The Distance Pan-pot: An Alternative Approach to the Distance Effect

Eoghan Tyrrell

Music & Media Technologies
School of Engineering
&
School of Drama, Film and Music
Trinity College Dublin

Submitted as part fulfilment for the degree of M.Phil.

2016

Declaration

I hereby declare that this thesis has not been submitted as an exercise for a degree at this or any other University and that it is entirely my own work.

I agree that the Library may lend or copy this thesis upon request.

Signed: ________________ Date: ________________

Abstract

The purpose of this research is to further the understanding of auditory distance perception so that distance illusory software can be designed more effectively. Current methods of creating auditory distance illusions are inadequate. A sound source distance illusion is usually only crudely achieved with significant timbre altering processes. These processes are not conveniently implemented and are often computationally expensive. A method for a sound source distance illusion that is timbrally transparent, computationally efficient, and easily implemented is desirable.

This research investigates how a change in the early reflection pattern received by a listener affects the perceived distance of a sound source. In these investigations, the number of early reflections provided and the directions from which these early reflections arrive are changed. To conduct these investigations, software that makes use of simulated early reflections for a distance effect is designed. Audio samples processed with this software are presented to listeners in an online survey. Data from the survey is used to resolve speculations about human distance perception.

This research shows that the perceived sound source distance changes as the number of early reflections provided changes. It also shows that a change in early reflection spatial distribution does not cause a change in the perceived distance of a sound source. Furthermore, the research suggests that a distance illusion can be achieved with as few as 3 early reflections.

Acknowledgements

Firstly, I would like to mention and thank profusely Dr. Dermot Furlong; teacher, thesis supervisor, and psychoacoustician extraordinaire! This project would not have been remotely realisable without his expertise and guidance.

I would certainly be remiss not to mention the other MMT staff whose advice and help was imperative to the completion of this project, particularly Dr. Enda Bates whom I offer my sincerest gratitude to.

I would like to express my appreciation to Daniel Ward, MSc., who proof-read this thesis and advised me when it came to the data analysis stage of this project.

I am also forever indebted to my Dad, who supports me in all my academic and musical endeavours.

Contents

List of Figures

<u>List of Tables</u>

1. Introduction

1.1 Chapter Introduction.

Sound reflects off multiple boundaries as it propagates through an environment. The first few reflections (early reflections) arriving at a listener can inform the listener of the sound source distance. It is not known if the number of early reflections received by the listener affects the perceived source distance. There is also no evidence to determine if a change in the spatial distribution of early reflections causes a change in the perceived sound source distance. This research examines both of these unknowns. In order to carry out these investigations, software that changes the perceived sound source distance is designed. This software achieves different perceived distances by adding simulated early reflections to the source sound.

1.2 Motivation.

The purpose of this research is to further the understanding of auditory distance perception so that distance illusory software can be designed more effectively. The current methods of implementing a distance illusion are inadequate. Only through computationally expensive processes and significant timbre alteration of the source sound can a crude impression of distance be achieved. This is largely due to the limited understanding of human auditory distance perception. With a better understanding of distance perception, more effective processing techniques can be designed; processes that are computationally efficient, and timbrally transparent.

1.3 Method.

This research was undertaken by first building distance illusory software to Michael Gerzon's specifications. *The Design of Distance Pan-pots* [Gerzon, 1992] provides a design method for software that makes use of early reflections for a distance effect. Empirical listening surveys were then conducted with audio samples processed by Gerzon's distance software. A large number of survey participants were sourced online. The results from these surveys were then used in an attempt to resolve speculations about human distance perception.

1.4 Thesis Overview.

This thesis is presented in 7 chapters. The following paragraphs present an overview of each chapter.

Chapter 2 entitled *Background to the Study* provides the reader with the fundamental information needed to understand later chapters. An overview of human sound source localization is given, stereophonic reproduction of sound is explained, and the concepts underlying the designed distance software are explored.

Chapter 3 entitled *Research Question and Methodology* states the question to be answered by this thesis. It explains where the research question came from and why it needs to be explored. This chapter details the research approach. It recounts how processed audio samples were presented to listeners for the collection of empirical data. Problems faced during this data collection period are also explained here.

Chapter 4 entitled *Literature Review* compares important and relevant research relating to distance perception. Studies that support and oppose the design of Gerzon's distance software are examined side by side. A state-of-the-art review of the entire research field relating to early reflections and distance perception is also given.

Chapter 5 entitled *Implementation* first explains how the distance software algorithm works. Secondly, it accounts for the necessary considerations in the design of an early reflection simulator. Lastly, it describes how the distance software (The Distance Pan-pot) was made. A description of the programming language used to build the software is also given.

Chapter 6 entitled *Research Findings* presents the data gathered by the surveys. An analysis of the results is made, as well as a discussion of the research findings.

Chapter 7 entitled *Conclusion* finalizes the thesis. The research findings are summarized, a critical evaluation of the author's approach to the research is made, and areas in need of further research are discussed.

Appendix A of this thesis contains software code for the distance illusory software. Appendix B contains data that was collected for this research. A CD-ROM accompanies this thesis. The software code can also be found on the CD-ROM so the reader can compile and test the software if he or she so wishes. A video demonstration of the distance software, a spreadsheet of the research data, and a PDF file with links to the online surveys conducted, can be found on the CD-ROM too.

Dr. Dermot Furlong, co-ordinator of the Music and Media Technologies department at Trinity College Dublin, supervised this research.

2. Background to the Study

2.1 Chapter Introduction.

Many audio post-production scenarios require a sound source to appear at a distance. For example, in film it is desirable for sound objects to sound far away if they are visually seen to be far away. This distance effect is usually achieved with a combination of different processes. Such processes often give an unconvincing impression of sound source distance. They are also computationally expensive, and can result in significant colouration of the source sound. Therefore, a simpler, less computationally expensive process that gives more reliable results is needed.

However, if a better process for the creation of a distance illusion is to be designed, an understanding of sound source distance perception is needed. Only then can an attempt be made to artificially recreate the conditions needed for such an illusion. This background chapter explains how human sound source localization is achieved. An explanation of distance hearing is also given. The distance software designed for this research is based on the Craven Hypothesis. The Craven Hypothesis speculates how the auditory system makes use of early reflections for distance hearing. An explanation of this hypothesis is given. The distance effect will also be designed for stereo loudspeaker presentation, so an explanation of stereo sound reproduction is provided.

2.2 Hearing Direction.

Figure 1 shows the coordinate system for sound direction. This coordinate system is useful for explaining human sound source localization. The horizontal plane refers to the horizontal azimuth angle from which a sound comes. The median plane refers to that which divides the head into left and right portions. All positions on the median plane are equally distant from both ears. The frontal plane is that which divides the head into front and back portions. These coordinates can also be used to specify the direction from which a sound arrives at a pair of microphones.

Sound source localization is achieved with two physically spaced ears. Human ears are separated by the head; a distance of about 17.5cm. This physical separation means that a sound wave arriving from the side of the head will reach one ear before the other. In *Figure 2.2*, sound source **B** is positioned on the frontal plane, right of the head. A wavefront travelling from **B** will reach the right ear before the left. There is a sound wave arrival time difference between the ears. The mind subconsciously interprets this timing difference and informs the listener that sound is travelling from the right.

Sounds arriving from directly in front, directly behind, or from any position on the median plane will provide an interaural time difference of zero. Sound source **A** in *Figure 2.2* illustrates this. The sound wave travelling from **A** reaches both ears at the same time. The mind subconsciously notices this timing similarity indicating that sound has occurred on the median plane. Interaural Time Difference (ITD) is the term used to refer to *timing* localization cues.

