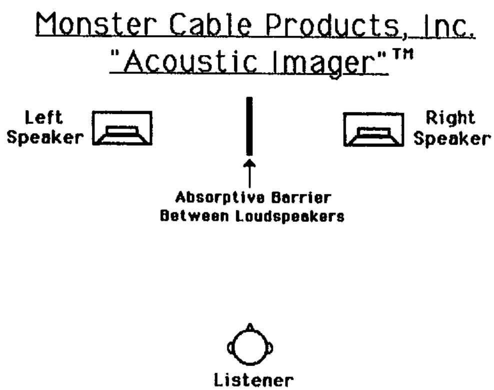


Fig. 17. Illustration of the placement of an absorptive barrier to decrease the acoustic coupling between the speakers in a stereophonic setup.

Nearfield Stereo/Binaural Monitoring System Using a Reflective Barrier

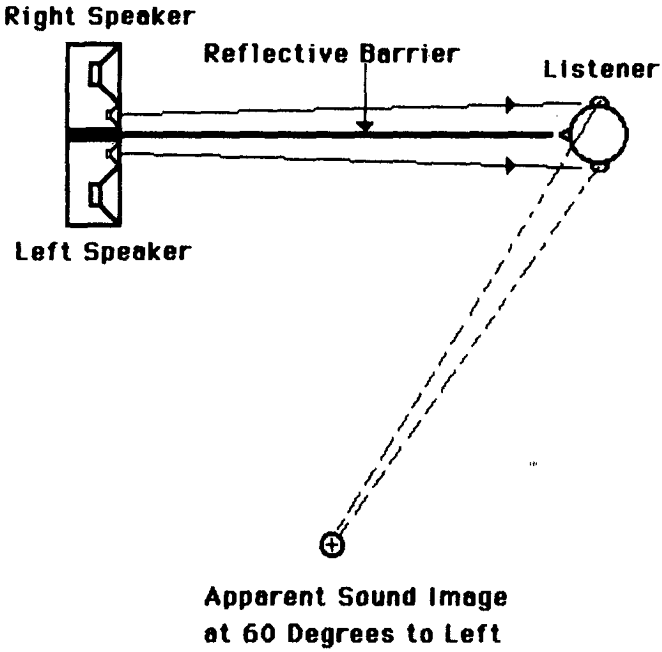


Fig. 18. Use of a reflective barrier between closely spaced speakers to create a stereo/binaural playback monitoring system. Measurements (Figs. 23, 24) show that a potential 120 degree sound field can be generated for standard amplitude and delay panned stereo signals.

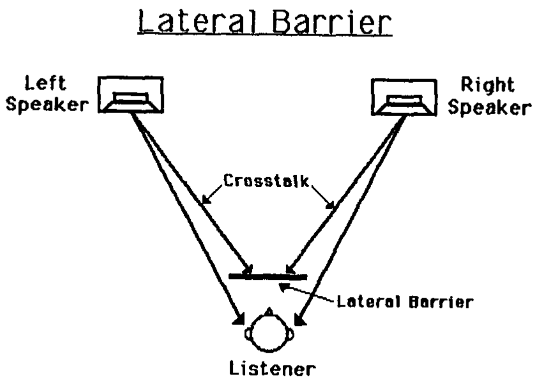


Fig. 19 (a). Idea for a lateral barrier positioned to block interaural crosstalk signals. This has not yet been tested by the authors of this paper.

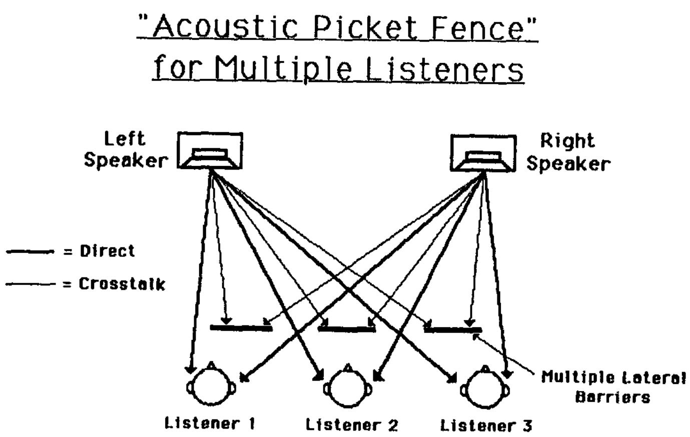


Fig. 19.(b) Idea for several lateral barriers positioned to block crosstalk signals for multiple listeners. This has not yet been tested by the authors of this paper.

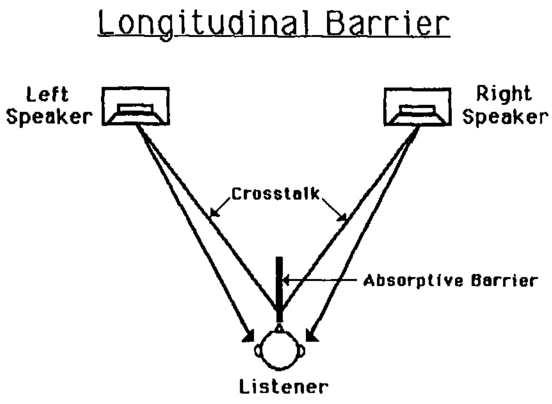


Fig. 2Ø (a). A longitudinal barrier along the center line of the listener to minimize interaural crosstalk

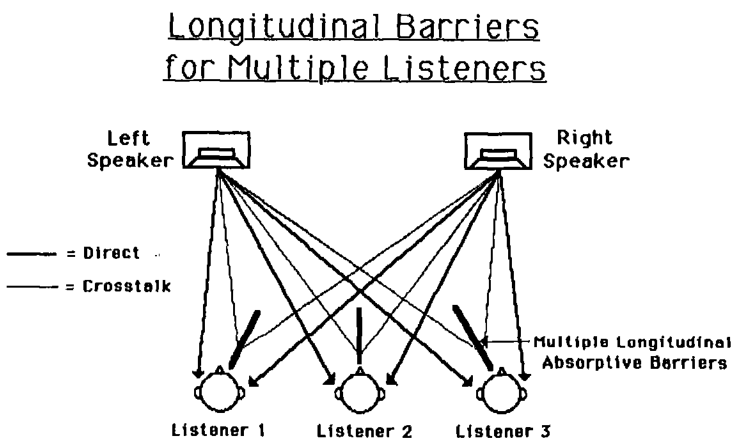


Fig. 2Ø (b). Idea for several longitudinal barriers to minimize crosstalk for several listeners. This has not yet been tested by the authors of this paper.

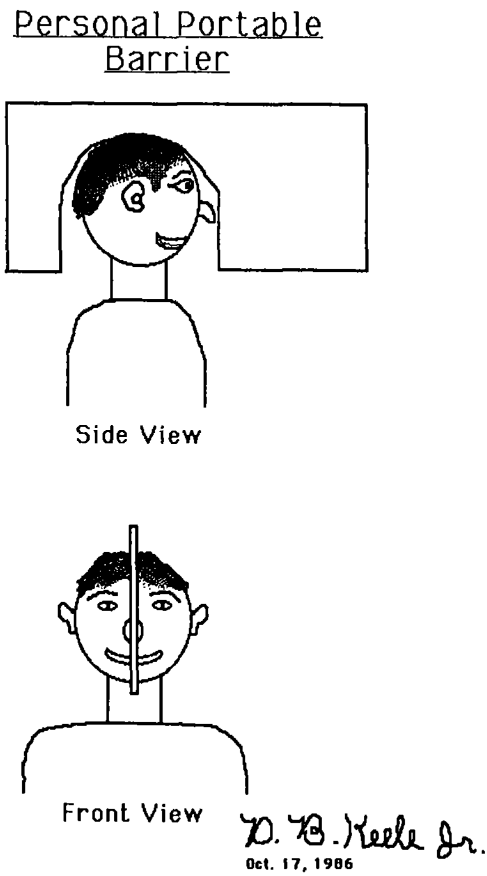


Fig. 21. Idea for a single longitudinal barrier worn by the listener to minimize interaural crosstalk (don't laugh, this is a serious paper!). This has not yet been tested by the authors of this paper.

