Defining an Audio Production Pipeline for Mixed Reality

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Abstract

While established mediums such as film have clearly defined conventions for production, interactive simulation requires a whole new approach for the production process that addresses the specific needs and requirements of non-linear, immersive experiences. This paper describes an audio production pipeline for what is possibly the most complex and demanding of interactive simulations, Mixed Reality (MR). MR simulations can cover the full spectrum of experience from real, to augmented, to virtual. This unique challenge requires a new perspective on methods of capturing, synthesizing, mixing and mastering, designing and integrating, and delivering soundscapes. The approach described here has been developed with the Media Convergence Laboratory's (MCL) MR Testbed and during the creation of over 9 separate MR experiences including three phases of the military training scenario, Mixed Reality Military Operations in Urban Terrain (MR MOUT), demonstrations at SIGGRAPH, IITSEC, and IAAPA, and an installation at the Orlando Science Center. An overview is provided of production tools and techniques used for designing sounds for MR and interactive experiences in general. Intentionally omitted from discussion here is the topic of pre-production and planning which is a subject for another paper in and of itself.

1 Introduction

In the film industry there is an expression that "the audio is half the experience." This expression is validated by the careful attention given to sound and music in film. However, audio production in the simulation community is often given little attention, if any at all. While simulation companies or research institutes may own expensive audio equipment (such as tracked 3D headphones, etc.) they often may not allocate resources towards production techniques or sound designers, depending instead upon non-audio specialist to insert generic sound effects from purchased libraries. The end result of this process is a shallow, unrealistic, non-immersive auditory environment.

The irony in this arrangement is that audio is at least half of the human experience. Auditory cues are perceived in 360 degrees and on all three axes. Sound can travel through walls and around corners providing information that is well out of the line-of-sight. Additionally, audio plays a crucial role in environmental recognition, immersion, and presence, and is essential in most forms of communication.

A natural and appropriate first step in defining an audio production pipeline for interactive simulation is to examine existing models and extract useful knowledge and techniques. It is very common to look to the gaming industry since it has the most established production process in the world of interactive simulation. However, games are designed primarily for consoles or PCs with a stationary user and a single, frontal perspective. This is really more akin to the film experience whereby a captive audience stares straight ahead at a screen. While games do provide dynamic content and multi-linear narratives, it is still mostly a passive medium. Multi-modal immersive simulation, on the other hand, often demands active participation from users. Events may occur in all directions and the user is often required to navigate physically through their environment. In this kind of environment, audio production and 3D sound techniques become essential. Adequate methods of capturing, synthesizing, mixing and mastering, designing and integrating, and delivering soundscapes are crucial to creating immersive and compelling experiences. The following three sections overview these areas of production and the lessons learned from creating MR simulations, while the last two sections discuss the concept of "artistic research" and other related topics of interest.

2 Capture

After pre-production, the first phase of the audio pipeline is capture. This is the process of recording, using either analog or digital devices, and converting this data to a format that can be used within a digital audio workstation (DAW). There are a variety of ways to capture audio: stereo and surround configurations, mono and omni-directional, underwater and transducer techniques, to name a few. To create a richly layered atmosphere, it is often necessary to employ many of these different technologies and philosophies. MR experiences can be some of the most challenging simulations for sound design and control. The following subsections describe the tools and techniques that have been used in designing these simulations.

2.1 Microphones

2.1.1 Hydrophones

Hydrophones are hermetically sealed transducers designed specifically for underwater or damp capture. When recording the audio for MR SeaCreatures (an interactive learning game for the Orlando Science Center) it was important to create both a realistic and immersive ambient track. To achieve this objective, a hydrophone array was used to capture the ebb and flow of the turbulent shore break at Cocoa Beach (see *Figure 1*). The end result was a highly detailed and textured soundtrack which post-experience interviews showed to be effective in creating a sense of place within the underwater experience.

Figure 1: Surround Hydrophone Capture

2.1.2 Surround Mics

There are many different approaches to surround miking. These techniques and tools vary from all-in-one devices that offer to capture 'accurate' sound fields, such as the Holophone (http://www.holophone.com) and the SoundField (http://www.soundfield.com) system, to inventive techniques that aim to capture a perspective to which human ears would not normally have access. The Holophone is an eight-channel microphone that captures audio in 360 degrees and on the vertical plane (see *Figure 2*). This capture device can record a fairly accurate spatial impression and has the advantage of portability and ease of use. The Holophone is especially useful in capturing general ambience for military simulations where an accurate sound field is required. For entertainment or artistic applications, more experimental techniques can be used. One such technique is that of 'spatial scaling' whereby individual microphones can be placed over extended distances. The effect created by this technique is unlike anything that human ears are accustomed to hearing. Where a car passing by may take only a few seconds, this capture technique stretches the spatial image out over a longer span of time, avoiding changes in pitch or additional audio artifacts. Likewise the reverse can be done with miniature microphones embedded in places such as ant mounds. These experimental techniques may very well create perceptual changes that can be used to alter the emotional experience of a simulation.