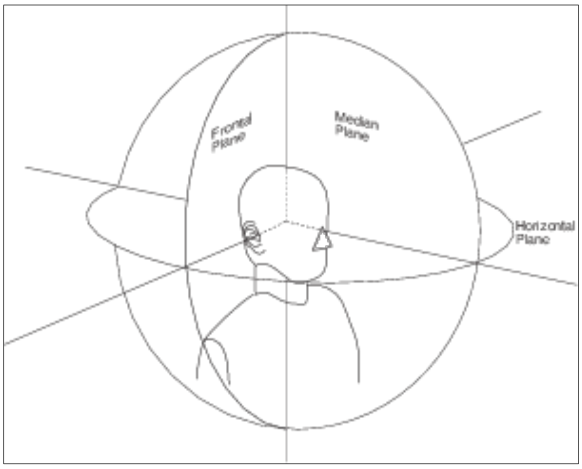

Figure 2.1: Sound Direction Coordinate System [Bech, 2006]

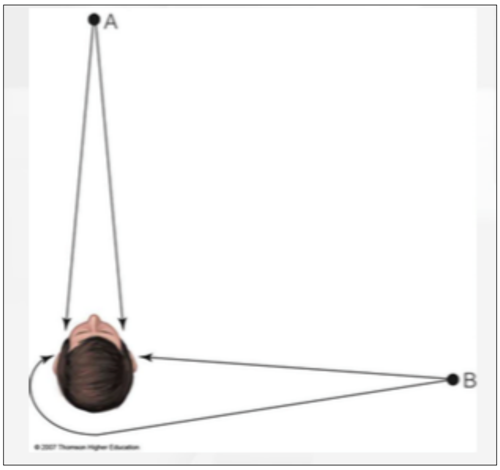

Figure 2.2: Interaural Difference/Similarity [Thompson, 2007]

There is a second consequence of having physically separated ears. Consider again the scenario of sound arriving from one side of the head (sound source **B,** *Figure 2.2*). The far eardrum, soon after, mimics movements of the near eardrum as the wavefront moves past the head. Sound arriving at the near ear will have a different phase angle to that of the far ear. The auditory system makes a comparison of the phase angle between the ears and figures out which ear leads the movement [Handel, 1989]. The listener experiences sound as travelling from the leading (near) side. Interaural Phase Difference (IPD) is the term used to refer to such *phase* localization cues. The IPD cue is related to the ITD cue. A phase difference *is* a timing difference.

The auditory system can also make use of interaural level differences to localize sound. Sound travelling from the side of the head can be obstructed *by* the head and be of a lower amplitude when it reaches the far ear. The head casts an acoustic shadow over the far ear, as shown in *Figure 2.3*. There will be a sound level difference between the near and far ear. Sounds arriving from a direction on the median plane will be of equal level in both ears. A comparison of the sound *level* detected by each ear is referred to as the Interaural Level Difference (ILD) cue.

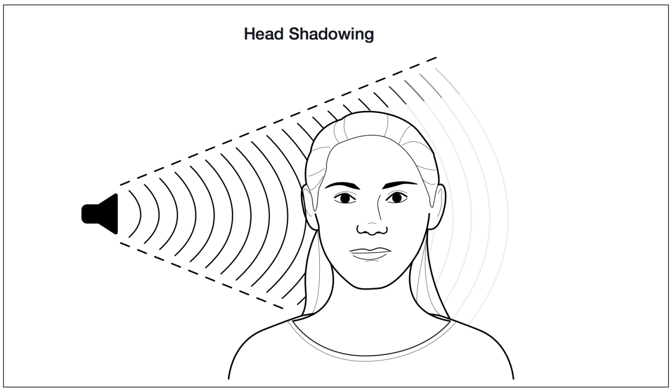

Figure 2.3: Head Shadowing [Oculus VR, 2016]

It is important to note that both ITD, and ILD cues do not indicate if a sound has occurred in front, behind, above, or below the listener. Interaural signal differences are absent at all positions on the median plane. This is illustrated in *Figure 2.4*. Sound source **A** and sound source **B** are the same distance from both ears. Both **A** and **B** provide the listener with the same timing and level localization information. With ITD and ILD cues alone, there is no way of discerning if the sound source has occurred in front, or behind, due to the geometrical symmetry of the spatial organization. Front-back sound source location information is not provided.

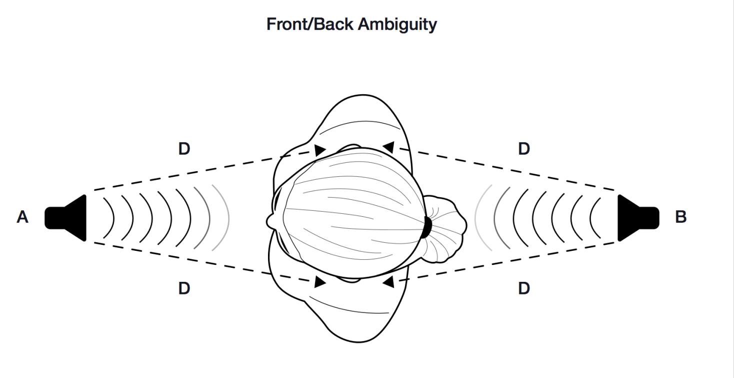

Figure 2.4: Median Plane Confusion [Oculus VR, 2016]

Similarly, sounds located on the *Cone of Confusion* also provide ambiguous localization information. The Cone of Confusion, as seen in *Figure 2.5*, describes a cone shaped surface area. All sound source positions on this cone provide the listener with similar interaural difference information. It will not be clear to the listener where on this cone the sound has occurred. ITD and ILD cues alone cannot provide explicit localization information. For such explicit information, a head related transfer function (HRTF) cue is also needed.

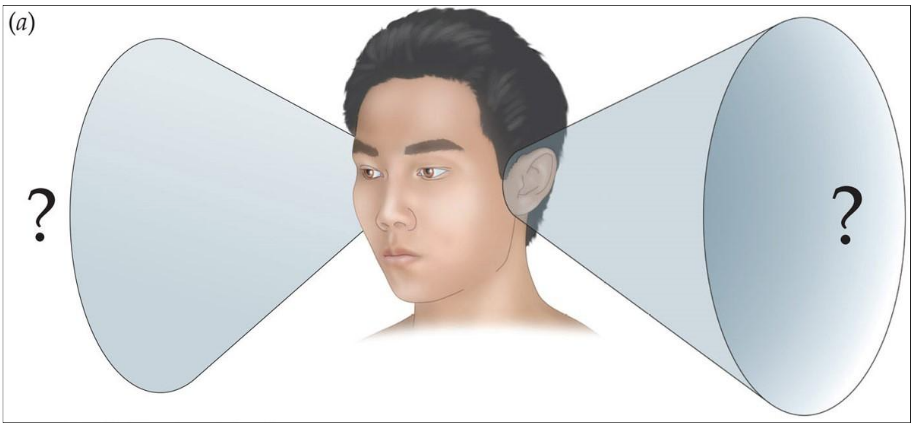

Figure 2.5: Cone of Confusion [Broadbridge, 2015]

> If the sound source is located in the median plane, or if identical signals are present at both ears, the auditory event generally also appears in the median plane. If the hearing apparatus is to determine the position of the auditory event on the basis of attributes of the ear input signals, then these must be monaural attributes [Blauert, 1983].

The HRTF cue refers to the spectral alteration of sound as it comes in contact with the head, shoulders, chest, and pinnae of the outer ear. Such body parts will reflect, defract, absorb, and consequentially alter the spectral profile of the sound wave before it enters the ear. The pinnae are asymmetrical, which means that every direction from which a sound comes is associated with a unique signal shaping profile (transfer function). Some frequencies of the arriving sound wave will be attenuated while others are amplified. Every incidence angle will have a unique transfer function associated with it. The mind has the subconscious ability to interpret the transfer function imposed on the arriving sound wave and with it can resolve front-back localization confusion [Begault, 1994]. The HRTF cue is a monaural cue. A person who is deaf in one ear can still make use of HRFT attributes for localization. Head movements (auditory parallax) can also resolve such localization confusion. If the head is moved, the sound may no longer occur at an ambiguous position [Hirsh, 1971].

All ITD (IPD), ILD, and HRTF cues are frequency dependent. That is, the effectiveness of the cue depends on the frequency. The wavelength determines the localization cue provided. Higher frequency sounds with wavelengths small enough to be obstructed by the head and pinnae will provide ILD and HRTF cues. Lower frequency sounds whose wavelengths are long enough *not* to be affected by the head and pinnae provide ITD cues. ITD (IPD) cues are effective for frequencies below

≈700Hz. ILD cues are effective for frequencies above ≈500Hz. Pinna filtering occurs on frequencies above ≈2kHz. Broadband spectrally rich sounds will provide all cues and can be localized quite easily. Simpler spectrally sparse sounds can be more difficult to localize because they may only present one cue.

All the previously stated cues inform listeners of the direction from which a sound comes. However, the sound's incidence angle alone does not reveal the sound source location. It is also necessary to discern the sound's depth in order to identify its position in three-dimensional space. The next section explains how distance hearing is achieved.

2.3 Hearing Distance.

If a sound is familiar to a listener, its level may be crudely used as an indication of a sound's distance. A sound increasing in distance will decrease in level. Such a cue is more accurately employed in the presence of other sounds [Mershon and King, 1975]. This level cue is also better exploited if the sound source distance is changing [Ashmead, 1995].