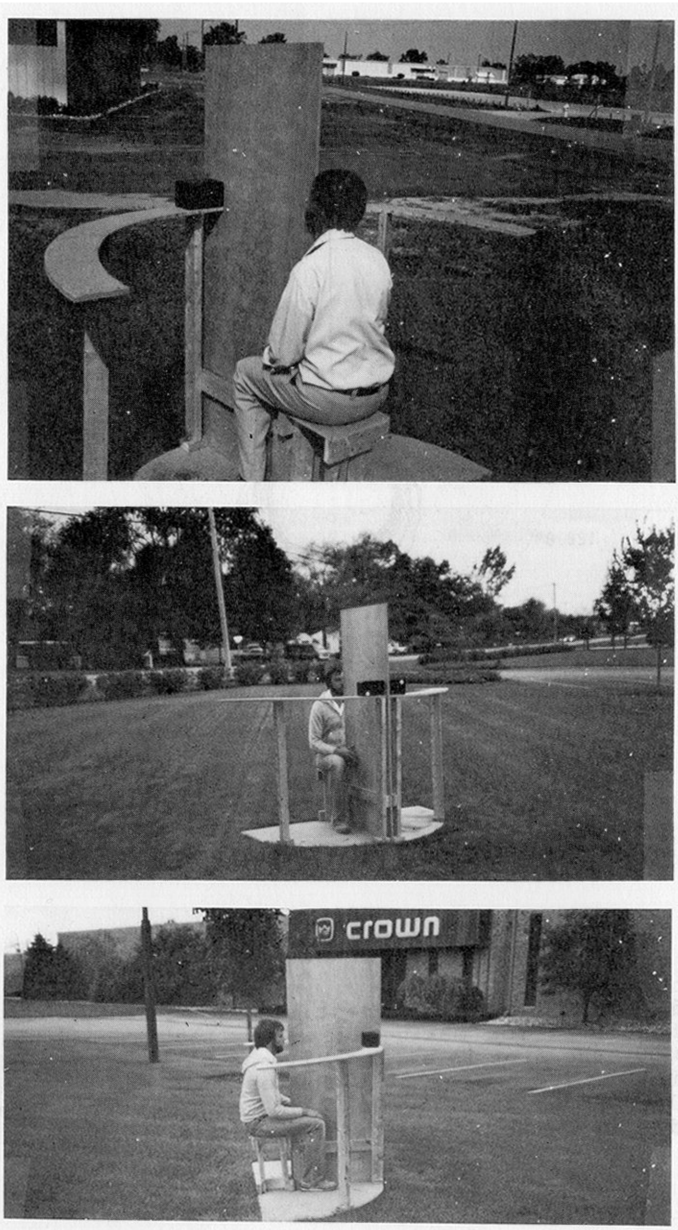


Fig. 22. Photographs of the barrier testing apparatus for subjective testing of image location, with the test subject present. Small speakers are located on either side of the barrier, with their tweeters located closest to the barrier. The speakers are 30" from the test subject's ears. Angles for sighting are marked along the circular portion of the structure. Both amplitude and delay panning ~~was~~ were tested.

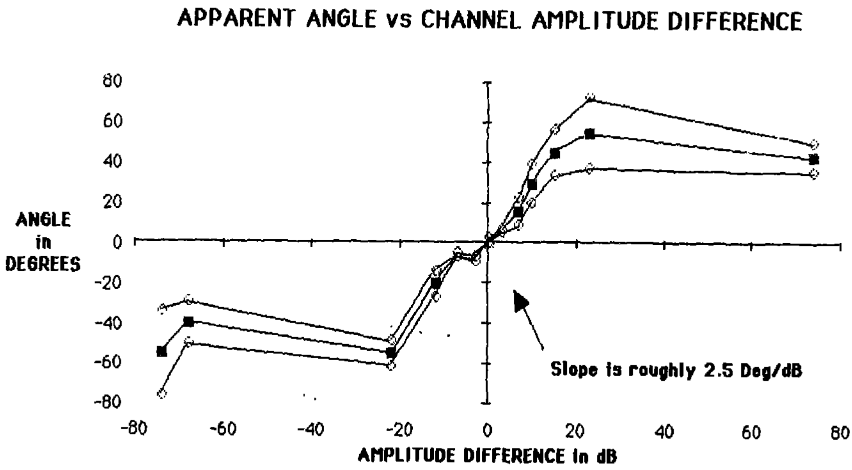


Fig. 23. Preliminary results of subjective image tests of amplitude panned signals using the test station of Fig. 22. Statistical data for only two subjects (the authors) was gathered. The middle plot line is the mean of the measurements. The top and bottom lines are plus or minus one standard deviation from the mean. Data was gathered for amplitude imbalance, primarily in the range of +/- 22 dB. Full right or left was an imbalance of 70 to 80 dB. The data indicates an approximate slope of 2.5 degs per dB of imbalance in the range of -22 to +22 dB . This means that 20 dB swings the image around roughly 50 degs. The data also indicates a limit of roughly plus or minus 60 degrees in the amount of image swing.

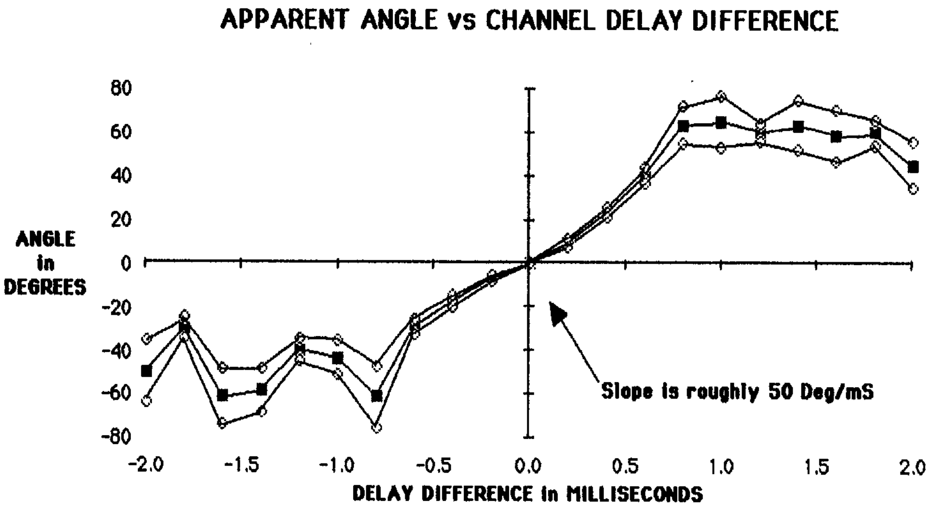
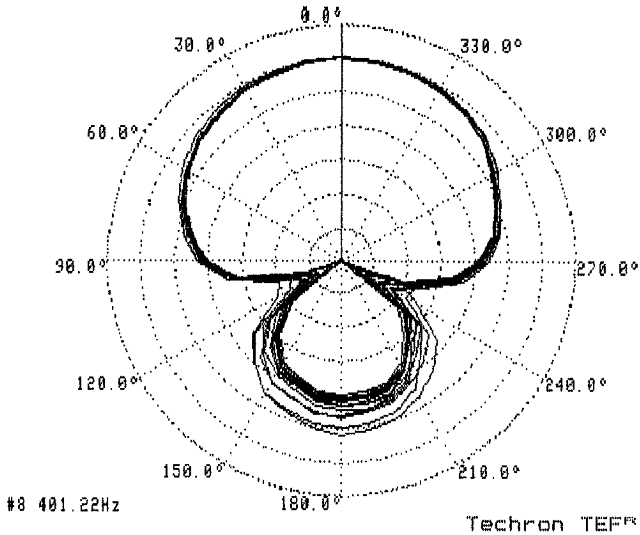