Figure 2: Holophone 7.1 microphone

2.1.3 Binaural Mics

Binaural microphones are typically worn as earbuds or placed in a dummy head to capture the natural reflections of the ears and skull. Capture from binaural microphones can be de used in conjunction with either headphones or loudspeakers. When binaural capture is delivered through headphones, they are capable of reproducing a fairly accurate representation of a first person auditory experience. However, for MR simulations where real world sounds are important, loudspeakers are a more appropriate delivery system. The most interesting aspect of binaural capture is that the source motion is captured. In other words, if the individual wearing the binaural microphones is walking or traveling through an environment, that motion can be effortlessly translated to a surround delivery experience. Binaural microphones become much less useful when a first person perspective is not desired.

2.1.4 Transducers and Original Creations

Transducers are a particularly useful tool for capturing the direct vibrations of an object. This is useful when either the desired source does not transmit a sufficient signal for standard microphone capture or when the sound designer is interested in only capturing the direct vibration of a source and not the sound it creates in air. Very dramatic effects can be created when transducer capture is delivered through a subwoofer or “bass shaker” beneath a user in an interactive experience.

Original and non-conventional capture devices can fulfill more specific needs especially when a designed experience calls for sounds that are either difficult to capture or when unrealistic spatial impressions are desired for dramatic effect. One such example is the miniature homemade surround microphone pictured in *Figure 3*. This device simply consists of two very small stereo microphones attached back-to-back with rubber bands, yet it is capable of capturing a four channel surround image in locations that ears, or other surround mics, could never fit. Capture from this device can create very dramatic effects whereby subtle sounds can be scaled up to large delivery systems. An application used at MCL involved capturing the sounds of an ant mound and then delivering this capture through a large, amplified 7.1 surround system.

2.2 Location and Mobile Recording

A crucial capability of the capture process is mobile recording and storage. For immersive, multi-modal simulations it is necessary to perform capture in many different environments. Mini-disc is the most lightweight of these options but has the downside of low quality analog-to-digital conversion and cheap pre-amplification. However, there are applications where Mini-disc is sufficient and the fact that it can fit in a pocket makes it a useful tool. Alternatives to Mini-disc are flash drive or hard-disk recording devices. These tend to be slightly heavier and bulkier than Mini-disc but they have higher quality conversion, better pre-amplification, and professional (XLR) input jacks. Mini-disc, flash drive, and hard-disk recording devices are all battery operated and require no additional hardware (other than a microphone) to perform in the field. A more encumbered option is a laptop/firewire recording device combo with the addition of an external battery power unit. Many firewire recording devices have 8 or more analog inputs and tend to be higher quality in performance than typical mobile recording devices. Each of the options listed above have distinct advantages and disadvantages. Where mobility is of the utmost importance, Mini-disc, and flash drive devices are the best option. Where high resolution recording with many inputs is the most important quality, firewire recording devices will typically be the right solution.

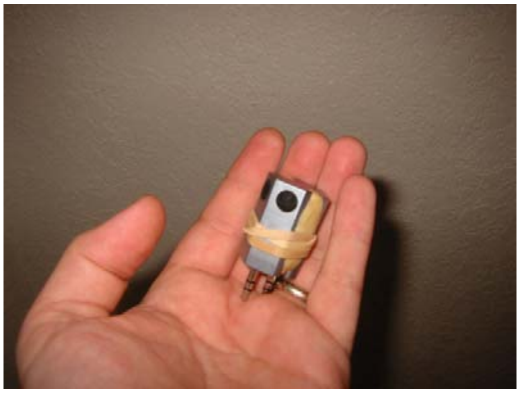

Figure 3: Miniature homemade surround microphone

3 Synthesizing, Mixing, and Mastering

The process of synthesizing, mixing, and mastering is when all the assets are gathered together and mixed, when appropriate, with effects libraries and synthesized sounds. This stage most closely resembles that of standard audio production in that industry standard tools are typically used such as DAWs like Sonar, ProTools, Cubase, etc. *Figure 4* is a screen shot of a surround mix using Sonar 4 Producer Edition. In this example there are two sounds, the top sound is a helicopter taken from Lucas Sound Effects Libraries, while the bottom sound is a mono capture of wind. This kind of production is most important for the creation of prescripted effects that have a predetermined spatial image (as opposed to real-time spatialized sounds during an interactive scenario).