A comparison of the direct sound level relative to the reflected sound level by the ear can also provide a cue for distance localization. This cue is referred to as the direct to reflection ratio, or *D/R ratio*. A change in this D/R ratio leads to a change in perceived sound source distance. The D/R ratio cue has been shown to be one of absolute measure, which means it can be used to discern distance of an unfamiliar sound in an unfamiliar environment [Mershon and Bowers, 1979].

The term *early reflections* refers to those reflections that occur within ≈100 milliseconds of the direct sound. According to a hypothesis by Peter Craven, an early reflection's amplitude and arrival time, when compared to the direct sound's amplitude and arrival time can provide a cue for sound source distance [Gerzon, 1992]. The relative amplitudes and arrival times of early reflections are often referred to as *fine structure*. Early reflections not only provide distance cues, but also increase the clarity, intimacy, size, and loudness of a sound source.

The temporal distribution of reflected energy is another cue known to affect distance perception. Altering the time delay between the direct sound and the arrival of reflected sound results in different perceived distances [Michelsen and Rubak, 1997]. Artificial reverb generators often refer to this time delay as *pre-delay*. Longer pre-delay times result in a closer perceived sound source. Shorter pre-delay times produce a farther perceived sound source. The onset of reflected energy (pre-delay) is illustrated in *Figure 2.6*.

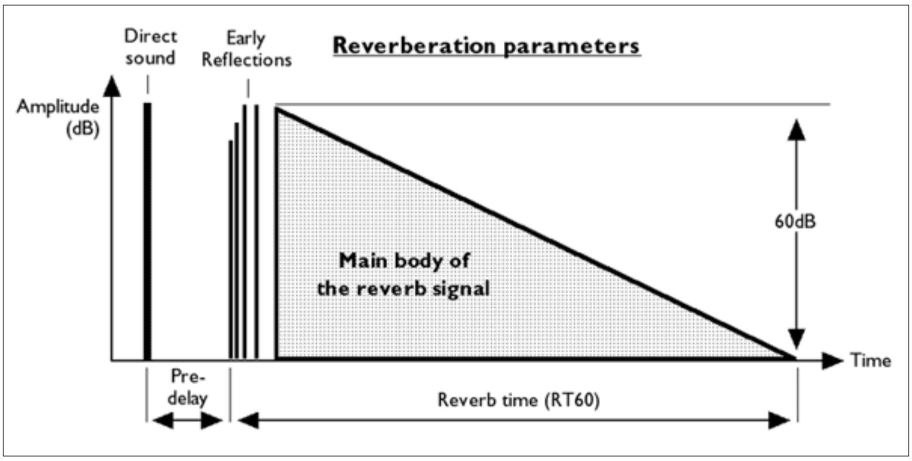

Figure 2.6: The Temporal Distribution of Reflected Energy [Ottewill, 1999]

A sound's high frequency content will be subject to attenuation when the source is at a distance greater than ≈15 meters [Blauert, 1983]. Coleman [1962] found that effective use of this cue for distance deduction requires familiarity with the sound. High frequency absorption of sound also occurs in rooms as sound reflects off surfaces. This spectral alteration of sound is often regarded as a subsidiary cue for distance perception. Alone this cue does not provide a good indication of a sound's distance. However, when this cue accompanies others, the distance impression becomes more robust.

Binaural localization cues (a comparison of signals received by both ears) are used to detect the close proximity of a sound. Brungart and Rabinowitz [1999] found that at distances close to the head, significant differences in sound level between the two ears indicate the sound's closeness.

2.4 The Law of the First Arriving Wavefront.

A sound source will be located at the direction from which the first arriving wavefront comes. A sound traveling the direct path will always arrive first because the direct path is the shortest path. This direct source may immediately be followed by a number of reflections arriving from various directions, but these reflections will not influence the perceived sound source direction [Everest, 2015].

As will be explained thoroughly in later chapters, the distance pan-pot creates a distance illusion by succeeding the source sound with a number of simulated early reflections. These added reflections do not alter the perceived direction of the source sound because they arrive after it.

Cues that indicate a sound's direction and distance can be reproduced during a stereophonic loudspeaker presentation. Localization cues can be captured with the source sound when recording, or artificially created when mixing. The following section explains how this is achieved.

2.5 Stereo.

Alan Blumlein [1933] is credited with the invention of stereophonic sound. Stereo refers to a method of sound reproduction that employs two or more channels of audio. Two-channel stereo is its most common form. The two-channel stereo effect is best received if the listener is roughly facing two speakers so that an equilateral triangle can be formed between the speakers, and the listener's head. *Figure 2.7* illustrates how speakers can be optimally positioned for two-channel stereo listening. Robust illusions can then be presented to the listener; illusions that result in the perception of a sound source at any position between the loudspeaker arc. Auditory scenes can be captured with stereo microphone techniques and reproduced in a manner that preserves the spatial relationships of these recorded sounds. Stereo also allows for the artificial creation of an auditory scene. This section describes how stereo can be used in the recording and creation of an auditory scene.

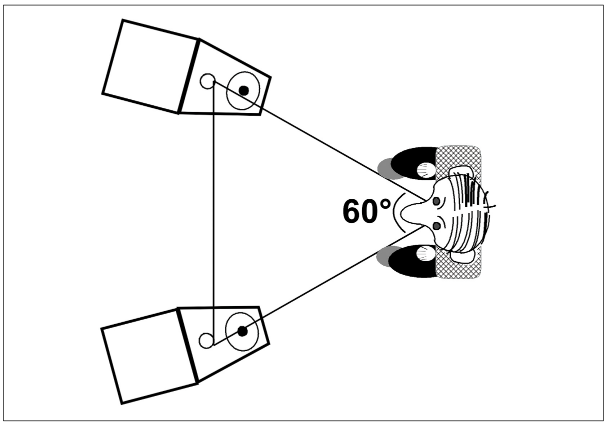

Figure 2.7: Two-Channel Stereo Listening [Clip Art, 2016]

Alan Blumlein secured a patent entitled *Improvements in and relating to Sound-transmission, Sound-recording and Sound-reproducing Systems* in 1933. In this patent, methods of recording and reproducing stereophonic sound are described. Blumlein uses a sound-for-cinema example to explain his technology. He explains how a two-channel system can be used to improve the reproduction of sound for the presentation of talking moving pictures (or "talkies"). His intention was to provide sound directionality so that sound created by the on-screen character was localized at the on-screen character. Blumlein's stereo technology was not thoroughly embraced for reconstruction of recorded music until 1954 when RCA and EMI began making two-channel stereo recordings for commercial release [Schoenherr, 2001].

Blumlein's patent introduced the stereo microphone positioning technique now commonly known as the *Blumlein Pair*. The Blumlein Pair technique involves two figure-8 patterned microphones. The microphones are positioned such that their capsules occupy the same physical location. Microphones positioned in this manner are referred to as *coincident pairs*. The microphones are oriented such that an **X** is created between their axes (polar patterns). Due to the microphone polar pickup patterns, each microphone is more sensitive to the direction in which it points. A sound source *off* the median plane will be louder in one microphone than the other. A sound source *on* the median plane will be equally loud in both microphones.

Due to the close proximity of the microphone capsules, sound presented to the microphones will reach both microphone capsules *at the same time*. Timing information that could reveal the sound source position, as is the case with our physically separated pair of ears, is not captured at the recording stage. However, each microphone does have a directivity characteristic. So, although such a microphone configuration does not capture *timing* localization information, it does capture *level* localization information. The following diagram (*Figure 2.8*) shows how two separate sound sources presented to a Blumlein Pair would be reproduced on a two-channel stereo playback system.

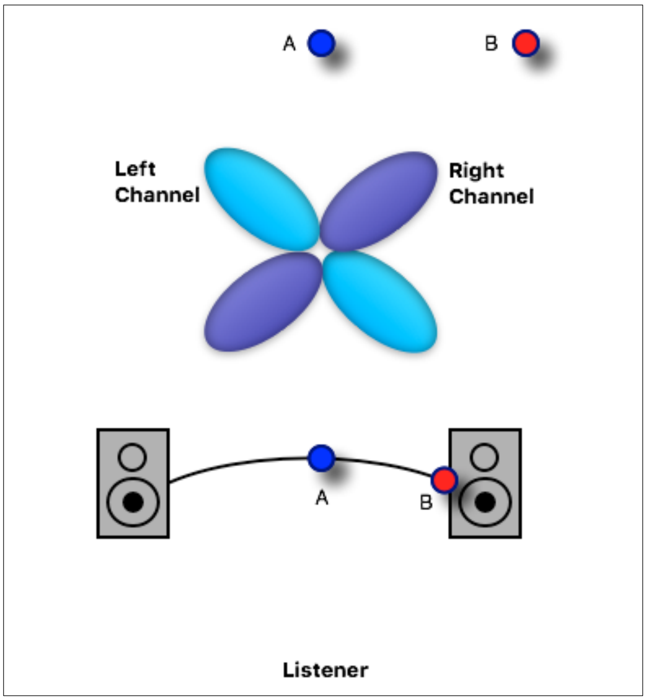

Figure 2.8: Blumlein Reproduction

During the stereo *reproduction* of signals recorded with the Blumlein Pair technique, timing localization information *is* actually provided, despite not being captured. When such signals are reproduced over loudspeakers, timing difference cues manifest.