Fig. 24. Preliminary results of subjective image tests of delay panned signals using the test station of Fig. 22. Statistical data for only two subjects (the authors) was gathered. The middle plot line is the mean of the measurements. The top and bottom lines are plus or minus one standard deviation from the mean. The data shows an approximate slope of 50 degs per msec in the range of -1.0 to +1.0 msecs. This means that 1.0 msec swings the image around roughly 50 degs. Similar to the amplitude data (Fig. 23), the data also indicates a limit of roughly plus or minus 60 degrees in the amount of image swing.



Curve #00 is on axis

Grid spacing of 5.00 dB and data gathered at 10.0 degree increments

Center of display is 30.00 dB down

Fig. 25. Composite polar directional plot of hyper-cardiod microphone used for making listening test recording (Crown GLM-200). The plot is a composite of all the data taken at one-third octave center frequencies from 400 Hz to 16 kHz. The polar curves are extremely uniform over this frequency range due to the very small size of the microphone.

Microphone Configurations for Listening Tests

D. B. Keele, Jr., Aug. 13, 1986

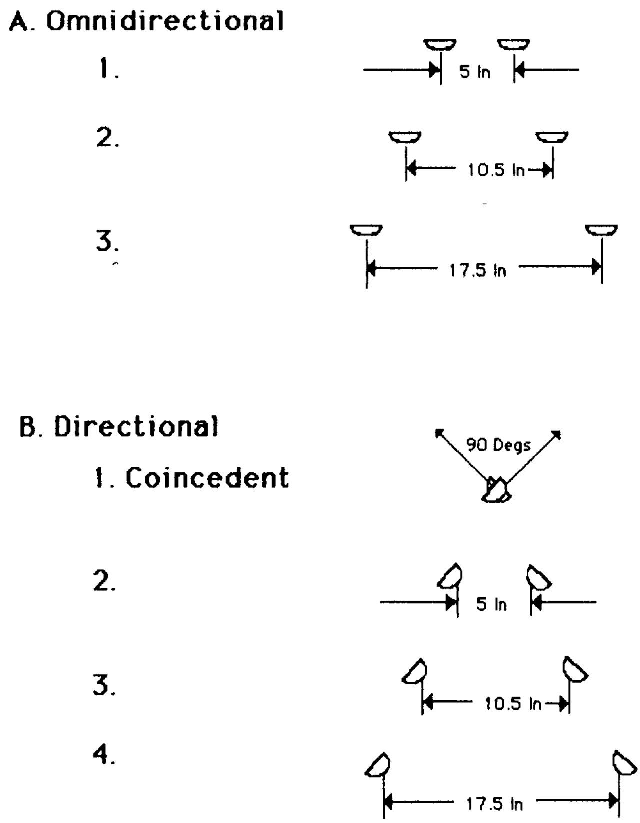


Fig. 26. Microphone configurations for listening test recording. Both omnidirectional and directional (hypercardiod) microphones were used at different spacings. The omnidirectional mics provided essentially delay panned data. The crossed cardiods provided amplitude and combination amlitude-delay panned data. The 17.5" spacing was chosen to give an approximate 1.0 msecs interchannel delay for a sound source 50 degs off axis. This matched the slope data for delay panned signals (Fig. 24).

