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The Challenge to Find the Optimum Radiation Pattern and Placement of Stereo Loudspeakers in a Room for the Creation of Phantom Sources and Simultaneous Masking of Real Sources.

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ABSTRACT

Stereo sound reproduction relies upon the creation of an illusion. Ideally the two loudspeakers and the room disappear, leaving only a phantom acoustic scene to be listened to. The polar frequency response of a loudspeaker determines the angular distribution of room reflections and their spectral content. The placement of the loudspeakers relative to the room surfaces determines the initial delay of the reflections. Together they affect the formation of phantom sources. A proven loudspeaker and room configuration is proposed as starting point for listening tests to determine the optimum loudspeaker radiation pattern. It is an invitation to extend our understanding of the psycho-acoustic processes that are involved with stereo listening in a room and to replace anecdotal with scientific evidence.

1. INTRODUCTION

Stereo sound reproduction over two loudspeakers in a room has a long history that is filled with many studies about different types and sizes of loudspeakers, with optimum placement of loudspeakers and listener(s) in a room, and with room treatments that seem to be necessary to obtain a balanced frequency response [4, 7, 17, 19, 22, 23, 28, 31, 32, 33, 34, 37, 41, 46, 50]. Fundamentally these reports deal with finding the optimum loudspeaker-listener-room configuration for a given pair of loudspeakers when they are placed in a room that may not have been built just for listening, but more likely a room that is used for many purposes. Stereo relies on the creation of an auditory illusion, on the perception of phantom sources that appear to be located between and behind the two loudspeakers, when a listener is seated equidistant from each loudspeaker. Each loudspeaker's sound is reflected from adjacent room boundaries and objects. Whatever effect those reflections may have upon the phantom sources, it is reasonable to require that they should not unbalance the phantom source symmetry and their distribution between the loudspeakers. Thus left and right loudspeakers should be placed equidistant from the sidewalls. Furthermore it is known that any effects from room reflections can be reduced by attenuating them, by diffusing them, by delaying them or by combining those three mechanisms to varying degrees. Thus, a large room where the loudspeaker-listener triangle is far from all walls would seem ideal and indeed it can yield a phantom source presentation as if listening to very large headphones, except that the phantom sources are localized in front and out of the head rather than between the ears.

More commonly, rooms are not that large and to position loudspeakers away from walls can cause a number of difficulties. It therefore would be useful to know the minimum distance beyond which the perceived timbre and imaging of the loudspeakers is not affected by reflections. Most importantly, though, the popular assumption that room reflections are detrimental to phantom source creation should be questioned. There is strong anecdotal evidence, from many listeners, that the brain is quite capable of making the loudspeakers and the room disappear. But the associated perceptual mechanism is not completely understood. Also, the contribution of the loudspeaker's radiation pattern to the disappearance effect has not been fully investigated, though it determines the spatial distribution and the spectral content of the reflections. The timing of the reflections relative to the direct sound must be significant for the brain to be able to differentiate the streams of sound, two of which are coming from the loudspeakers and are responsible for the phantom source creation, and in addition to the multitude of reflected sound streams that characterize the listening room and the location of the loudspeakers in it. When this differentiation occurs spontaneously attention is solely placed upon the phantom sources and their changing stream of information. The consistent talk-back of the room apparently can be safely masked.