Consider the scenario where a reproduced sound is localized at the centre of the stereo image. For this to occur, both loudspeakers must output the sound at equal amplitudes. Both ears receive identical signals, and the sound is localized directly in front. If it is required to reposition the sound so it appears off-centre, this amplitude relationship must be altered. This can be done with a process known as *amplitude panning*. By increasing the sound's amplitude in the right loudspeaker and decreasing the sound's amplitude in the left, the sound will move to the right. The greater the level difference between the speakers, the further right the sound will move. When the left loudspeaker has been attenuated enough so that it outputs nothing, the sound will be localized at the right loudspeaker.

As mentioned previously, this is not just a consequence of level differences, but timing differences too. So how does a change in loudspeaker level manifest as a timing difference?

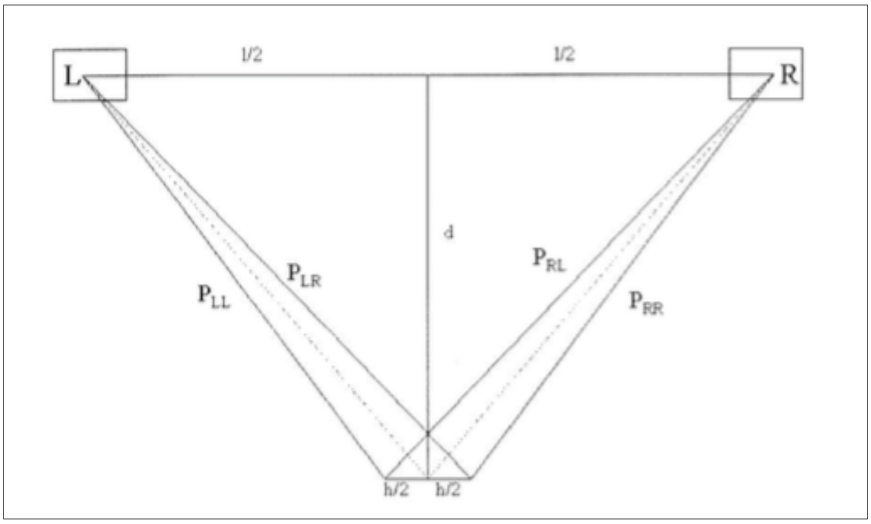

Figure 2.9: Manifestation of Timing Cues [Lipshitz, 1986]
L = left loudspeaker. R = right loudspeaker.

As seen in *Figure 2.9*, both speaker signals get summed at both ears. The right loudspeaker signal reaches the right ear before the left. The phase angle at the right ear will differ from that at the left. The same is true for sound emitted by the left loudspeaker. Its signal reaches the left ear before the right, and the phase angle at both ears differ. The summation of phase differing signals at each ear provide the auditory system with ITD information that is very similar to information provided by real sound sources. *Figure 2.10* illustrates how this occurs for a signal panned right-of-centre.

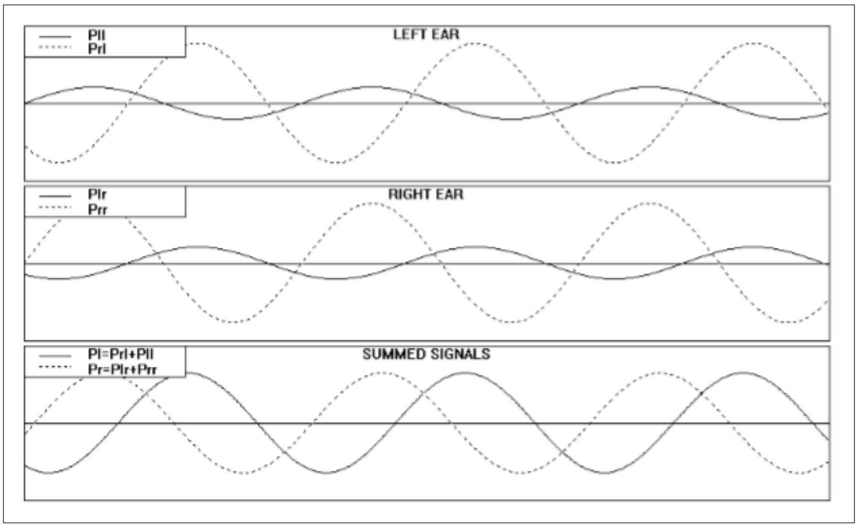

Figure 10: Summation of Phase Differing Signals [Lipshitz, 1986]

Whether the level difference is due to a sound's position in front of a Blumlein pair, or due to amplitude panning, timing difference cues are presented to the listener during stereo sound reproduction. Listeners can localize different sounds at different positions across the stereo stage. When listening to stereo recordings over headphones, the stereo image becomes distorted. This is because the left channel is isolated to the left ear, and right channel is isolated to the right ear. No timing cue is provided.

The Blumlein Pair is just one of many contributions Alan Blumlein made to the stereo reproduction of sound. A number of other microphone techniques that retain directional information for stereo reproduction are also described in his 1933 patent. Various methods of incorporating both stereo channels into a single groove when cutting shellac discs are described, as well as methods for storing both channels in the sound-on-film format. More than 60 claims to ownership were awarded to Alan Blumlein through the submission of his patent.

Auditory perspective can be defined as audio reproduction that preserves the spatial relationships of the original sounds. Blumlein understood the potential of stereophonic reproduction for width and depth perspective. In 1933, J.C. Steinberg and W.B Snow closely examined auditory perspective in stereo. Their experiments are explained in the following section.

2.6 Sound Reproduction in Auditory Perspective.

In 1933 for a *Symposium On Auditory Perspective*, Steinberg and Snow examined the two-channel and three-channel stereo reproduction of speech. Their attention was aimed, not only at angular localization, but at depth localization too. Their investigations involved two rooms. One was a medium sized acoustically treated space, and the other a large auditorium. The medium sized space was used as the *pick-up* room where a caller, from various positions around the room, would present his voice to three microphones. Three speakers on the stage of the auditorium reproduced the sound captured by these microphones. Listeners in the auditorium were to note the perceived reproduced position of the caller. The respective positions of the microphones and speakers can be seen in the following illustration (*Figure 2.11*).

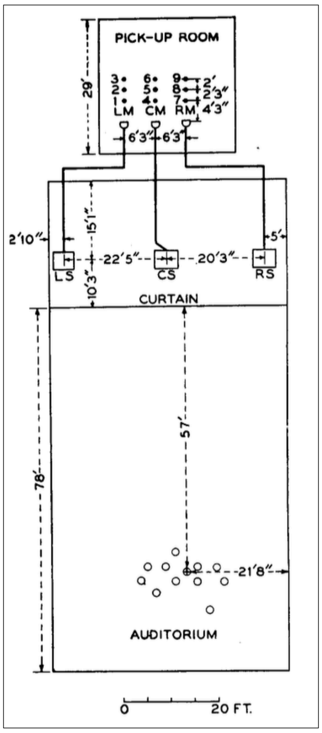

Figure 2.11: Speech Reproduction for Auditory Perspective [Steinberg and Snow, 1933]

LM = left microphone. CM = centre microphone. RM = right microphone.

LS = left speaker. CS = centre speaker. RS = right speaker.

Each individual microphone was not just channelled to a respective speaker. Experiments that employed various *bridging* techniques were conducted. For example, one experiment made use of two microphones (LM and RM) and three speakers. The centre speaker signal was a summation of both microphone channels (CS = LM + RM). *Figure 2.12* illustrates the various bridging techniques employed.