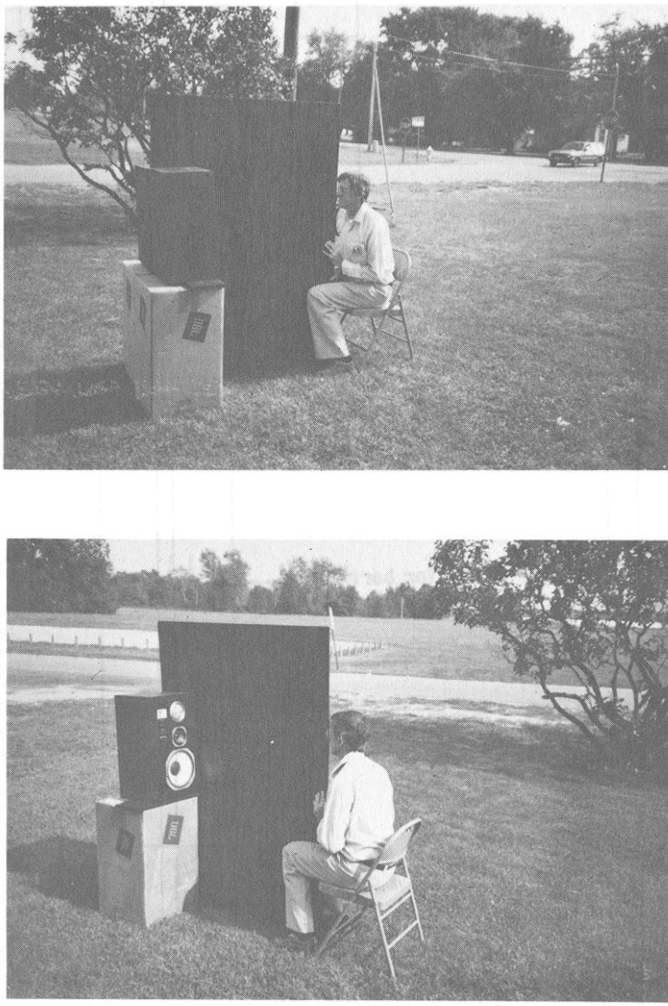
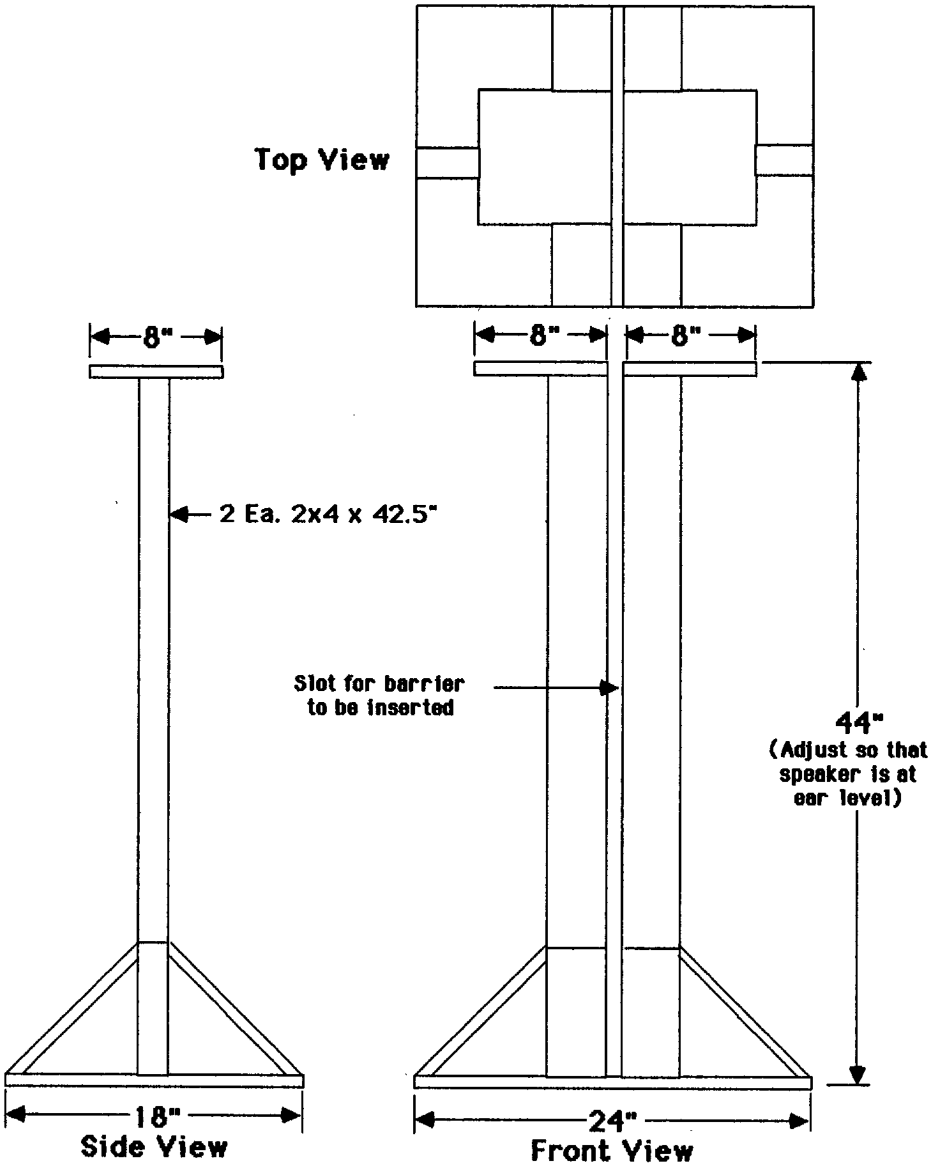
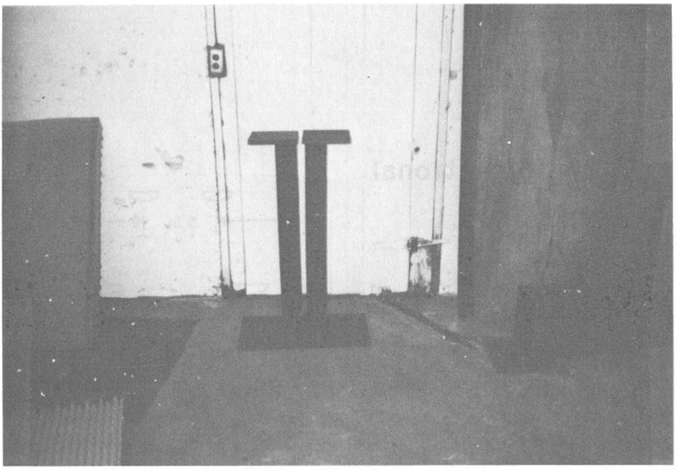


Fig. 27. Photographs of author Keele's barrier listening setup that was used for all his initial listening. Later, absorption material was added to the sides of the barrier to decrease reflections. The barrier is a 4 ft (deep) x 6 ft (high) x 1/8th inch wall panel board. The loudspeakers are the JBL model L96.



Split-Style Speaker & Barrier Stand

Fig. 28. Construction plans for the split-style speaker and barrier stand. The barrier is inserted in the gap between the split stands. The 8" x 8" surface is intended to hold a small "near-field" type loudspeaker system.



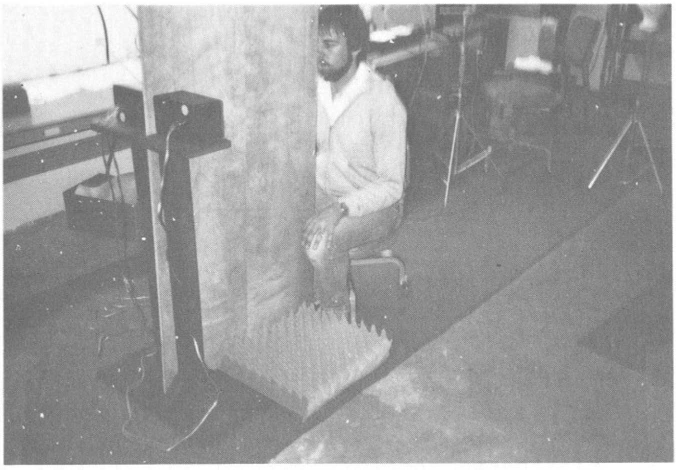
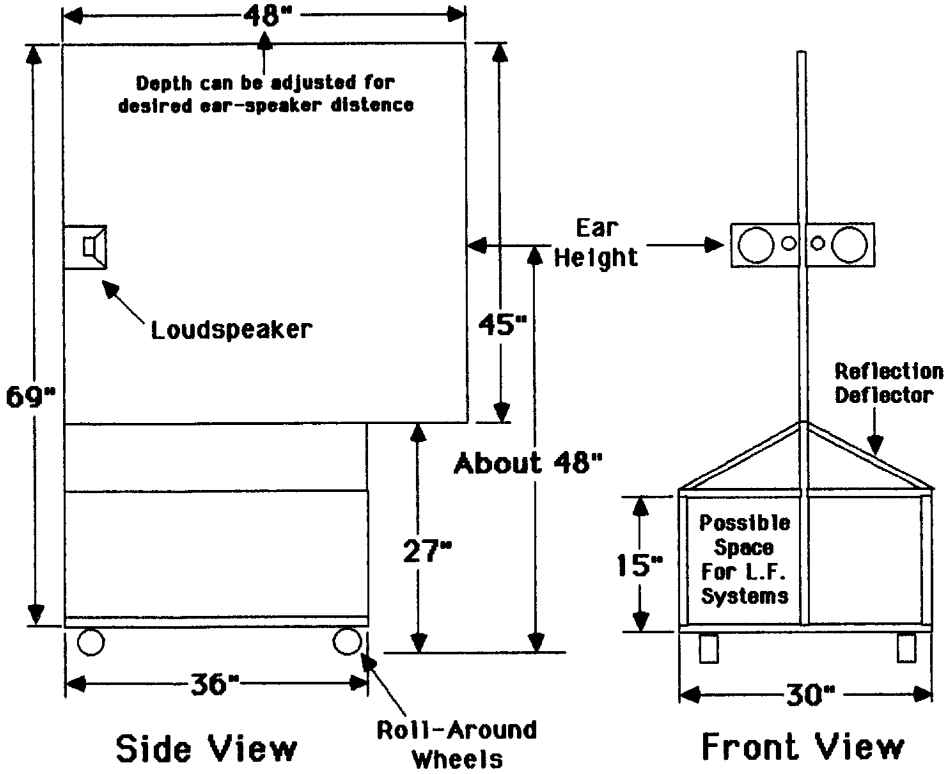


Fig. 29. Photographs of the split-style speaker and barrier stand, alone (top) and set up for operation (bottom). The barrier is a 30" (deep) x 6 ft (high) x 3/4 inch sheet of plywood. The loudspeakers are the Radio Shack Realistic Minimus-7's. Sound absorption material was placed on the floor to decrease floor reflections.