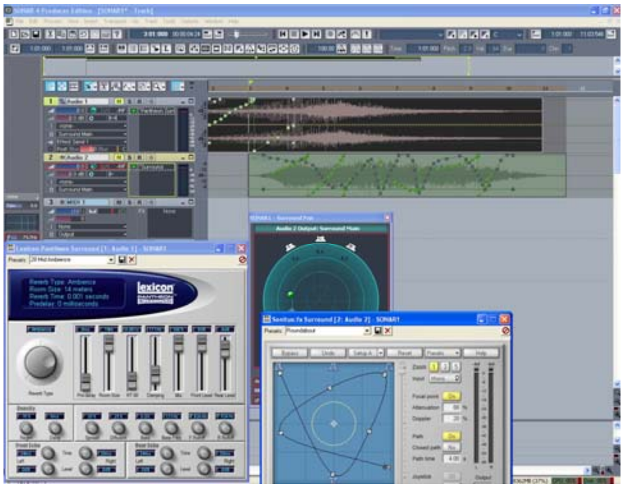

Figure 4: Surround mixing in Sonar 4 Producer Edition

3.1 Creating Layered Ambience

This stage of production is also crucial in the rendering of ambient environments. In the MR MOUT scenario, live surround capture was taken from a courtyard that roughly resembled the physical set of the actual MOUT structure (see *Figure 5*). This capture was then mixed with various 'virtual' sounds such as flies buzzing and distant bombs exploding to match the environment of the scenario. Taken together the finished surround ambience has the appropriate acoustical signature of a MOUT setting and at the same time provides a certain 'legitimacy' to the virtual sounds embedded in the sound track.

Figure 5: Back-to-back stereo

3.2 Surround Mastering

The final process in this stage is mastering. This is a rather standard process whereby all the sounds are leveled appropriately and dynamics are compressed (where necessary to achieve the desired effect). The finished audio files are rendered out in a variety of single or multi-channel PCM .wav files for integration into the MR SoundEngine and high-level interface SoundDesigner.

4 Sound Design and Integration

The desire to create an easily configurable, powerful audio engine and high level interface came about over the course of designing audio for interactive experiences during the last several years. These experiences include exhibits at SIGGRAPH 2003 (*Figure 6*), ISMAR 2003/2004, IITSEC 2002/2003, IAAPA 2002/2003 and the Orlando Science Center, as well as long-term installations at the US Army's Simulation Technology Training Center (STTC, Orlando). Standard media production tools such as Sonar, ProTools, Cubase, etc., while very useful for synthesizing, mixing, and mastering, cannot provide the kind of dynamic control necessary for interactive simulation. In addition to lacking any support for real-time spatialization, they do not have features to compensate for suboptimal speaker placement or expanded multi-tiered surround systems. Both the previously mentioned features are essential since many interactive experiences must occur in environments where optimal speaker placement is not possible and where sounds along the vertical plane are essential both for immersion and for accuracy of training.

The shortcomings of using one of these media production tools in simulations are well documented in the Institute for Creative Technologies 2001 audio technical report (Sadek, 2001). Their system was based around ProTools. Sounds were generated dynamically by sending midi triggers to the applications. While this arrangement had some success with "tightly scripted and choreographed scenarios," it was entirely incapable of creating any dynamically created panned sounds. Additionally, their system was further hampered by an inability to trigger more than three premixed sound sets simultaneously.

We also purchased and investigated the AuSIM 3D Goldminer system which is an integrated hardware and software solution for audio simulation. While producing fairly realistic surround impressions, its main draw back for mixed reality is its use of headphones as its delivery method. It is very important to be able to hear real world sounds in an MR experience. This is especially true in a military training scenario where it is not only essential to hear the footsteps and movements of virtual characters but also of other human interactors. More information can be found about AuSIM 3D through their website, http://ausim3d.com.