2. WHAT HAS BEEN OBSERVED

2.1. A single loudspeaker and reflections

The perceptual effects of reflections, when added to a single sound source in an anechoic space, have been studied extensively [5, 7, 27, 29]. The findings can be related to the case of a single loudspeaker in a room where the walls, floor and ceiling generate the reflections. Figure 1 shows a simplified model with only three walls, a loudspeaker and an observer. The observer receives both the direct signal from the loudspeaker and reflections from all walls. In reality all these signals continue to bounce between all six surfaces, arriving ever more delayed and attenuated from various directions at the observer's ears. The loudspeaker, in effect, sets up a reverberant soundfield that decays at a rate, which is determined by the lossy and dispersive properties of the reflecting surfaces and objects in the room. At low frequencies, below 200 Hz for typical domestic spaces, room resonances may be observed as the frequency spacing between modes increases, absorption decreases and the sound builds up. At higher frequencies, above 2 kHz typically, reflections are more easily absorbed and diffused leaving the initial reflection to dominate. The model in Figure 1 with its few sound rays is useable for describing the onset of reflections, the timing between direct and reflected sounds, their directions, and relative magnitudes. These are quantities that determine the perceptual effects of reflections.

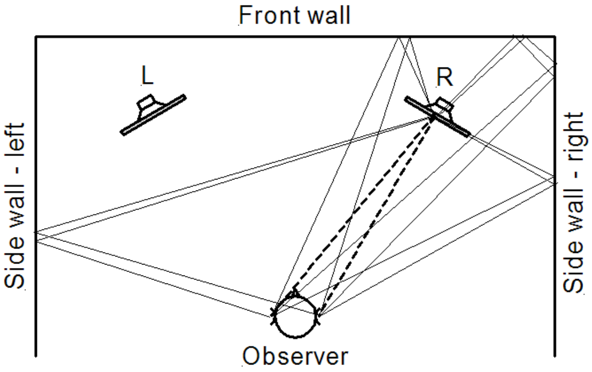

Figure 1: Direct sound and first wall reflections that arrive at the observer's ears from a single loudspeaker.

What is known scientifically about reflections that might relate to listening to a single loudspeaker in a room?

1. There exists a threshold level below which the presence of reflections is not detected [7, 42]. This rarely applies to domestic loudspeaker and room setups.

2. Reflections can cause a spreading of the source, a change in timbre and a change in loudness when above the threshold of detection [5, 27].

3. The level of a reflection has to be higher than the direct sound to cause a perceived shift in the direction of the source [5]. This might apply if the off-axis radiation from the loudspeaker has a high level lobe.

There are also a number of relevant observations from designing and evaluating loudspeakers.

4. Reflections within <1 ms, as from cabinet edges, are perceptually attributed to the loudspeaker's sound while reflections with >6 ms delay are not. Thus loudspeaker baffles should be very small and no larger than the driver diameter or very wide and with large radii to soften edge diffraction.

5. Loudspeakers with a flat on-axis frequency response and with wide and smooth dispersion are preferred over loudspeakers with inconsistent directivity [45].

6. Dipole loudspeakers are generally considered superior in openness and clarity of sound. Large panel radiators tend to be sensitive in their sound to room placement.

7. The floor reflection, which is mostly unavoidable, and which is readily seen in the steady-state on-axis frequency response as dips and peaks, is not necessarily audible on program material [40].

8. Equalization of the loudspeaker for a flat steady-state frequency response at the observer's listening position will change the timbre. It can effectively attenuate a few low frequency modes. It will change the observer's spatial perception of the source if done with DSP to cancel room reflections, as they arrive at the listener's ears.

9. The perceived direction, distance and timbre of the source do not change with small and even large head movements. The HRTF to each ear, though, changes significantly [41].

Points 2 to 7 relate to the off-axis frequency response of the loudspeaker, its polar response in horizontal and vertical direction. The maximum strength with which reflections from various angles can be generated at different frequencies depends completely upon the polar frequency response. It determines the beneficial or detrimental interaction of the loudspeaker with the room. Next to the on-axis frequency response it is the most important loudspeaker parameter. The radiation pattern of consumer loudspeakers is rarely shown nor discussed as to how it qualifies a particular loudspeaker for domestic use.