Roll-Around Stand-Alone Style Barrier System

Fig. 30. Suggested construction plans for a self-contained roll-around stand-alone barrier listening setup with added space for low-frequency augmentation speakers. The depth of the unit can be adjusted for other desired ear-to-speaker distances. The speaker height is approximate for a seated listener.

Allowable Head Movements for Nearfield Barrier System

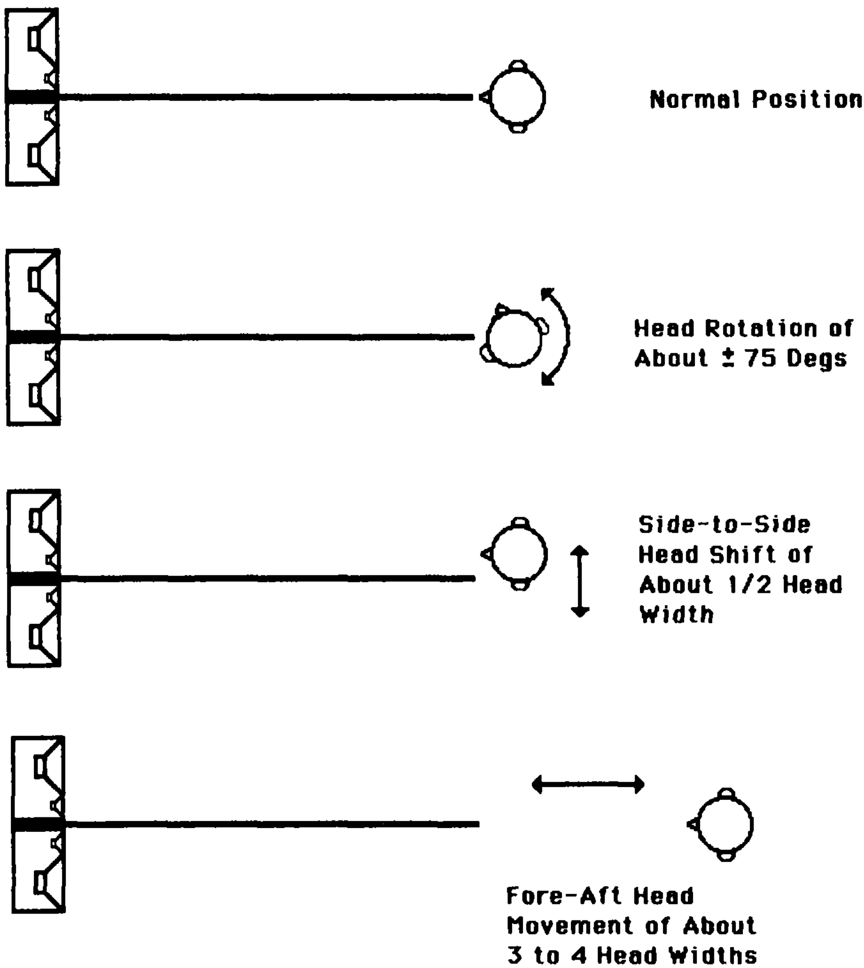
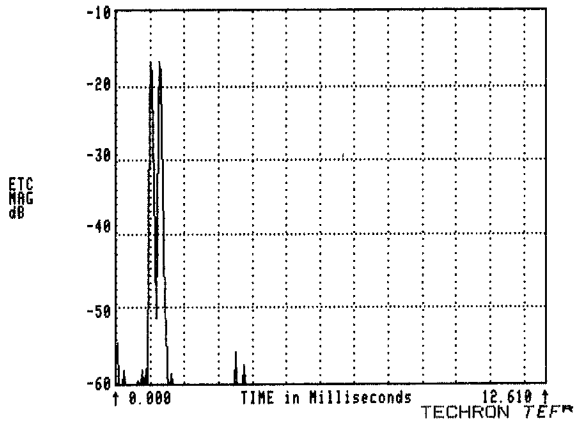


Fig. 31. Allowable head movements for nearfield barrier listening setup. The listener's head can rotate roughly +/- 75 degs, shift side-to-side one-half head width, and shift fore-aft about 3 to 4 head widths. Most movement is possible, as long as the listener keeps his/her ears on the proper side of the barrier.

Simulated Direct plus Crosstalk Signals



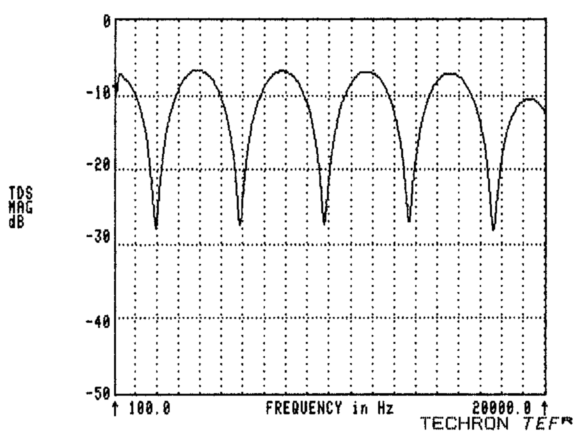
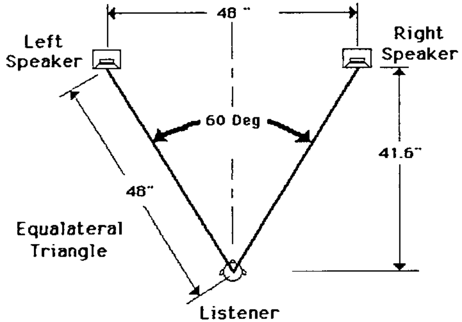


Fig. 32. Measurement of time and frequency response data for a simulated interaural crosstalk signal using a digital delay line. The setup simulates a direct plus crosstalk signal of equal amplitudes, but with a differencial delay of 250 usecs. The resultant response was measured with the TEF System 12. (a) Energy vs time data (ETC). (b) Energy vs frequency data (EFC). The top response shows the two signals in the time domain. The bottom response clearly shows the resultant comb-filtering in the frequency domain. The TDS time resolution was set to 2 msecs with a frequency resolution of 500 Hz.