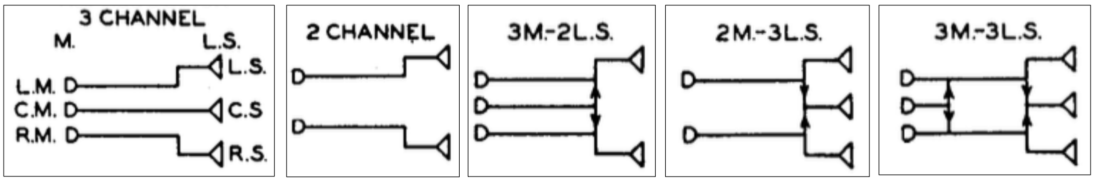

Figure 2.12: Bridging Techniques for Auditory Perspective [Steinberg and Snow, 1933]

M = microphones. L.S. = loudspeaker

Their work revealed that a three-channel system is superior to a two-channel system, but good auditory perspective can still be realised with as few as two channels. The three-channel systems demonstrated good correspondence between the caller's actual position in the pick-up room, and the caller's reproduced position in the auditorium. The two-channel systems, although not as accurate, still demonstrated good auditory perspective. Experiments that involved the removal of the centre microphone (CM), centre loudspeaker (CS), or both, demonstrated a reduction of virtual stage depth, but an increase in virtual stage width.

Steinberg and Snow [1933] make the point that human auditory depth perception is often imprecise, even when listening to the sound source directly. As a result, such inaccuracies in depth when reproducing sound over stereo are not that harmful to the listening experience. Steinberg and Snow found that in the reproduction of orchestral music, satisfactory results are achieved as long as different sounds are dispersed around the stereo stage. Exact reproduction of the instrumentalist's position is not critical for an engaging musical experience.

So far this chapter has explained how human sound source localization is achieved. It has shown that localization cues *are* provided during stereophonic sound reproduction. The capability of stereo for auditory perspective has also been discussed. The following section explains how a sound reproduction system can be used to present an illusion of sound source distance.

2.7 The Distance Pan-pot.

A pan-pot, or panoramic potentiometer, is a control that allows a mixing engineer to change the horizontal position from which a sound comes during sound reproduction. This horizontal repositioning of sound, as described above, is achieved by redistributing the sound's amplitude between loudspeakers (amplitude panning). In 1992, a paper submitted by Michael Gerzon to the Audio Engineering Society (AES) proposed the design of a pan-pot that does not change the angular location of the reproduced sound, but the depth location.

Gerzon's paper, entitled *The Design of Distance Pan-pots* advocates that early reflections provide the most significant cues for distance hearing. His distance pan-pot creates an impression of distance by adding simulated early reflections to the sound. Peter Craven (a colleague of Gerzon) conceptualized that for a transient sound, the auditory system discerns sound source distance by comparing the amplitude and arrival time of each early reflection to that of the direct sound.

> The Craven Hypothesis assumes that the apparent distance of sounds is derived by the ears deriving, for each early reflection of a transient sound, the relative time delay and the relative amplitude gain of the early reflection sound, and deduces from these two quantities the apparent distance of the direct sound source [Gerzon, 1992].

This concept inspired Gerzon's distance pan-pot design. The Craven Hypothesis can be more easily understood if the *Image Method* is first examined. Formulated by Allen and Berkley [1978], the image method concept underlies the Craven Hypothesis suggestion.

2.8 The Image Method.

The reflection of sound off a wall or surface can be thought of as occurring in a similar manner to light reflecting off a mirror. A wavefront radiates from a sound source, meets a surface, changes direction, and arrives at a listener. *Figure 2.13* illustrates this through ray tracing. The incidence angle (αI) is equal to the reflection angle (αR). The sound can be described as coming from a virtual sound source (or image) behind the reflecting boundary.

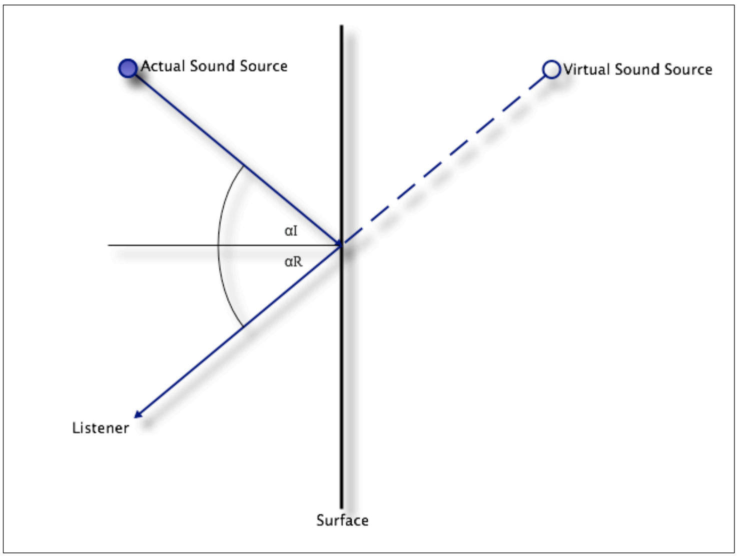

Figure 2.13: Single Virtual Image

However, typically sound reflects off multiple boundaries.

> Using this modelling technique, we can ignore the walls themselves, and consider sound as coming from many virtual sources spaced away from the actual source, arriving at time delays based on their distance to the source [Everest, 2015].

This is illustrated in *Figure 2.14*. All sound in an environment travels at the same speed; the speed of sound (≈ 340 meters per second). The direct sound will arrive at the listener first, then the closest virtual sound source (first early reflection), and so on. The farthest virtual sound source will arrive last.

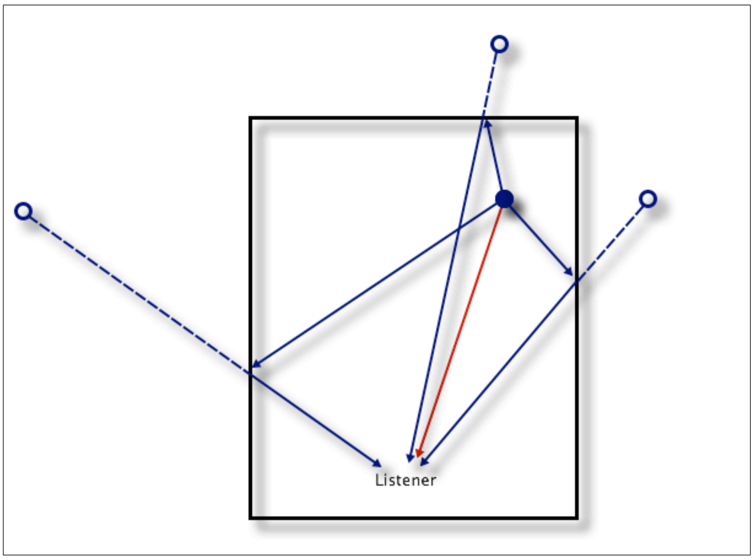

Figure 2.14: Many Virtual Images

The later arriving early reflections (waves that travel the furthest) will usually be of lower amplitudes than those that arrive first. The intensity of a sound source (or virtual sound source) is inversely proportional to the square of the distance. The further a wavefront has to travel, the lower its amplitude will be when it reaches the listener. Sound is also subject to high frequency attenuation due to the frictional resistance of air. The same is true for sound when it meets a boundary. Perfect reflections do not exist. High frequencies are often absorbed and attenuated at a boundary, more easily so than mid-range and lower frequencies. The more absorptive the boundary is, the greater the attenuation. Furthermore, acoustically, reflections in physical proximity to each other have the ability to add together (constructive interference), or cancel each other out (destructive interference). Interference between reflections may alter their amplitudes too.

2.9 The Craven Hypothesis.

The image method is the concept underlying Peter Craven's Hypothesis. Peter Craven theorized that the auditory system compares the amplitudes and arrival times of early reflections to the direct sound, and from this makes a distance evaluation. His hypothesis suggests that each early reflection arriving at the ear provides a separate cue for distance, i.e. that each individual early reflection provides another opportunity for the mind to decipher distance information from the presented signals.

The Craven Hypothesis provides a method for calculating the amplitudes and arrival times (delay times) of these early reflections (virtual sound sources) for a given distance. They can be calculated as follows. The relative amplitude gain ($\boldsymbol{g}$) of each early reflection is given by:

$$\boldsymbol{g} = \boldsymbol{d} / \boldsymbol{d'},$$

where $\boldsymbol{d}$ is direct sound source distance, and $\boldsymbol{d'}$ is the reflected sound source distance. The relative time delay ($\boldsymbol{T}$) of each early reflection is given by:

$$\boldsymbol{T} = (\boldsymbol{d'} - \boldsymbol{d}) / \boldsymbol{c},$$

where $\boldsymbol{c}$ is the approximate speed of sound in air (≈ 340 meters per second). Simple algebraic rearrangement of these equations can be used to remove $\boldsymbol{d'}$:

$$\boldsymbol{d} = \boldsymbol{cT} / (\boldsymbol{g}^{-1} - \mathbf{1}).$$

Michael Gerzon's distance pan-pot, from the direct signal, generates reflections and applies this final equation to each simulated early reflection. These equations can be more easily understood with examination of *Figure 2.15*.

