Why Things Don't Work: What You Need To Know About Spatial Audio

Kendall, G., & Cabrera, A. (2011). *Why Things Don't Work: What You Need To Know About Spatial Audio*. 37-40. Paper presented at International Computer Music Conference, Huddersfield, United Kingdom.

WHY THINGS DON'T WORK: WHAT YOU NEED TO KNOW ABOUT SPATIAL AUDIO

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ABSTRACT

Composers engaged in the sonic arts have frequently found themselves attempting to use spatial audio in ways that didn't work as intended. Maybe more than any other facet of technological music, mastering spatial audio seems to involve a learning process in which one slowly discovers the things that work and those that don't. The purpose of this paper is to foster understanding of spatial audio through examples of practical problems. These problems reveal some general misconceptions about spatial hearing that explain why things go wrong. A particular lesson to be gleaned from this discussion is that there is no silver bullet for solving spatial audio problems, and every situation needs to be understood in its proper context.

1. INTRODUCTION

Composers engaged in the sonic arts have frequently found themselves attempting to use spatial audio in ways that didn't work as intended. Maybe more than any other facet of technological music, mastering spatial audio seems to involve a learning process in which one slowly discovers the things that work and those that don't. That this learning process is so tentative and empirical reflects the lack of a conceptual foundation that could guide the artist when conceiving spatial ideas and when translating these ideas into practice. It is also easy to be misled by preconceptions about how spatial audio should work. The purpose of this paper is to foster understanding of spatial audio through examples of practical problems.

The early pioneers of electroacoustic music pushed the frontiers of spatial audio and achieved monumental successes in the artistic use of space. Varese, Stockhausen, Schaeffer and Poullin, Bayle with the Acousmonium, Chowning and onwards---spatial audio has been an expanding area of artistic expression. On the other hand, the great advantages in computer and audio technology that we enjoy today have not necessarily led to great advances in spatial audio. Quite possibly, pushing back the frontiers of spatial audio practice depends more on understanding spatial perception and cognition than on raw computing power.

2. GENERAL MISCONCEPTIONS

In everyday life, every person is able to navigate the spatial world, to think about space and even to imagine unknown spaces; spatial thinking is one of our most deeply embedded cognitive capacities. The ease with which we think about space is possibly a miscue to how easily spatial ideas can be translated into spatial audio, which has its own intrinsic nature and inherent limitations. Sonic artists need to be alert to the nuances and idiosyncratic relationship of spatial hearing to spatial thinking. Not every spatial idea can be reverse engineered into sound.

Clearly, our expectations about spatial audio should be in alignment with the fundamental capacities of the auditory system. For example, consider how auditory spatial acuity varies with the direction of the sound source. In front of the listener, horizontal *localization blur* is ±3.6º, and to the sides it is ±9-10º. Above the head and slightly to the rear, vertical localization blur is ±22º [3]. Apparently, what listeners perceive is not well described as a point source. More appropriately listeners' perceptions can be described in terms of a small set of auditory spatial attributes. Following work by Rumsey [16], Kendall [11] offered the image in Figure 1 as an illustration of these attributes.

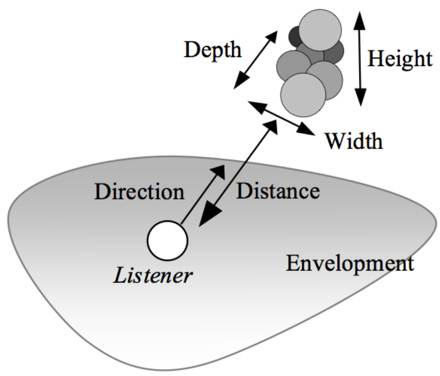

Figure 1. Auditory spatial attributes (from [11]).

Important for spatial audio is the primary role of envelopment as a spatial attribute. Envelopment has been the focus much research in spatial audio [5, 20]. One of those idiosyncratic aspects of spatial audio is that there is no clear separation between auditory width and envelopment; one can blend into the other.

3. WHAT WENT WRONG?

The way that most composers and audio engineers discover their misconceptions about spatial audio is through direct encounters with things that don't work.

3.1. Why doesn't the sound image get broader when I distribute a signal to three of more adjacent loudspeakers?

Everybody learns about the precedence effect, but the practical consequences of it often take time to absorb. The precedence effect is a psychoacoustic phenomenon in which the auditory system gives precedence to the first arriving sound [2, 7, 19]. It is usually described as an aid to spatial perception in reverberant spaces, where the direct sound from a sound source reaches the listener before the reflected sound. The listener's spatial image is dominated by the first-arriving/direct sound, and the perception of the early reflected sound is suppressed.