RESPONSES at RIGHT EAR POSITION for LEFT SPEAKER ON, RIGHT SPEAKER ON and BOTH SPEAKERS ON

TIME RESPONSE

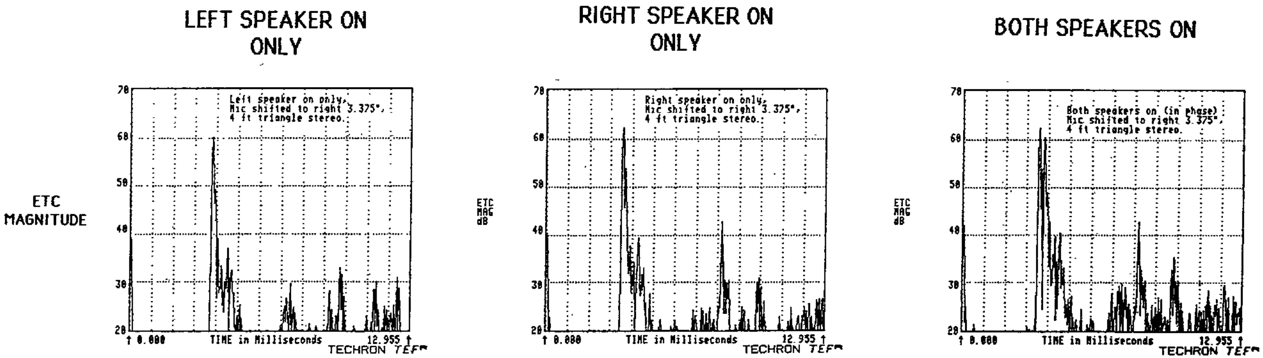


Fig. 33 (a). Time response data. Experimental measurements of two small speakers set up in a standard 4 ft equilateral-triangle stereo playback setup. Measurements were done in a lab environment. The microphone was placed where the right ear would be of a center positioned listener. Both time and frequency response data was taken for three different conditions. (Left): Left speaker on only (crosstalk signal). (Center): Right speaker on only (direct signal). (Right): Both speakers on (simulates both direct and crosstalk signals on). Note the comb filtering in the frequency response data when both speakers are on (right responses).

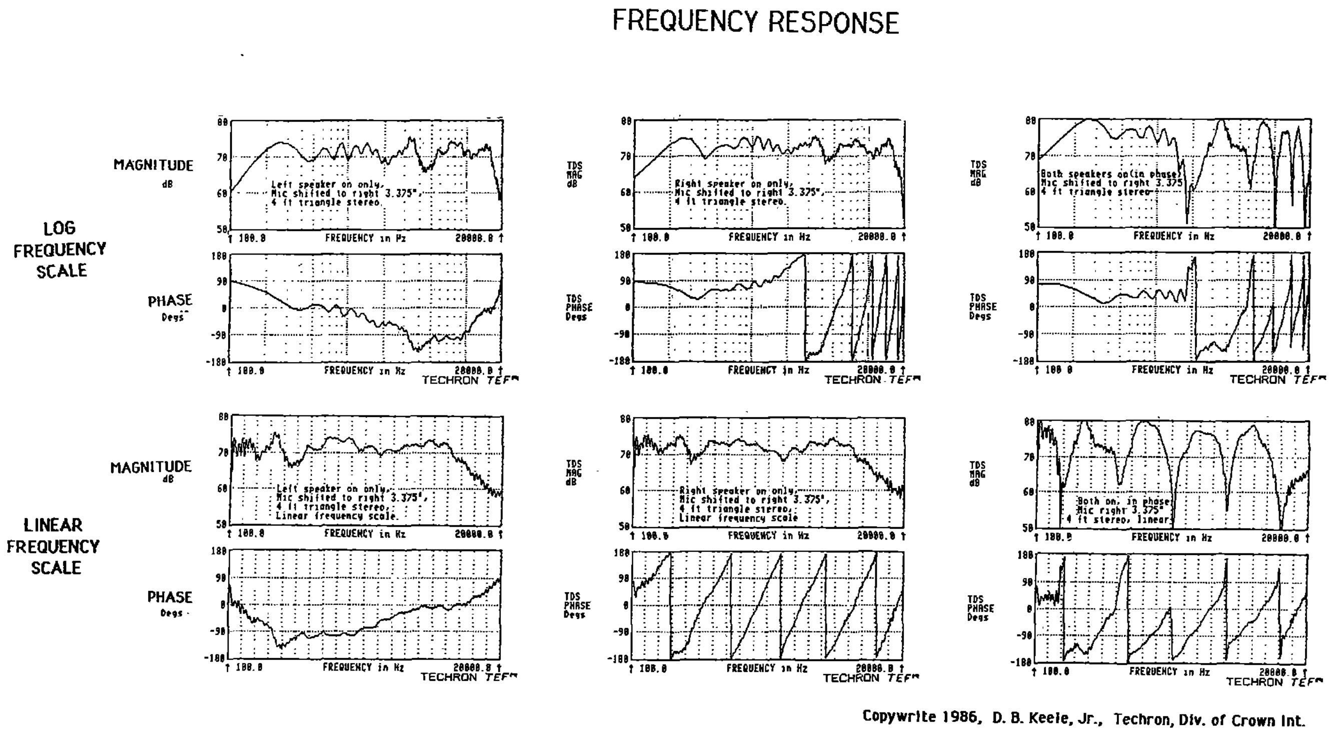
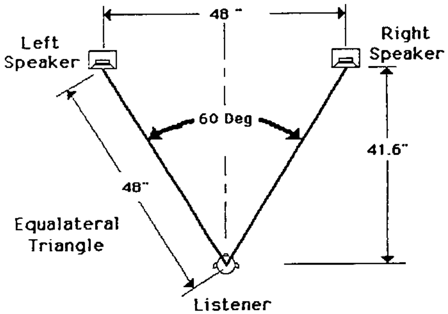


Fig. 33 (b). Frequency response data. See comments on Fig. 33 (a).



RESPONSES at LEFT EAR, CENTER HEAD and RIGHT EAR POSITIONS for 4 FT SPACED STEREO SPEAKERS

(with EQUAL IN-PHASE SIGNALS to BOTH SPEAKERS)

TIME RESPONSE

AT LEFT EAR POSITION

AT CENTER HEAD POSITION

AT RIGHT EAR POSITION

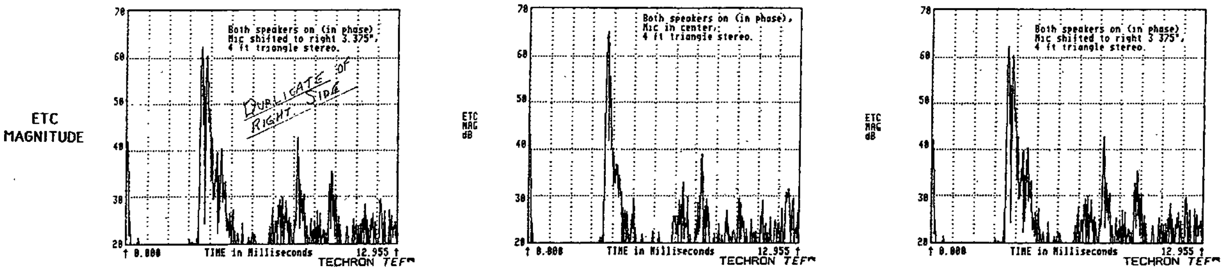


Fig. 34 (a). Time response data. Experimental measurements of two small speakers set up in a standard 4 ft equilateral-triangle stereo playback setup. Measurements were done in a lab environment. These measurements compare the responses at three different locations for a center panned signal (equal levels in both channels). (Left): Left ear location. (Center): Center head location. (Right): Right ear location. Note that the response is very good at the center location, but heavily comb filtered at either ear location.