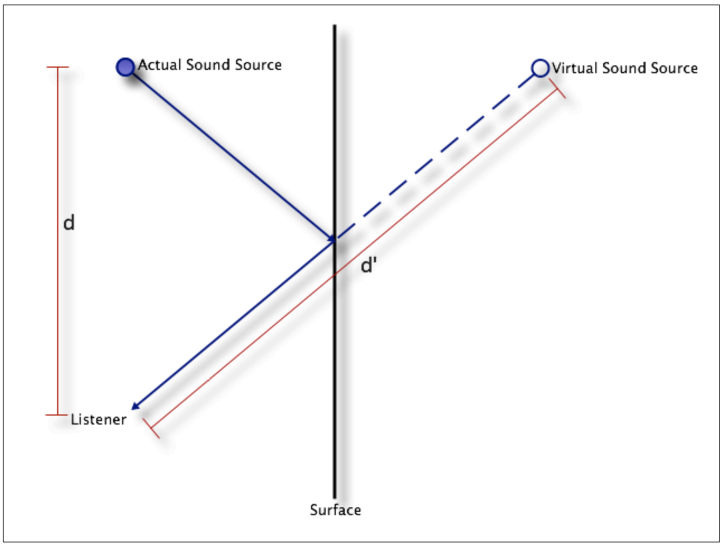

Figure 2.15: The Craven Hypothesis

Peter Craven states that as long as the reflections do not deviate by more than 1dB from their expected level, i.e. their level if perfect reflections were to occur, a strong impression of sound source distance will persist. If absorption at a boundary occurs and the reflection is attenuated by more than 1dB, a distance cue will not be provided. If constructive or destructive interference between two reflections occurs and combined their amplitude changes by more than 1dB, a distance cue will not be provided. Craven suggests that by analysis of a large number of early reflections. The mind can still make accurate estimations of distance despite errors caused by imperfect reflections, constructive interference, or destructive interference.

During the reproduction of audio it is possible to accompany a sound with artificial simulated reflections. If these simulated reflections comply with the Craven Hypothesis, a distance illusion can arise. This is how the distance pan-pot works. The source sound is used to generate a pattern of simulated early reflections. As the distance pan-pot is rotated, the direct signal path is attenuated and delayed. This delay and attenuation is such that the direct and early reflection signal relationship is always in accordance with the Craven Hypothesis. This method is illustrated in *Figure 2.16*.

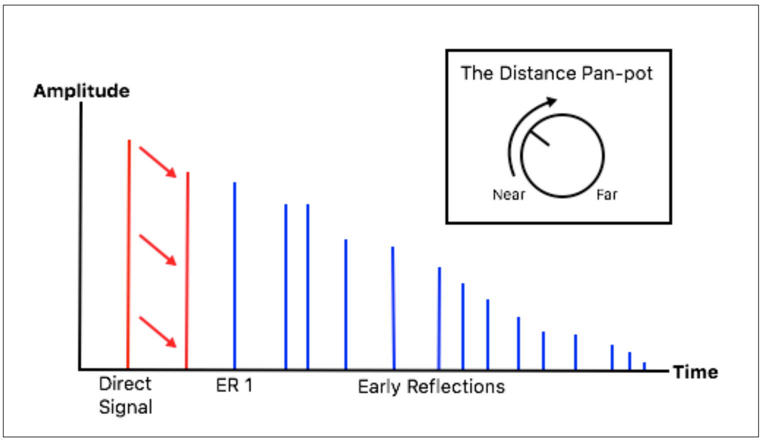

Figure 2.16: The Distance Pan-pot

Gerzon's distance pan-pot is not the first attempt at a process for creating a distance illusion. Distance illusions are usually achieved through a combined number of different processes. However, such processes often give an unconvincing impression of sound source distance. They are often computationally expensive, and can result in substantial timbre alteration of the sound. Gerzon's design, with a single control, intends to make the distance effect more easily implemented. His design also strives for a process that is computationally efficient and transparent in timbre. The following section describes the usual methods employed when creating the distance effect. It also inspects existing distance software programs.

2.10 Usual Methods for Simulating Sound Source Distance.

There are a number of different processes usually employed when implementing the distance effect. Such processes achieve a crude impression of sound source distance, and do so with considerable timbre alteration. Paul White in an article for *Sound On Sound* magazine describes common techniques used to create the illusion of sound source distance [White, 2009]. These techniques involve the addition of artificial reverberation and high frequency attenuation of both the direct (dry) signal and the reverberant (wet) signal. White also describes how other time based processes such as the chorus and flange effects can contribute to a distance illusion. It is these excessive timbre-altering techniques that Gerzon wishes to avoid in *The Design of Distance Pan-pots* [Gerzon, 1992].

Software designers Tokyo Dawn Records and Vladg Sound collaborated in the design of a distance effect plugin called *Proximity*. *Proximity* and Gerzon's distance pan-pot share the same intent: the creation of distance illusions with minimal timbre alteration. *Proximity* supplies a number of auditory distance cues which include high frequency attenuation, stereo width manipulation, distance gain loss, and distance based early reflection cues. The companies, unsurprisingly, have not made public the methods by which the early reflection delay times and amplitudes are calculated. However, Vladg Sound stated to the author that Gerzon’s AES paper [Gerzon, 1992] was used as a starting point for the design of *Proximity*’s early reflection simulator.

Panorama, a plugin by Wave Arts, promises panning capabilities in all three dimensions. The software manual indicates that the D/R ratio is the only cue taken advantage of for the distance illusion.

The Waves *S360* surround-sound imager plugin is equipped with a distance control that makes use of early reflections. The distance control balances the direct signal against the early reflection signal. It is not known if this balancing complies with the Craven Hypothesis. The instruction manual states that the early reflection pattern is a room-modelling pattern, which suggests there is not a compliance with the Craven Hypothesis. As will be explained in later chapters, it is best to avoid room modelling when designing an early reflection pattern for distance effects that comply with the Craven Hypothesis. The Waves S360 distance control is intended for use with the accompanying surround-sound reverb plugin. When used alone, an undesirable crunchy timbre results. Many of the Waves plugins, such as *TruVerb* and

RVerb, can be attributed to Michael Gerzon [Alexander, 2008], but the author was unable to find any information that suggests their algorithms comply with the Craven Hypothesis.

Facebook and Two Big Ears collaborated in the design of the *FB360 Spatial Workstation*. This software suite is for virtual reality audio mixing. It employs a control that makes use of distance gain loss and 5 early reflections for a distance effect. The early reflection pattern is a room-modelling pattern, which again suggests that it does not satisfy the Craven Hypothesis.

2.11 Chapter Conclusion.

This chapter provides the theoretical foundation on which this research is based. The software designed for this research repositions the perceived sound source location, so an explanation of human sound source localization is provided. The distance illusion is presented over two-channel stereo, so a description of auditory perspective in stereo is given. An understanding of the Craven Hypothesis is necessary for an understanding of the distance illusion created, so this hypothesis is explained in detail. Other software for distance illusions are discussed.

3. Research Question and Methodology

3.1 Chapter Introduction.

This chapter informs of the question to be answered by this research. Empirical data is needed to answer the research question. This chapter describes in detail how this data was collected. The data collection process presented some obstacles to overcome. These obstacles are discussed.

3.2 The Research Question.

Michael Gerzon in *The Design of Distance Pan-pots* [1992] makes a prediction based on the Craven Hypothesis. As the Craven Hypothesis states, each early reflection provides a separate cue for distance, and each arriving early reflection provides another opportunity for the auditory system to deduce the sound source distance. Gerzon predicts that a greater number of early reflections will give a better impression of distance, providing early reflection overlap does not occur.

> Another observation consistent with the Craven hypothesis is the prediction that the deduced sense of distance will become more reliable as the number of early reflections is increased [Gerzon, 1992].

Gerzon also raises an issue relating to early reflection spatial direction in the deduction of sound source distance. Normally, early reflections arrive at a listener from a multitude of directions. These early reflections inform the listener of the acoustical environment. It is not yet known if the directions from which early reflections arrive affect perceived distance. It is known that monophonic recordings can demonstrate a sense of distance. However, it is not known if this distance impression is improved with spatially distributed early reflections.

> A second uncertainty is the role of the spatial direction of early reflections in deducing distance…there is little evidence as yet that this contributes very much to the actual sense of distance [Gerzon, 1992].

A more recent study by Kearney *et al* [2012] states that the importance of spatially distributed early reflections for distance perception is still unknown “and remains an open question that needs to be addressed.”