If room reflections are problematic, then would their absence be ideal? Listening to a single loudspeaker without reflections should be equivalent to listening binaurally over headphones. For headphone listening, though, the electrical signal from the loudspeaker must first be equalized by the HRTF of the azimuth and elevation angle under which the loudspeaker was seen by the observer. Doing so creates the perception of a sound source that is inside the observer's head for frontal angles, or that is too close when the represented loudspeaker is to the side or behind the head. The distortion in distance perception does not occur for the observer when listening to the loudspeaker in the room. There he uses head movement and the ensuing changes in the HRTF to localize and find the distance to the source. Room reflections diffuse the sharpness of the source but provide information about its surroundings. Distance localization problems with headphones are resolved when the HRTF changes with head movement in real time. In such case a source that has been localized outside the head and at a fixed point in space, remains at that location even after the head tracker has been turned off, as long as the head is not moved. It takes a few head movements before the source recedes smoothly back into the head. This is an example of how an observer accumulates information and learns about source location in space. The learning remains in effect until contradictory cues break it down. With insufficient and inconsistent cues to localize the source externally, it is placed between the ears, inside the head.

In the absence of visual cues the distance between loudspeaker and observer is derived from HRTF cues and probably also from reflections and the perception of room size. If the single loudspeaker reproduces a recording that contains realistic cues about the size of the recording venue and the staggering of sound sources in it, like the recording of an orchestra and choir in a cathedral, then there can also be the perception of distances greater than that to the loudspeaker or to the wall behind it. Depth is heard in the recording, but the horizontal and vertical size of the image is a drastic miniaturization of the venue.

2.2. Stereo loudspeakers and phantom sources

We will only consider symmetrical room-loudspeaker-observer setups as in Figure 2 for reasons that were given in the introduction. Again, the graphic shows an incomplete model for the multitude of reflections that occur in an enclosure with six surfaces. When identical electrical signals are applied to left and right loudspeakers, then the observer is put into a state of confusion. He is faced with an unnatural phenomenon. The symmetry of the loudspeaker-room-listener arrangement forces him to hear a single source halfway between L and R loudspeakers. It is a phantom source because sound is not coming from that direction. At what distance should the source be imagined? There is no HRTF from the phantom source to each ear of the observer to judge by. Instead there are HRTFs from L to both ears and from R to both ears. They interfere with each other. There are also room reflections. It appears that they are used in this situation to confirm a minimum, plausible distance between the phantom source and the observer, which is the distance to the loudspeakers. It has been observed that loudspeakers, which are highly directional at higher frequencies, could create a center phantom source in front of the plane between them. The loudspeakers had been set up in a large room, away from walls and with large amounts of absorptive material covering the walls. Thus it appears that room reflections provide distance to the phantom source. Identical left and right electrical signals when applied to headphones tend to cause inside-the-head localization.

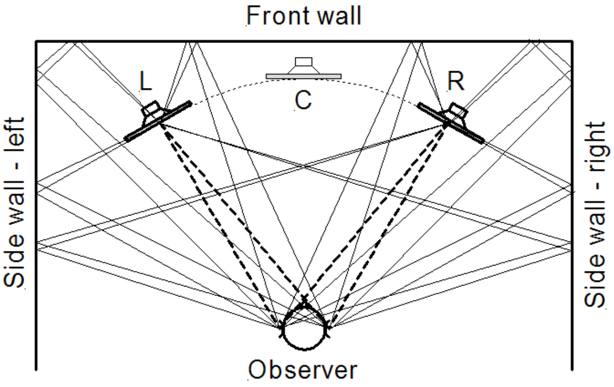

Figure 2: Direct sound and first wall reflections that arrive at the observer's ears from symmetrically left and right loudspeakers. A phantom source is perceived half-way between and at the approximate distance of the loudspeakers when identical electrical signals are applied to left and right loudspeakers.

If, for example, the phantom source between the loudspeakers is due to a mono recording of an orchestra and choir in a cathedral, as discussed for a single loudspeaker above, then the image may again extend to greater distance than the observer-to-loudspeaker distance or the distance to the front wall. The image will also have more width and height than when reproduced over a single loudspeaker. It will be centered between L and R loudspeakers and be blurry. Lateral movement of the observer shifts the whole phantom image to the closer loudspeaker.