FREQUENCY RESPONSE

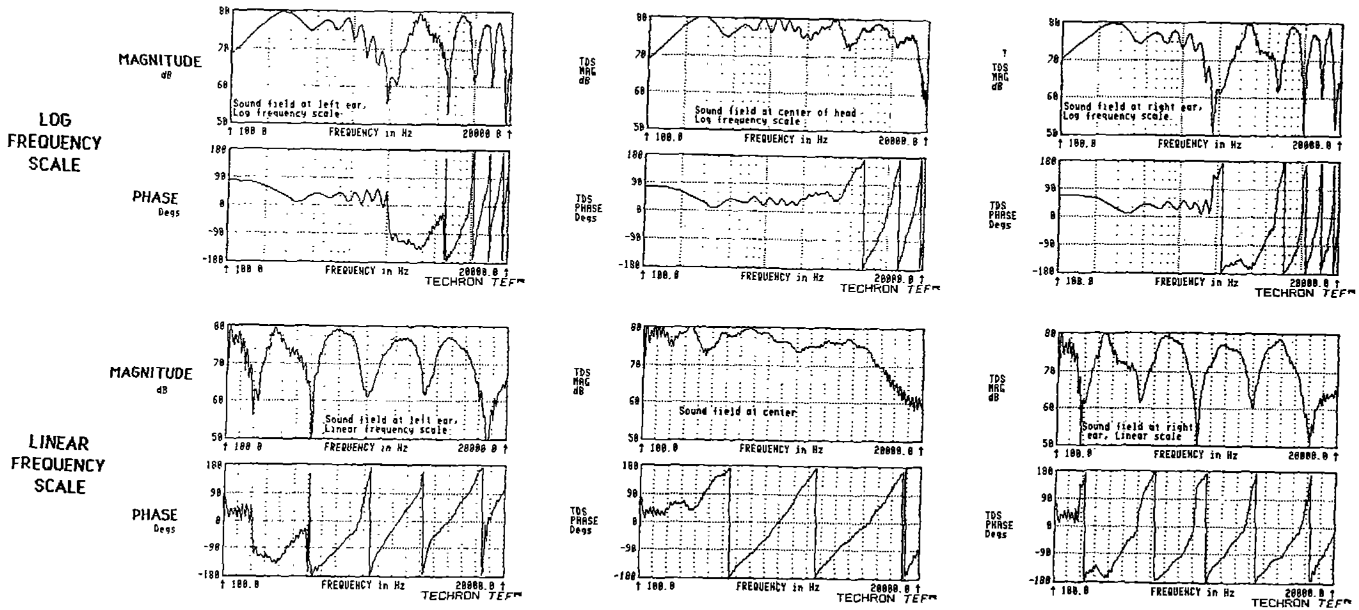


FIG. 34 (b). FREQUENCY RESPONSE DATA. SEE COMMENTS ON FIG. 34(a).

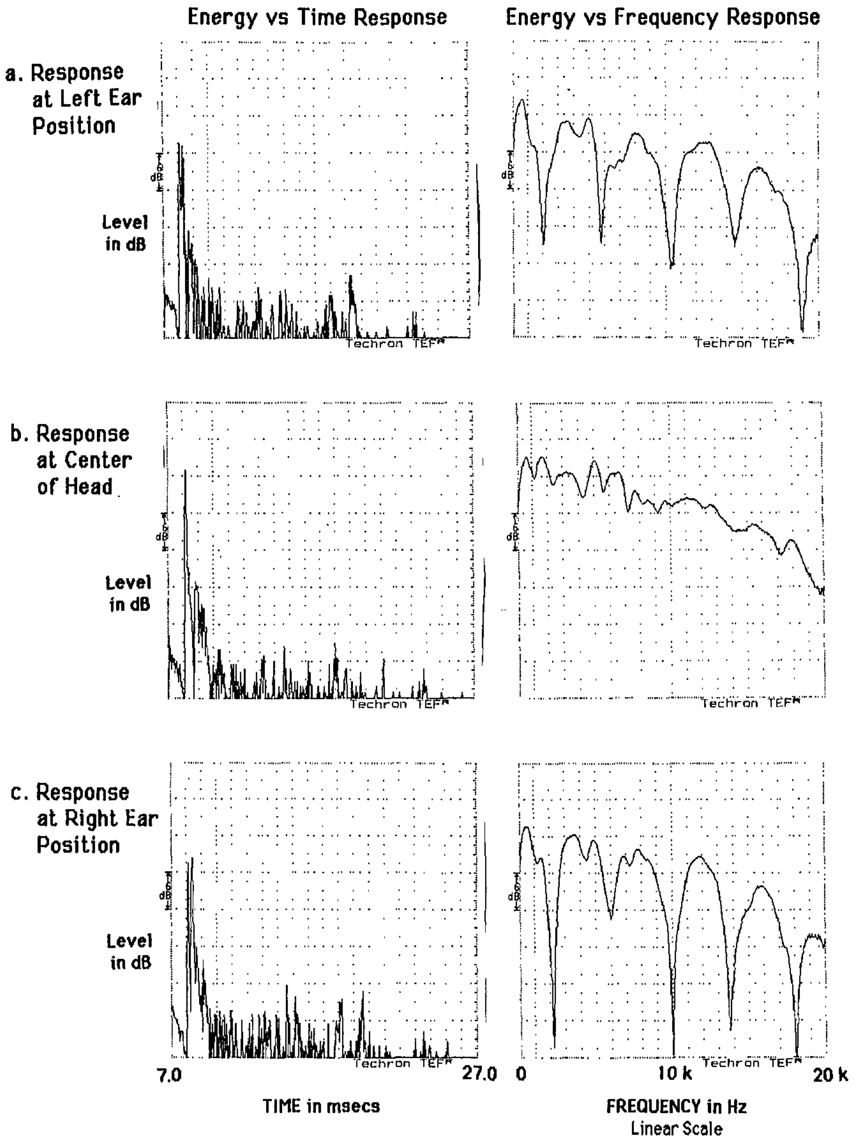


Fig. 35. The sound field at the mixer's position, behind the center of the console, of a recording studio control room. Three sets of time-frequency data were taken at three locations. (a) At the mixer's left ear position. (b) At the mixer's center-of-head location. (c) At the mixer's right ear position. The frequency response at the center head location is quite good (b), but note the response comb filtering at both ear positions (a), (b).