This research aims to answer the following questions:

1) Does the distance pan-pot work? Can it successfully alter the perceived distance of a sound source?

2) Does a change in the number of early reflections generated cause a change in perceived distance? Does it matter to the perceived source distance if the early reflection simulator generates 5, 10, 15, 20, 25, or 30 reflections?

3) How many early reflections are necessary for a perceived distance effect? What is the minimum number of reflections needed for the creation of a distance illusion?

4) Does a change in the early reflection stereo width (spatial distribution) cause a change in perceived sound source distance? Is a monophonic distance effect as robust as a stereophonic distance effect?

The research question that encompasses the above list is as follows:

- Is the perceived distance of a sound source affected when there is a change in early reflection number or early reflection spatial distribution?

3.3 Methodology.

Audio samples were presented to 90 listeners through an online survey. The survey collected quantitative data. From the author's experience with the distance pan-pot, it was clear that the nature of the source sound determined the effectiveness of the distance illusion. The extent of colouration also changed with the source sound. To ensure the data collected was representative of a wide variety of sound types, three sonically varying source signals were presented to the survey participants. These three signals included a spectrally rich synthesized click sound, a spectrally rich synthesized organ sound, and a high quality recording of anechoic speech. The organ was the only definitely-pitched source sound. Throughout the survey, the organ's pitch never changed. This was to ensure survey participants did not perceive a change in pitch as a change in height, or distance. An increase in pitch could be perceived as an increase in sound source height. The organ was also synthesized with a quick attack and slow decay.

The survey was divided into four ***sections***. Each section gathered data to address one of the four research questions listed in the previous section.

Section 1 (relating to research question **1**) tested for a successfully implemented distance illusion. Each survey question involved two audio samples. Each sample had been processed to a different extent by the distance pan-pot. For example, one sample would have been rendered with the distance control set to a low value. The other sample would have been rendered with the distance control set to a high value. The listener was to audition both samples and choose the more distant sounding sample. In this section, twenty early reflections were used in the creation of a distance effect. Each listener had to perform five of these judgements.

Section 2 (relating to research question **2**) tested for a change in perceived distance as the number of early reflections generated changed. For example, two audio samples were presented to the listener. One sample created a distance illusion with 5 early reflections. The other sample created a distance illusion with 30 early reflections. All other distance parameters remained constant. The listener was to audition both samples and choose the more distant sounding one. Each listener had to perform fifteen of these judgements. The audio samples used were processed with 5, 10, 15, 20, 25, and 30 early reflections. All possible combinations of sample pairs were presented to the listener.

Section 3 (relating to research question **3**) explored the minimum number of early reflections needed for a distance illusion. This section also employed a paired comparison approach. This time a processed (wet) audio sample was compared to an unprocessed (dry) sample. Each wet sample was processed with a unique number of early reflections, ranging from 1 to 30. All other distance parameters remained constant. If, for example, the wet audio file processed with 1 early reflection sounded more distant than the equivalent dry audio sample, the listener would select the wet sample. If there was no difference in perceived distance between the samples, the listener would indicate this instead.

Section 4 (relating to research question **4**) tested for a change in perceived distance as the spatial distribution of early reflections changed. Each sample had been processed to a different extent by the distance pan-pot's stereo width control only.

When the width control is at zero, all reflections arrive from the centre of the stereo image. When the width control is at 1, each early reflection has a unique horizontal position on the stereo stage. Each sample was processed with a unique early reflection width (spatial distribution). Twenty early reflections were used for the distance effect. Through paired comparison, the listener was to choose the more distant sounding sample. Each listener performed fifteen of these judgements.

Samples processed to varying extents sometimes differed in loudness. For section 2, 3, and 4 of the survey it was imperative that every sample equalled in loudness. This ensured listener distance perception was not influenced by level differences. The samples were balanced to the same level with loudness meters before they were embedded into the survey.

All questions were randomized so ordering effects would not compromise the data. Clear trends could be seen in many of the participant results. However, some results demonstrated a very erratic inconsistent pattern from which it was clear the survey was not completed with good intention. For example, some malicious or disinterested participants repeatedly chose the same answer throughout the survey. This is to be expected when sourcing paid survey participants online. Participants may quickly and carelessly complete the survey just to receive payment. These results were not included during the data analysis process. Limitations of online crowdsourcing and methods for reducing compromised data are discussed in the following section.

3.4 Crowdsourcing and Crowdflower.

Participants of the survey were sourced through the online crowdsourcing platform *Crowdflower*. This online approach meant that a large sample of participants from a wide variety of geographical locations could be accessed.

The limitations of crowdsourcing for auditory perception experiments were reviewed by Oh and Wang [2012]. They describe how data, gathered with crowdsourcing platforms such as Crowdflower, can be compromised by a number of factors. These potential factors are as follows. There is no way to ensure the participants are using suitable hardware for audio playback. Disinterested participants may quickly and carelessly speed through the survey. Menacing participants may deliberately provide compromised data. A participant’s environment may be distracting. Measures were taken (as much as was possible) to avoid the compromise of data collection.

Crowdflower evaluates its participants with *test-questions*. Test-questions are quality evaluation tests disguised as normal participant tasks. The Crowdflower participants are rated based on their performance in these test-questions. The surveys used for data collection were presented to Crowdflower's highest rated participants only. This reduced the amount of unusable compromising data collected.

The participants also had a time window within which to complete the survey. Anyone who completed the survey too quickly was disqualified. The same was true for overly slow survey takers.

A short evaluation was employed to ensure the participants were listening in stereo. A speak-and-spell player presented a string of six numbers to the participants. The first three numbers were presented on the left channel, and last three numbers were presented on the right channel. Listeners unable to identify the entire number string were disqualified from the survey. The inability to identify the entire number string suggests that the participant was listening in mono, listening with only one ear bud, or listening on a broken playback system.

Participants were asked if they regarded themselves as expert listeners. They were also asked to state their playback medium (headphones or speakers). These questions were included to see if listener experience or playback medium type resulted in different data trends. Survey participants were also required to complete a training question before the survey began. This ensured the first few survey questions were answered appropriately.

Crowdflower is an incredibly powerful platform. A large audience can be accessed, and a large amount of work can be completed in a short period of time. However, the platform is not optimized for listening test conduction. It does not handle audio files effectively. Survey design on the Crowdflower platform was limiting too. After weeks of toying with the platform, the author found the following solution to be the most reliable and effective. Audio samples were hosted on the *Soundcloud* website. Each audio sample player was embedded into a questionnaire designed with *Survey Gizmo*. A link to this questionnaire was presented to the Crowdflower audience.

On the CD-ROM that accompanies this thesis, a PDF document entitled *Survey Links* can be found. Within this document are hyperlinks that will navigate the reader to the exact surveys conducted during this research.

3.5 Alternate Approach to the Research.

The author considered conducting listening tests in a controlled environment. This approach to the research would have been advantageous, as many of the obstacles associated with online crowdsourcing would not have been faced. The sourced listeners would be less inclined to submit compromised data. It would also ensure the survey participants are listening on a suitable playback device.

The author decided against this approach because sourcing a geographically varying listening audience is important to this research. The results of this survey intend to be representative of human perception. Survey participants taken from a research department of expert listeners and musicians only, would provide data that less confidently extends from the sample to the population.

3.6 Data Analysis.

The survey results were interpreted with the help of a data analyst. The recommended approach was to use the survey questions that compared audio files differing *significantly* in processing extent for inference. For example, when testing for a successfully implemented distance illusion, it is best to use the results from those survey questions that compared a lightly processed file against a heavily processed file. Data from questions that compared samples differing only slightly in processing extent was not as useful. Such data “watered down” the results and did not help to answer the research questions. This approach also meant that difficult statistical analysis procedures were not necessary for interpretation of the results. Chapter 6 will more thoroughly demonstrate how the data was interpreted.

That being said, proper statistical analysis would still further the validity of this research. A test of significance could be used to support the conclusions drawn from the data. “No Change in Perceived Distance” could be established as the *null hypothesis* ($\mathbf{H_0}$). A two-tailed alternative hypothesis ($\mathbf{H_\alpha}$) would then be established as “A Significant Change in Perceived Distance”. If there is sufficient evidence against the null hypothesis, it can be rejected, and the validity of the alternative hypothesis would be suggested [Mullins, 2003]. Such an approach could verify the distance pan-pot's ability in the creation of a distance illusion. It could be used to establish if a change in the number of early reflections generated causes a change in perceived distance. It could also be used to determine if early reflection spatial distribution affects perceived distance.