Figure 6: MR TimePortal at SIGGRAPH '03

For the specific demands of a highly dynamic and immersive mixed reality simulation, it became clear that a system must be built either on top of an existing API or from scratch. Some of our early attempts involved the use of the Java Media Framework (JMF) which, while providing dynamic cueing, did not support multi-channel output, spatialization, and channel control among many other things (Hughes, Stapleton, Micikevicius, Hughes, Malo & O'Connor, 2004)

An extensive review of the available technology was conducted including both proprietary and open source, hardware and software solutions. Due to the specific demands of the MR audio, EAX 2.0 was selected as the appropriate environment for building interactive audio experiences. However, this technology was also limited in its ability to address specific channels and provide control of multiple hardware arrangement through a single application. In addition, EAX does not provide the kind of low level support for creation of digital signal processing (DSP) effects—rather a static set of effects are provided. The frustration of working with these technologies due to the particular demands of interactive, immersive simulation led to the design and creation of a custom built audio engine and high-level interface.

4.1 SoundDesigner

SoundDesigner was conceived as an intuitive application that allows the user to create or modify entire soundscapes, control all output channels of connected sound cards, designate sound states, and support a variety of delivery systems and classifications. The user of SoundDesigner can individually address audio channels and assign some to a surround system while leaving others open for use with devices such as point source speakers (see *Figure 7*). To achieve this, SoundDesigner needed to be built on top of an API which allows low level control over audio hardware.

Most computer-generated simulations lack the ability to be reconfigured easily and quickly. SoundDesigner allows non-programmers and audio novices to assert a high level of control over the soundscape and auditory structure of a scenario. This is particularly useful in simulations where various factors such as ambient noise, cueing, expectation, and other important variables can be modified for purposes of evaluation. This software also allows for easy configuration of new audio scenarios or the alteration of previous simulations without the need for reprogramming.

The implementation of a high-level interface to an advanced audio architecture such as SoundDesigner requires the definition of new abstractions to represent system components in an intuitive way. The SoundDesigner interface represents individual sound clips in terms of *buffers*, which represent the discrete samples of a sound and *sources*, which represent instances of a buffer currently being played. These are common audio concepts in other libraries such as OpenAL, but SoundDesigner is unique in providing an explicit representation of individual *speakers*, which it groups and addresses through the interface of *channels*. Each sound source is played on a specific channel, which is to say that the samples generated by that source are mixed, filtered, and output to the speakers bound to that channel. The two fundamental channel types are *point-source* channels (which simply mix and copy channels to all speakers), and *spatialized* channels (which use information about the position of sounds and speakers to perform a per-speaker attenuation on samples in order to associate each source with a specific spatial direction). An overview of SoundDesigner features are listed below:

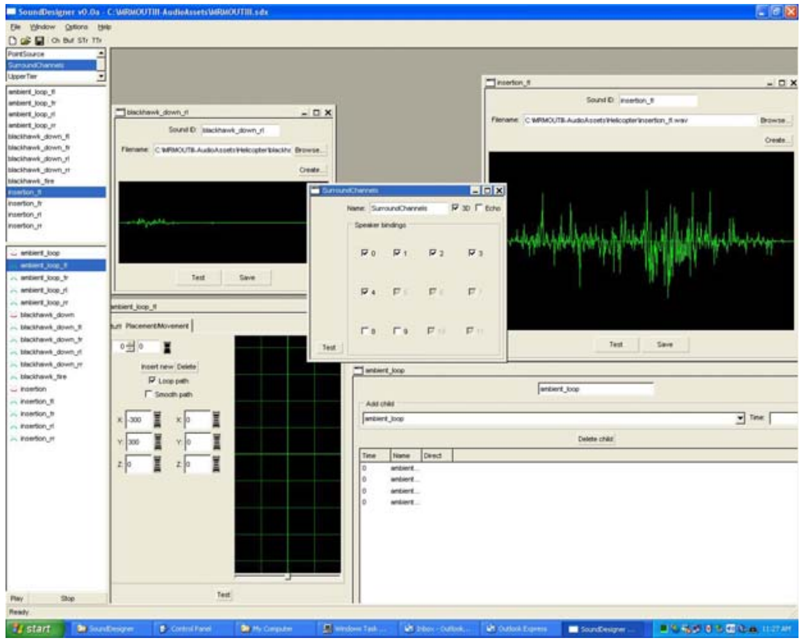

Figure 7: SoundDesigner

- *Support for 3D sound*
- *Assignable channels (3D, point source)*
- *Multi-tiered speaker configurations*
- *Configurable speaker placement*
- *Real-time spatialization*
- *User placement compensation*
- *Time-line triggers*
- *Prescripted paths with waypoints (linear and curved)*
- *Real-time capture and playback of sound (with full SoundDesinger support)*
- *Basic DSP (echo, reverb)*
- *Savable configuration files*
- *Standard features: looping, volume control, envelopes*
- *Ability to address multiple sound cards*

Once sounds have been arranged inside of a SoundDesigner configuration file or set aside as mono, real-time sounds, a “naming and associations” document is passed along to the MR StoryEngine programmer for the final phase of integration into a scenario. This document contains all the user ids, their story associations (e.g. trainee_fire is called when the gun trigger is pulled), an indication of whether the sound is prescripted or real-time, and the appropriate file directory to find the configuration file and real-time sounds. For full implementation details, see (Hughes, Vogelpohl & Hughes, 2005).