Pink noise is often used to investigate the properties of the center phantom source. It is a test signal that must be highly confusing to the brain, particularly in an anechoic space. Its closest natural equivalent is probably the sound of breaking ocean waves. The phantom source is a construct of the brain. As such it involves memory and learning. When the center phantom source is compared to a real loudspeaker C in its place, Figure 2, then not surprisingly, differences are heard [7, Chapter 9]. For example the phantom source changes in timbre with small lateral head movements due to comb filtering between left and right loudspeakers. A real loudspeaker C will not produce this effect. With pink noise applied there is no confusion about the location and timbre of the physical source. But if the test signal is a stereo recording of a centered voice and instruments in a reverberant venue and played back over two loudspeakers in a room with reflections, then such timbre change with head movement is not noticeable. Now the brain receives enough information about the acoustic scene to create a realistic phantom scene.

A center loudspeaker is useful for movie sound and dialogue because the brain always wants to lock a sound to its physical origin. With L-C-R loudspeakers there are now three physical sources to lock to and the difficulty increases to place phantom sources linearly between L and R. Having an image greatly helps this process. While this arrangement works well for off-center viewing and listening, it is surprising how well a stereo down-mix for two loudspeakers pulls the sound to the image on screen, even when seated at extreme off-axis angles. It just takes a few minutes for the brain to compensate. This is also the reason why a center loudspeaker below the movie screen can be tolerated when the height of image and sound source above the floor are different and the floor reflection gives misleading cues. The brain compensates.

The phantom source in the stereo setup is easily panned to any location between left and right loudspeakers by level and/or time differences in the electrical signals for L and R. This produces a lateral shift but not a sense of distance and space. Those are often simulated by artificial reverberation or by convolution with the response from a real space. When reproduced over an accurate loudspeaker/room system such practices are easily recognized as artificial. The different instruments and voices in the sound mix do not appear in a spatial continuum in the overall phantom image. They appear as a collage of subspaces. This is in contrast to recordings where individual instruments and voices where picked up in unison and together with the response of the recording venue. Now the playback system creates a phantom auditory scene that is highly believable, even when it is only in front of the observer. The presentation takes on a sense of openness, transparency and space. It can be highly realistic, if the loudspeakers are capable of the necessary output volume levels to not miniaturize the acoustic event and put it at too far a distance. I have seen the surprise and delight when people recognize within 30 seconds what the 2-channel stereo format is capable of.

It is of course well known that crosstalk cancellation of the ear signals significantly improves phantom image accuracy [5, 53]. Ambiophonic is an extension of this [6]. Neither method of sound reproduction has the simplicity of the arrangement that should be investigated here. It would be of interest, though, to run a comparison test to quantify the merits and practicality of the different approaches at a later time.

3. REQUIREMENTS FOR LOUDSPEAKERS AND THEIR SETUP

The author has found much evidence that loudspeakers can be optimized for realistic phantom image presentation, including a 3-dimensional phantom space. Under optimized room setup conditions it is then possible for a listener to completely withdrawn attention from the physical presence of the loudspeakers and from the presence of the room. They simply “disappear”. This can open up a frontal sound stage of great realism if the recorded material contains the relevant cues for the brain.

It appears that loudspeakers must have a 360 degree polar response that is smooth and independent of frequency from 50 Hz to 5 kHz. Below 50 Hz the response is allowed to become omnidirectional. Above 5 kHz it may become increasingly directional. This is fortuitous because of practical loudspeaker driver limitations. Two loudspeaker types can most easily fulfill the radiation pattern requirements: an acoustically small, omnidirectional loudspeaker and an acoustically small, dipolar loudspeaker [19]. The dipolar radiator is preferred because it excites fewer room reflections.