The precedence effect works the same with multiple loudspeakers: the listener's spatial image is determined by the first-arriving sound and the later arriving sound from the loudspeakers is largely suppressed. When a source signal is distributed among multiple loudspeakers, a listener will hear the source as emanating from the closest loudspeaker. (See [13] for an excellent review of the precedence effect.) The primary way to overcome this limitation is to trick the auditory system into believing that the delayed sounds are not reflections. This can be done by decorrelating the signals sent to each loudspeaker [9, 10].

3.2 Why does my dynamic panning work sometimes and not others?

When a listener is equidistant from all loudspeakers, in the location called the *sweet spot*, there is no one loudspeaker from which sound arrives first, and therefore, precedence does not affect spatial imagery. When listeners are closer to one loudspeaker than another, all spatial panning is affected by the precedence effect, no matter whether it is amplitude panning, power panning, Ambisonics or VBAP. In multichannel-reproduction settings, this involves everybody except the one person in the sweet spot.

Because of the precedence effect, listeners will experience a discontinuity instead of a smooth panning when the amplitude in the closest loudspeakers is enough to trigger the precedence effect. The degree of the discontinuity depends on the exact distances of the loudspeakers from the listener because these distances determine the time delay of the sounds reaching the listener. The degree to which a continuous spatial path is perceived is also dependent on the transient content of the sound material. Sound sources with rapid re-attacks and high-frequency content are generally the most successful. Then too, plausibility and comprehensibility affect whether the listener understands the changing sound as spatial motion along a path.

3.3. Why did the spatialization in my piece sound so different in a large space than it did in the studio?

Although differences in room acoustics (reverberation and coloration) can cause some differences, most major changes in perceived spatialization are due again to the precedence effect. An important property of precedence is that it ceases to affect perception when the arrival time difference (ATD) between signals exceeds a critical threshold. Depending on the nature of the sound material, that ATD may vary anywhere from 5 to 50 msec [13]. When one monitors inside of a small studio, the differences in the distances of the loudspeakers generally creates ATDs of less than 5 msec. In a large space, the ATDs can easily range up to 12 msec or more. The change in ATDs affects which sounds are affected by precedence. This is true even when the relative angles of the loudspeakers are exactly the same in both the small and large space. Then too, in a large space the ATDs are different for nearly every listener. An important factor to bear in mind is that it is easier to be located in the sweet spot in a smaller environment than a large one.

3.4. Why doesn't my circular panning work?

Composers working with multiple loudspeakers frequently aspire to move sound sources around the listener by use of multichannel circular panning. Nearly every composer has acquired their understanding of panning from working in stereo with one loudspeaker to their left and another to their right. With this kind of stereo, one experiences a *phantom image* that can be positioned between the two loudspeakers. (This is approximately the same whether the loudspeakers are in front or in back of the listener.) However, that experience does not transfer to situations in which there are two loudspeakers to one side of the head. It is not that sounds cannot be positioned on the side, but rather that there is seldom a coherent phantom image: the image is spread in what Kendall [11] describes as *image dispersion*. This dispersion blurs the location of the sound image in a way that depends on the transient and spectral characteristics of the source. This becomes particularly evident with broadband sources when different parts of the source material are biased toward the front or the rear. For this reason Tom Holman [8] recommends against panning between the front side and surround loudspeakers in 5.1 systems. This effect is also difficult to predict and will depend on the source material and the precise location of the listener.

It is easy to understand how image dispersion makes it difficult to create an effective impression of circular motion around the listener with arbitrary sound sources. As mentioned before, some source characteristics are more favourable to perceived motion than others (narrow-band, high-frequency, transients). Cognitive factors also help if the listener is able to apprehend an apparent path to the motion. On the other hand, it should also be mentioned that image dispersion has long been used in live diffusion to create a broad spatial effect. When a signal is placed in both the front and rear loudspeakers, image dispersion creates the impression of sound enveloping the audience [1].

3.5. Why don't the recordings I make with binaural mics sound the same as what I hear there?

The stereo signals recorded with most portable or clip-on binaural mics capture the most important acoustic information for directional hearing: the *interaural differences* in intensity and time caused by the separation of the ears. Because these mics also capture the acoustics of the head, the interarual differences will be frequency dependent. For example, the head affects interaural intensity differences because it is a more effective block for high frequencies than for low frequencies. The head affects interaural time differences too, but in a way that is too complex to describe here.

When you listen on headphones to binaural recordings, you get a pretty good idea of how these acoustic factors affect spatial perception. You will probably hear sound images to the far sides, behind you and maybe above you, but not very often in front of you. That is the main problem with binaural recordings: something about the experience is quite different from being there. That difference is largely caused by the lack of coordination between body movement and acoustic changes at the ears. When the head moves, the sound at the ears should change in an appropriate way. Without the ear acoustics being coordinated with head movement, it is difficult to perceive sound sources directly in front of you. What typically happens is a kind of localization error in which frontal sounds are heard to the rear; this is called *front-back reversal*. It is also possible that sound images are stuck inside the head and there is a lack of *externalization*.