5 Delivery

The delivery system for the MR AudioEngine is a hybrid arrangement of multi-channel surround sound systems, point source speakers, directed sound, 3D headphones and haptic audio devices. This hybrid approach enables a wide range of uses and capabilities to deliver audio for a variety of environments with the potential for large numbers of participants. Sounds can be delivered globally to all participants, selectively to subgroups, or privately to individuals within an interactive experience. The goal of MR Audio is to provide a more dynamic hybrid range between the system’s hardware and software that can adapt to a dynamic environment and to users within the environment, without giving up the ability to hear and mix real audio such as voice communication. In the following sections, the separate components of our hybrid approach to MR Audio are described.

5.1 Surround Speakers

The multi-channel surround sound system can deliver dynamic audio cues across multiple locations along the x-axis. In articulating the y-axis, the surround sound can consist of multiple tiers with the potential for simultaneous above, below and at head level arrangements. Each tier may consist of up to 7 channels of audio and an additional .1 channel for low bass frequency. Traditional single tier surround sound configurations can only reproduce audio along the x axes. The addition of multiple tiers allows for a more three dimensional audio experience. Y-axis simulation is particularly important in military training scenarios where enemies may attack from above and below, in places where visual perception may be limited. Additionally, important cues such as footsteps and airborne vehicles can be more accurately modeled with a multi-tiered system. The goal of sound accuracy is complemented by the listener's enjoyment, as an effective spatial impression is important in obtaining a subjectively pleasing and realistic sound environment (Soulodre, Lavoie & Norcross, 2003). A recent study conducted at MCL's MR Testbed involving 39 participants investigated the discriminability between pink noise sounds originating from either head-level or above-head level speakers in a two-tiered configuration. Results indicated that participants were generally able to differentiate between these two locations along the vertical axis. These results suggest that this configuration is effective in delivering y-axis simulation.

5.2 Point Source Speakers and Intimate Audio

A point source speaker is used when accuracy is critical and audio assets can be delivered at a predetermined position. This typically consists of a speaker device that is not part of a surround system, but is used to fill in the soundscape by providing audio that is either inappropriate or less effective when used as part of a surround system. Point source speakers are used for a variety of applications including personal audio (radio traffic), special effects (audio haptic vest), embedded sounds (haptic gun fire), and intimate audio (voices inside your head). Personal audio includes on-body speakers such as two-way radios, ear buds, and other such devices. These devices are important for delivering private audio including trainer commands, personal interface audio, and other audio associated with personal equipment (e.g., gun shots).

As a special effect, alternative speaker locations can be used to heighten tension and mood. One such example is the addition of a speaker on the participant's body for dramatic effect. Intimate audio refers to sounds that are very close to our personal space and may convey a strong emotional impact or even a sense of violation. One example of intimate audio is an effect played through a helmet embedded speaker behind the head. This intimate audio attempts to simulate extreme close proximity through the use of physically close speakers and creative sound design.

5.3 Directed Sound

Directed sound is a new technology sometimes referred to by the trademark names Hypersonic Sound (http://www.atcsd.com) or Ultrasound (http://www.audiospotlight.com). Directed sound encodes audio into a high frequency beam (well above the range of human hearing), which "distorts" in a predictable manner when it collides with a surface and reproduces the encoded sound. The effect of directed sound is that the audio is perceived to be emanating from the source at which it is pointed, not at its source of origin. There are two distinct effects that can be created with directed sound: virtual sound sources, and private audio. Virtual sound sources are sounds that appear to be transmitted by the object that the directed sound is pointed at and can produce the effect of speakers being embedded anywhere in an environment. Additionally, virtual sound sources can be moved so that a sound appears to travel along a surface or set of surfaces. Private audio are sounds that are directed at a participant's head. These sounds are perceived by the listener as coming from inside their own head. They have the effect of being dramatically louder to the individual they are directed at than other participants who may be in the general area. Private audio can be used for delivering soft sounds such as whispers or unique effects such as buzzing flies. Additional applications could include simulating internal thoughts in the form of "thoughts-out-loud."