Crosstalk at Right Ear Position vs Listener Position Behind Console

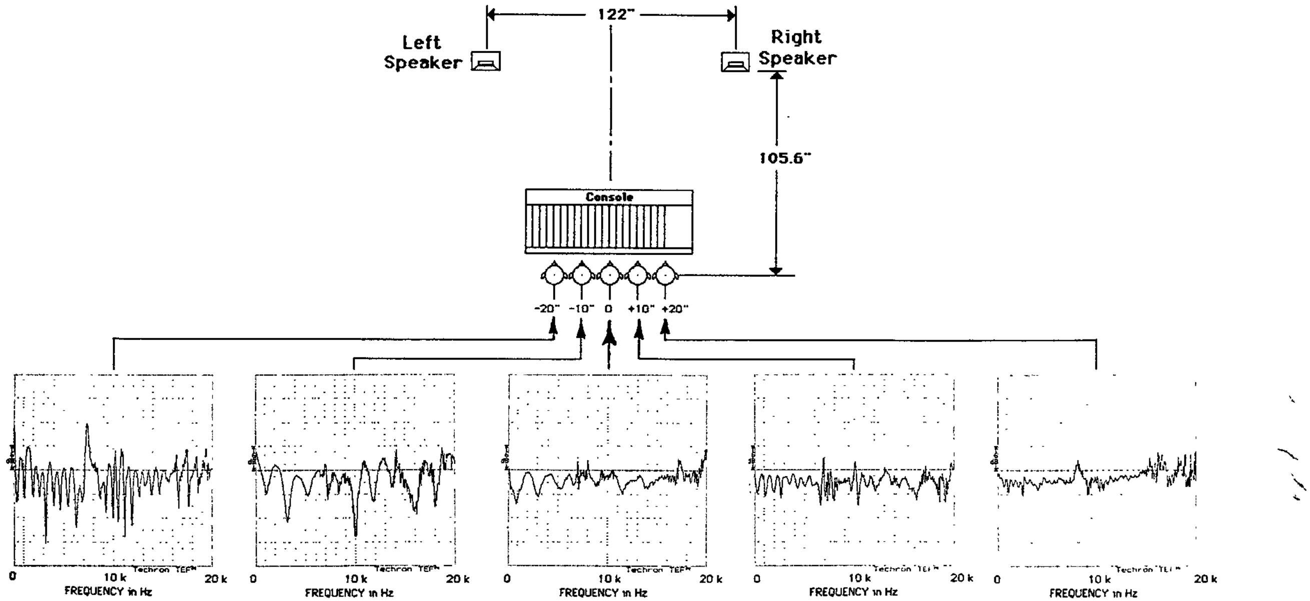


Fig. 36. Measurements of the effects of interaural crosstalk, on the frequency response, at the entrance of the right ear canal, for a live model. Five locations were measured at typical mixer positions behind the recording console. These locations correspond to head center locations of -20", -10", 0", +10", and +20" in reference to the center mixer position. The curves were generated by taking the difference in dB between the response with only the right speaker on (no crosstalk condition) and the response with both speakers on (response with crosstalk). The curves show that the effects of crosstalk, at the right ear, get worse as the listener moves to the left.

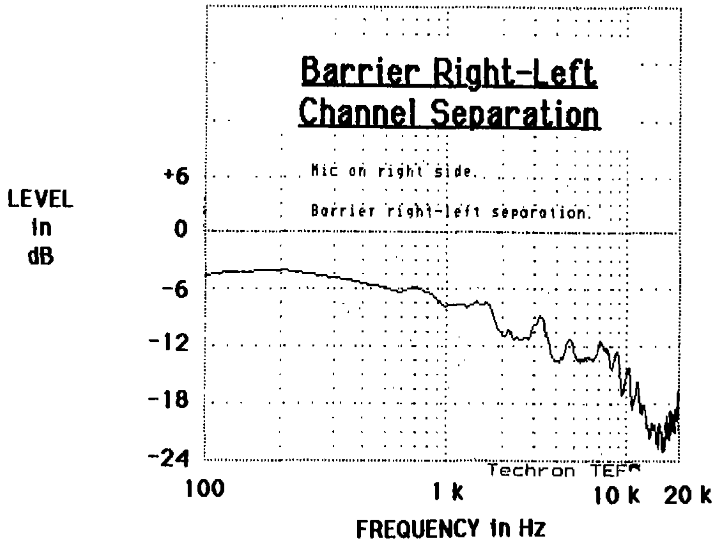


Fig. 37. Channel separation or rejection of interaural crosstalk afforded by the barrier setup of Fig. 29. The curve is the difference between a measurement on one side of the barrier as compared to the opposite side.

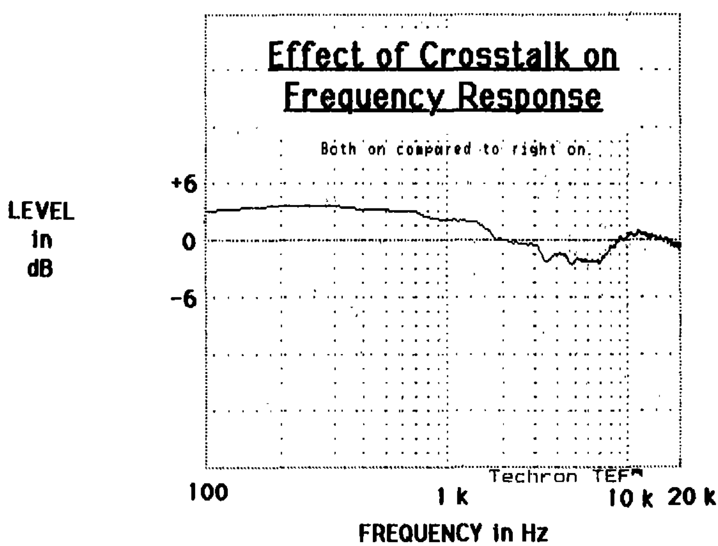


Fig. 38. Effect of interaural crosstalk on frequency response for the barrier setup of Fig. 29. The curve is the difference between one speaker on and both speakers on, for a mic on one side of the barrier.

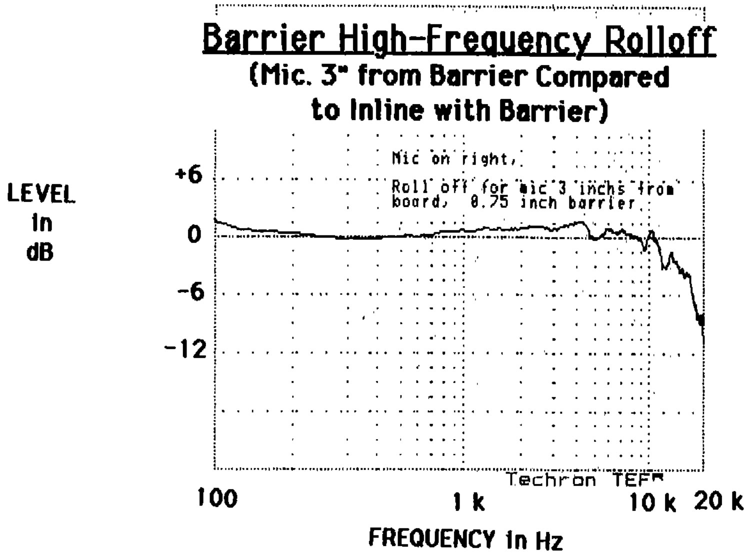


Fig. 39. Effect of barrier reflection on high frequency response for closely spaced speaker. Compares response for 3" lateral mic spacing to mic inline with barrier (0" lateral spacing).

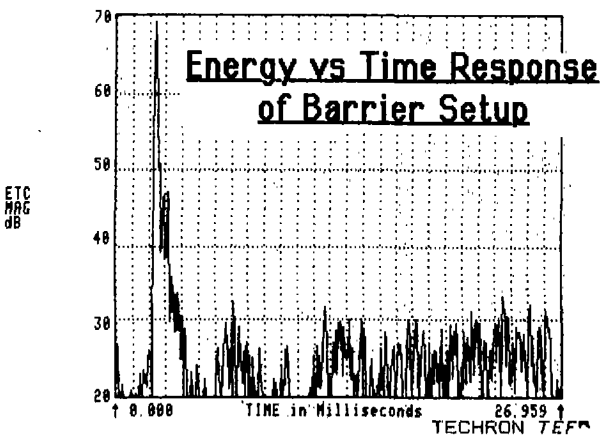


Fig. 40. Energy vs time response (ETC) of barrier setup shown in Fig. 29. Note that most room reflections are down more than 35 dB from the direct sound. The receive delay offset time was zero for this measurement. The delay for the direct signal was 2.38 msec.