If you do the recording with a dummy head, or with special mics inserted into the ear canals, your recordings will capture all of the acoustic information that people use in everyday life, the composite of which is called a *head-related transfer function* (HRTF). HRTFs include the acoustic effect of the outer ears or pinnae, which have a major role in perceiving elevation and assist in separating front from back. You can download laboratory recordings of HRTFs and use them to create binaural sound through convolution [12]. If you combine dynamic HRTF convolution with dynamic tracking of head position, frontal imagery is hugely improved. In fact, if you want to create a real 3D sense of being there, render multiple sources in a virtual environment with HRTF convolution and head-tracking as is done with real-time simulators.

3.6. What goes wrong with the 3D effect when I play my binaural recordings over loudspeakers?

Binaural recordings or 3D renderings have in them the HRTF information that encodes the direction of sound sources, but there is a big difference between listening with headphones and listening with stereo loudspeakers. For example, when the signal for the left ear is reproduced by the left loudspeaker, two things go wrong. First, the signal arrives at the listener's left ear with the HRTF for the left loudspeaker location superimposed on the signal, effectively piling two HRTFs on top of each other and creating conflicting or inadequate cues! Second, the signal also crosses over to the right ear with the HRTF for the left loudspeaker position superimposed on it and is then added to the signal reaching the right ear from the right loudspeaker. This is the more catastrophic problem, the *crossover* of signals between the left and right sides.

It is not an easy problem to solve, but an excellent system for crosstalk cancellation was devised by Schroeder [17] back in 1963 and numerous modifications have been implemented since [6]. Without attempting some form of correction for crosstalk, the best you can hope for is that the sense of elevation in the original material comes through.

3.7. Why do some phantom images seem higher than the loudspeakers?

Whenever listening to stereo loudspeakers, there are HRTFs for the loudspeaker directions and there is crosstalk. It doesn't matter whether you use amplitude panning, power panning or whatever: the effect of HRTFs and crosstalk is there. One result is that the elevation of the image is dependent on the source material. Spatial hearing cues for elevation are affected by the distribution of energy across frequency. High, bright sounds tend to localize higher than low, dark ones. This has been particularly well studied with filtered signals [4, 14, 15, 18]. That virtual images vary in their perceived elevation has long been known by recording engineers.

We should mention though that hearing virtual images of this sort depends on the acoustics of the reproduction environment. Spatial imagery can change dramatically especially depending on the presence of reflecting surfaces near the loudspeakers. Reflecting surfaces create additional signals reaching the ears and further ambiguating localization cues. A reproduction system can be very badly affected by environmental asymmetries in such reflections.

3.8. Why do I still hear a single image when I put the harmonics of a sound in different loudspeakers?

This is an issue that comes up often with frequency domain processing where it is easy to break a sound source up into multiple frequency bands. Distributing those bands to multiple loudspeakers or dynamically panning the bands in independent trajectories usually does not create the intended effect. Imagine a situation in which a short performance on the cello is broken up into multiple frequency bands that are distributed among multiple loudspeakers. This is an example of a situation in which different categories of auditory cues are put into conflict with one another. There is one set of cues that leads the auditory system to form a single, fused sound image of the cello and other cues that suggest multiple images in multiple locations. The fusion of the image wins and the listener most probably perceives the sound event as emanating from an indistinct, but nonetheless singular, location.

In order to create a listening experience more akin to the intended effect, the fusion of the cello tone has to be broken down. This can be accomplished by de-synchronizing the partials, or by adding contradictory vibrato patterns on the individual components. For the auditory system to recognize events in multiple locations, it first must recognize multiple events.

4. GETTING THINGS RIGHT

From the above discussion, we can recognize a few key concepts would help most composers to get their spatial audio right:

1. Precedence effect (Questions 3.1); its dependency on arrival-time difference (Question 3.3); its dependency on source characteristics (Question 3.2).
2. Asymmetry of multi-loudspeaker localization and panning (Question 3.4).
3. Directional Hearing and HRTFs: role of head movement (Question 3.5); understanding the role of HRTFs (Question 3.6 and 3.7)
4. Interrelationship of spatial hearing with auditory fusion and stream segregation (Question 3.8).

5. CONCLUSION

Experience is the master teacher and one hopes that its lessons lead us to an understanding of how we can avoid problems in the future. The questions we have sought to answer here reveal some general misconceptions about spatial hearing and hopefully lead to a better understanding of issues underlying spatial audio. A particular lesson to be learned from the above discussion is that there is no silver bullet for solving spatial audio problems. No single spatialization method or system (Ambisonics, VBAP, etc.) is in itself a solution, especially for the sonic artist who wants to employ the full range of spatial audio effects. And, every situation needs to be understood in its proper context. It is our hope that the most artistically exciting uses of spatial audio are yet to come!

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