5.4 3D Headphones

Headphone based 3D systems are effective tools for creating complete immersion, as they provide the sound designer with complete control over an auditory environment (Begault, 1999). The 3D headphone system uses an inertial tracking system to place sounds in space relative to the participant's head orientation. Headphone systems without tracking have the major problem of sounds moving as the user's head moves. In other words, if there is a sound source to the right of the listener, when they turn their head to look at it, the sound will still be to the right of them. In this situation, the participants would be constantly turning their head to try to find the sound but would never find the sound in front of them. A 3D headphone system with tracking keeps the virtual sound in the appropriate location and, when the participants turn to look in the direction of a sound, the sound will be positioned in front of them. The main drawback to any headphone based system is that real world audio is blocked. A truly mixed reality headphone system is currently under development at MCL by merging the AuSIM 3D headphone system with external microphones and an intelligent "listening" system that will deliver to the listener the fully spectrum of sound from real, to augmented, to virtual. More details are provided in the "Future Work" section of this paper.

5.5 Haptic Audio

Haptic audio refers to sounds that are felt more than heard. Such devices include "bass shakers" and haptic vests. They can be used to increase the sense of realism and impact, but can also be used to provide informational cues.

In the case of haptic vests, pressure points can be used to alert participants to the direction of targets or potential threats. These feedback mechanisms can be used in coordination with detection devices. As a personalized tracked audio display within a haptic audio vest, it provides directional cues without cluttering up the already intense acoustic audioscape. With the use of speakers that vibrate more for feeling than for hearing, an intimate communication of stimulating points in the body provides the approximate orientation of potential threats that may not be heard or seen. Thus, a threat may be identified by a vibration or combination of vibrations. This information can give an immediate sense of the direction of a threat and its proximity (e.g., by making the vibration's intensity vary with the distance to the threat). It works in essence like a tap on the shoulder to tell the user of a direction without adding to or distracting from the visual or acoustic noise levels. This message is transferred to an alternative sense and thus allows for this critical data to cut through the clutter of the audiovisual simulation. With targets outside of the line of sight, this approach can significantly reduce a user's response time.

5.6 Hybrid System Integration

Combined together, surround sound, point source, 3D headphones, and haptic audio provide a wide range of devices for displaying the necessary auditory virtual and mixed simulations. With the many challenges of simulating complex and diverse environments, a hybrid approach delivers the most options for MR experiences. These devices can then be simultaneously controlled by the previously described SoundDesigner.

6 Artistic Research: Validating Production Techniques

The next step in a convergence of artistic convention and scientific research will be to begin the process of validation of production techniques to achieve a better understand of the impact of these approaches. This kind of "artistic research" is absolutely crucial for not only creating compelling entertainment experiences but also for creating accurate and helpful training scenarios. Without this kind of understanding, it is possible that simulations may provide false or incorrect training. In the case of military applications, this can be a matter of life and death.

6.1 Sound Design and Expectations

Though a great deal of research has been conducted on the physical mechanisms that make up most of a human's auditory perception, almost no research has been done on what impact other factors may play in a human's ability to spatialize sound (Cheung, 2002, Cheung & Marsden, 2002). In a study conducted in MCL's labs, it was discovered that expectations play a very crucial role in spatial perception. Sounds such as helicopter and airplanes were perceived as being above head-level, even when the sounds were, in fact, being played directly at head level. While at the same time, sounds such as footsteps where perceived as being below head level, when they were also, in fact, being delivered to the listener at head level. See (Hughes, Thropp, Holmquist & Moshell, 2004) for more details on this study.

7 Future Work and Conclusions

The next stage of audio research at MCL is to investigate many of the production techniques described in this paper and determine their impact on immersion and presence. For instance, how does surround capture affect a user's sense of presence when compared to the same capture performed with a mono, omni-directional microphone? The aim is to validate or discredit certain aspects of audio production and design in an effort to have a better understanding of what the impact of these decisions are.

Audio is an essential part of the human experience. Not enough attention has been given to the importance of audio research and production in the simulation and training worlds. Too often, audio is treated as an afterthought or something that is relegated to a member of a programming team or other individuals with little to no experience in sound design. To create truly compelling, immersive, and effective simulations, audio must be studied to the same extent of its visual counterparts.

8 Acknowledgements

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