The loudspeaker must be capable of near realistic volume levels and free of the kind of distortion that identifies the loudspeaker position as its origin, like buzz, clipping or bottoming. Intermodulation and zero-crossing distortion must be low to preserve clarity and prevent harshness of the phantom sources [20, 49].

The two loudspeakers should be placed symmetrically in the room and at least 1 m from front and side walls, such that the initial reflections are delayed by 6 ms or more. The floor reflections, which generally do not meet these criteria, appear to affect primarily the height of the phantom sound stage center above the floor. The tweeter, between 1.0 m and 1.1 m above the floor, should be slightly above ear height for a seated observer.

The room itself should have minimum dimensions of 4.5 m x 6 m x 2.4 m as in Figure 3. The required equilateral triangle that is formed by the two loudspeakers and the observer will then have 2.5 m sides.

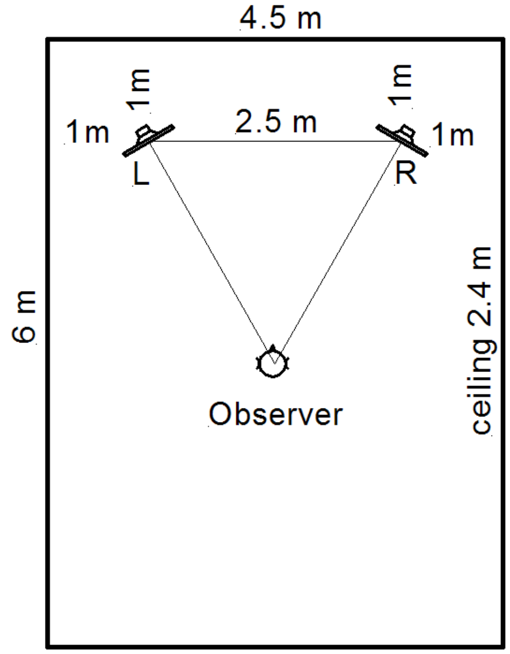

Figure 3: A symmetrical setup of loudspeakers and observer is required. The room has a minimum size for the proposed listening tests. The tweeter must be positioned at 1.0 m to 1.1 m above the floor.

4. THE CHALLENGE

The optimum radiation pattern and placement of stereo loudspeakers in a room has not been scientifically confirmed. There is agreement that symmetry of setup and distance from the walls improves phantom images. It is also widely accepted that a highly reverberant room destroys the precision of phantom images and a highly absorptive room feels unnatural for music reproduction. To limit the number of variables it is proposed to start with a setup as in Figure 4. The room should not be specially treated, but be filled with the normal stuff of live to diffuse and absorb sound for an RT60 equivalent initial reverberation time between 400 ms and 600 ms. It should be a room that feels comfortable for conversation, reading and play. This is obviously not a precise room specification, but the optimum radiation pattern for hiding loudspeakers, and room, and for accurate phantom source creation, should have some degree of independence from the room acoustics. Real living rooms in which people listen to music vary greatly. Even setup symmetry is often difficult to obtain.

It seems obvious and has been confirmed by experience that the sound from directional loudspeakers is less sensitive to the room. It has not been proven which radiation pattern is superior, but different ones have been proposed [5, 7, 10, 18, 36, 40, 43, 44, 47, 51, 52] . It is the contention here that an acoustically small dipole with a largely frequency independent radiation pattern in the horizontal plane is ideal [3]. Such loudspeaker is directional even at low frequencies and radiates to the rear even at high frequencies. The common box loudspeaker is omnidirectional at low frequencies and becomes increasingly forward radiating with increasing frequency. The dipole and box type radiators should be revealing test objects. They would be a good starting point for differentiating between the effects of radiation pattern and represent commonly used loudspeakers. An acoustically small omnidirectional source could be another type to test, but it has already been observed that it behaves very similar to a dipole in a reflective environment [10, 12].

The critical parameter in these tests is the quality of phantom images in the observers' brains. In particular, sharpness of images, front to rear separation, spatial coherence, and a sense of the venue's space are to be judged [13]. The sensitivity of these images to listening off-axis and at greater distance from the loudspeakers should be included.

The challenge is four-fold:

1. For the specified setup and for the two loudspeaker types characterize the differences in phantom image creation and loudspeaker/room masking.
2. Determine the sensitivity of the results to loudspeaker placement closer to, or further away from the walls.
3. Explain the results in psycho-acoustic terms.

4. Suggest improvements in the radiation pattern, implement them and verify their effectiveness.

The tests would have to be performed with large groups of listeners. The collected data would have to be evaluated statistically to resolve differences between previous studies and to give conclusive answers to questions about radiation pattern [2].

5. TEST RECORDINGS

Listening tests for phantom image accuracy require appropriate source material. Recordings for stereo are supposedly mastered for desirable phantom source distribution during loudspeaker playback. The quality of spatial presentation in commercial recordings, though, varies vastly. The left and right lumps of sound in early recordings have been replaced by a pan-potted spread, like laundry hanging from a clothesline between the loudspeakers. A sense of space has been added to the individual sources by artificial reverberation. This now tends to create a collage of subspaces between the loudspeakers with little overall depth. One must assume that the recording or mastering engineer's monitor loudspeakers and/or their setup were severely limited in their ability to create accurate phantom sources. Otherwise it is difficult to understand how such artificially sounding recordings could have been desired and produced. Far fewer recordings capture a realistic sense of space. They are mostly found amongst classical music and jazz, which are frequently recorded in their normal venues. The use of spot microphones often introduces artificial sounding spatial effects in these recordings. For example, the solo piano or violin becomes too large and close. Instrument groups slide to the center when it is their turn. Such distortions and temporal changes in spatial presentation are readily heard. In the listening tests they can serve as a measure for the accuracy of the loudspeaker/room system that is being studied.

It can and has been argued that it takes better recordings to improve the loudspeakers, but it also takes loudspeakers to know which recordings are better [7, Chapter 2]. The process can become a circle of confusion if there is no sonic reference outside of it. This reference must be the live performance, our perception and memory of it. Thus the listeners in the proposed tests should have familiarity with unamplified sound, with live acoustic music. Also the human voice in different environments, single or in groups, is familiar to everyone and recordings of it should be part of the listening tests. It must be avoided that the tests become a preference test between two loudspeaker systems where the reference is unclear [16]. It will be assumed that the more accurate loudspeaker/room system is that one, which reveals more of the spatial flaws and the spatial coherence of the phantom sources, and not merely the sharpness of their lateral position. It is the system that sounds more natural in perspective and less synthesized. Therefore the aim is not to find pleasant sounding recordings, but to tell with certainty what is in the recording, what is believable and what sounds artificial [13, 26, 38, 48].

Rarely the microphone technique that is used for a commercial recording is described in the accompanying leaflet, but recognizable and somewhat consistent styles of presentation can be traced to certain recording engineers or CD labels. This can help to find or avoid recordings when looking for source material that is rich in spatial information [54].

It may become necessary to generate specific recordings for the tests. One of the simplest microphone techniques should be used, such as a pair of near-coincident microphones for spatial resolution and augmented with a pair of widely spaced omnidirectional microphones [1]. The distance of the microphones from the source should be sufficiently large for recording an audience perspective that listeners in the test are familiar with. Proper attention must be paid to the stereo recording angle to spread the phantom sources between the loudspeakers, Figure 4, [21]. Near-coincident super-cardioid microphones may be needed to obtain sufficiently narrow stereo recording angles. The aim should be a recording that duplicates in playback what had been heard by the recording engineer at the location of the front microphone pair.

It may be possible to refine the recording technique by listening to playback over the more revealing loudspeakers. This could be a follow-on investigation and is not the aim of the proposed investigation into loudspeaker radiation pattern, room interaction and phantom source creation. The overall goal of these investigations is to find the optimum record-playback system solution, from live sound to phantom source and in particular the preservation of spatial information. It will add to our understanding of spatial and localization perception in reverberant spaces [7, 8, 9, 11, 14, 15, 22, 24, 25, 27, 28, 30, 35, 39]. A system solution would add insight and could benefit current recording and loudspeaker design practices. It might lead to more satisfactory products.

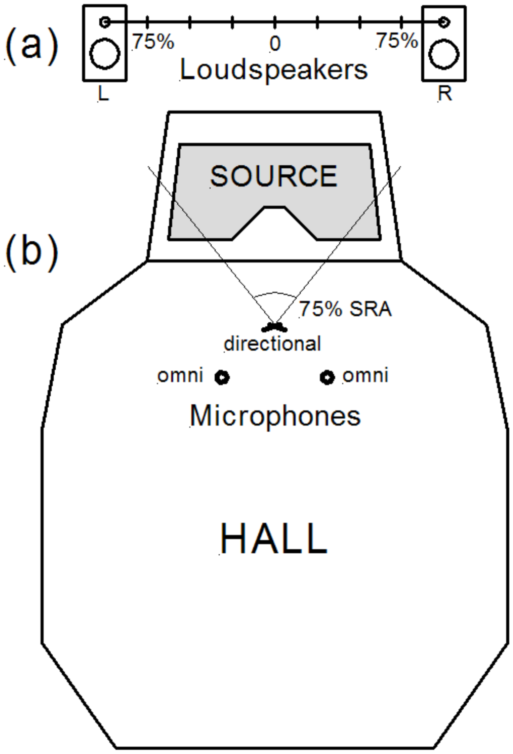

Figure 4: The reproduced stereo image appears at, between and behind the two loudspeakers in the listening room (a). In the recording venue a directional microphone pair maps signals inside the stereo recording angle as phantom sources to the space between the loudspeakers (b). Microphone signals from outside the SRA, from source and hall, are reproduced as mono signals in either left or right loudspeaker. Widely spaced and more distant omnidirectional microphones can provide decorrelated signals with a large proportion of reverberant hall sound to each loudspeaker.

6. SUMMARY

A set of listening tests has been proposed that will answer questions about the optimum radiation pattern of two loudspeakers for the creation of realistic phantom images in a symmetric room setup. The tests require the use of two specified sources as starting point, a uniformly directional dipole and a conventional box loudspeaker with frequency varying directivity. The spatial qualities of phantom sources and the masking of loudspeakers and room are to be judged. For reliability of data it is important to have a sufficiently large number of listeners and that the results are evaluated statistically. It is hoped that this work will be carried out in the open spirit of scientific investigation, free of commercial interests. The results might become an incentive to change current audio industry practices in order to satisfy discerning listeners and bring greater enjoyment to everyone.

7. ACKNOWLEDGEMENTS

Two discussions sparked the idea of this paper. The first was with John Vanderkooy at the AES 126th Convention about what might explain our ability to ignore loudspeakers and room in favor of phantom sources. A year ago he had heard the comparison between a dipole and a monopole loudspeaker in my living room. The sonic similarity between the two types of loudspeakers made it difficult to distinguish them [10]. How could that be? My hypothesis needed substantiation. The second discussion was with Wolfgang Klippel a few days later in Dresden. I had already decided to write a paper in which I intended to raise questions about perceptual issues that needed further investigation. He cautioned me that it is easy to raise questions but difficult to motivate others to search for answers. He suggested putting up a monetary prize, enough to attract the interest of doctoral candidates. Well, that is not within my means at this time in life. So instead, I post this challenge to work just for the advancement of science and for the recognition it can bring to the investigators who finally answer the remaining questions about optimum stereo loudspeakers, placements and rooms.

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