3.7 Chapter Conclusion.

This chapter states the research question. It also provides a description of the survey conduction and data collection processes. The survey conduction proved to be somewhat problematic. Careful procedures were employed to ensure reliable representative data was collected. An alternative approach to the research was discussed, and the approach to data analysis was explained.

The following chapter compares research that relates early reflections to distance hearing. Research supporting and conflicting with the Craven Hypothesis is compared. An overview of the state of the art is given. Gaps in current knowledge relating to distance perception are highlighted. Existing research that suggests answers to the research questions are discussed.

4. Literature Review

4.1 Chapter Introduction.

The Design of Distance Pan-pots [Gerzon, 1992] advocates the possibility of early reflections as the most important cue for distance perception. It is widely accepted that early reflections *do* contribute to the perceived distance of a sound source. However, information regarding the size of this contribution often varies from study to study.

This chapter provides an overview of research related to distance hearing. The main foci of attention are those studies that examine the impact of early reflection changes on perceived distance. Evidence supporting and opposing the use of early reflections for a distance effect are examined. An overview of the trend in distance perception research is provided. Gaps in current knowledge relating to distance perception are highlighted.

4.2 Research Supporting the Distance Pan-pot Design.

Peter Craven made the strongest argument for early reflections as the primary distance cue. The unpublished Craven Hypothesis, as explained in chapter 2, assumes that the auditory system compares the amplitudes and arrival times of early reflections to the direct sound, and from this makes a distance evaluation. The Craven Hypothesis was the inspiration for Gerzon's distance pan-pot.

The Design of Distance Pan-pots is the only paper that makes reference to the Craven Hypothesis. As an unpublished hypothesis, there is no thorough explanation of how Peter Craven arrived at this conjecture. However, Gerzon does provide compelling evidence in an attempt to validate the Craven Hypothesis. Early monophonic recordings made with a single omnidirectional microphone demonstrate good reproduced distance. This might be because such microphones capture D/R ratio information accurately i.e. the amplitude relationship between the direct and early reflected sound is preserved at the recording stage. Microphones with a directivity characteristic reject some reflected sound and the D/R ratio is not accurately preserved. Microphones with directional bias do not capture sound source distance as effectively.

Published work entitled *Recording Techniques for Multichannel Stereo* [Gerzon, 1971] also showed that some coincident pair techniques demonstrate near-omnidirectionality in front. Such techniques reproduce sound source distance effectively. While examining the mid-side microphone technique, Gerzon found that the distance impression was reduced if the side (reflection) microphone signal was set to an unnatural level. If the side signal's relative amplitude deviated by more than 1dB from the actual real level in the room, the distance effect was reduced. These findings were made before the Craven Hypothesis was made known to Michael Gerzon.

Another case for early reflections as the prominent distance cue is supported by James A. Moorer's unpublished work from the late 1970's. He showed that the effect of sound source distance could be achieved with as few as 5 simulated early reflections. This research also suggests that 5 reflections are the minimum number of reflections required for a distance effect.

Work by Kendall and Martens [1984] also showed that an effect of distance, implemented by convolving an acoustical impulse response with a dry sound, persists even when the reverberant tail has been removed. They demonstrated that reflections occurring within the first 33 milliseconds of the impulse were sufficient to produce a strong distance effect. These experiments also demonstrated that the distance effect could be achieved whilst maintaining a relatively dry sound.

Steinberg and Snow [1933] for a Symposium on Auditory Perspective proved that stereo reproduction systems are capable of reproducing distant sound sources effectively. They found that three-channel stereo reproduction has greater virtual stage depth than a two-channel system, but two-channel stereo does provide satisfactory results. Their research suggests that two-channel stereo is an adequate medium for the presentation of distance illusions.

Facebook and Two Big Ears developed software for the design of virtual reality auditory scenes. Their software (the *FB360 Spatial Workstation*) includes a control that makes use of 5 early reflections for a distance effect. This control has been developed with efficiency in mind and consequentially, the early reflections do not demonstrate a spatial distribution. As will be explained in later chapters, the distance software designed for this thesis project is equipped with a control that allows for a reduction in the spatial distribution of early reflections generated. Michael Gerzon [1992] also provides a method for a monophonic distance illusion.

The *FB360 Spatial Workstation* that makes use of a monophonic distance effect supports Gerzon’s approach to the distance effect and suggests that an early reflection spatial distribution is not important for distance illusions. The *FB360 Spatial Workstation*’s use of 5 early reflections only also suggests that 5 reflections are sufficient for a distance illusion.

4.3 Research Opposing the Distance Pan-pot Design.

Research by Michelsen and Rubak [1997] provides evidence that somewhat contradicts with Gerzon's method of implementing a distance illusion. Their work involved the simulation of room responses with which they could use to examine parameters affecting the perception of distance. The two parameters under examination were the temporal distribution of reverberant energy (pre- delay), and the fine structure of early reflections. Their work stated that the fine structure of early reflections acted only as a supporting cue to the more significant pre-delay and D/R ratio parameters.

Further conflicting research by Zahorik [2002] states that the primary cues used for distance perception are level and the direct to reflected sound ratio (D/R ratio). The same research suggests that all cues containing distance information are combined and used collectively by the auditory system to deduce the distance of a sound source. This research implies that early reflection information alone is not enough to produce a strong distance effect.

Bronkhorst [2002] concluded that lateral reflections are important for distance perception. In his research, when lateral walls were made completely absorbent, the sound source was perceived to be close to the head. This suggests that spatially distributed early reflections are important for sound source distance perception. Bronkhorst does not make a distinction between early reflections and the diffuse reverberant tail.

Studies by [Chowning, 1971], [Bronkhorst, 2002], and [Mershon and King, 1975] examine how the D/R ratio affects distance perception. These researchers do not make a distinction between early reflections and the diffuse reverberant tail. These studies conclude that the D/R ratio is a significant contributing cue for distance deduction. However, it is unclear if these researchers have included or omitted early reflections as part of the reflection signal. From these studies it cannot be known if it is the early reflections, the diffuse reverberant tail, or a contribution from both that result in a perceived distance.

4.4 The Temporal Fusion Zone and the Craven Hypothesis.

It is important to acknowledge the temporal fusion zone (Hass window) when considering the validity of the Craven Hypothesis. Reflections that arrive within ≈35 milliseconds of the direct sound are *fused* with the direct sound [Haas, 1972]. The direct sound and this very early reflected energy are perceived as one event. These integrated reflections can also increase the perceived loudness of the direct sound.

There are two consequences of this fusion in relation to the Craven Hypothesis. The first is that, for distance deduction, the direct sound cannot be compared to reflections occurring inside this fusion zone. How is a comparison between the direct sound and these very early reflections made if all energy occurring inside the Haas window is integrated and perceived as one event? If the Craven Hypothesis is true, then we must only compare the direct sound to early reflections that occur after this temporal integration window.

Secondly, how can accurate distance hearing be achieved if this fusion results in the direct sound's perceived loudness increasing by more than ≈1dB? If the early reflection pattern provided is such that the perceived loudness increases significantly as a result of fusion, then there is a possibility of the Craven Hypothesis not being complied with. A cue for the wrong distance would be provided.

4.5 An Overview of the Trend in Distance Perception Research.

In general, it can be stated that older research concerned with the perception of distance examined factors on a broader scale, while newer research is more concerned with the perceptual effects of finer details. For example, it makes sense to examine the effects of reverberation as a whole (early reflections *and* diffuse reverberant tail) first, before jumping the gun and examining the effects of early reflection fine structure. The list of works below demonstrate this. The D/R ratio was the primary initial concern, alongside intensity (level), and the frequency absorption properties of air. Early reflections then became an important point of interest. More recent distance perception studies are concerned with binaural techniques for virtual reality. This is not an extensive list. These are just the author's findings based on the background research conducted. Of course, there are exceptions to the above statement.

Steinberg and Snow [1993] examine auditory perspective in stereo reproduction.
Paul D. Coleman [1963] examines intensity, frequency attenuation at far distances, and ITD cues.
John Chowning [1971] simulates sound source distance by supplying the D/R ratio cue.
Mershon and King [1975] confirm the D/R ratio as an absolute cue for distance perception.
Christopher Sheeline [1982] investigates the affect of different D/R ratios on distance perception.
Kendall and Martens [1984] create the distance effect with early reflections only.
Michael Gerzon [1992] proposes a distance effect that adds early reflections to the signal.
Michelsen and Rubak [1997] investigate pre-delay and early reflection fine structure for distance.
Douglas Brungart [1999] examines ITDs, ILDs, and HRTFs for localization of nearby sources.
Shinn-Cunningham [2000] investigates distance cues for virtual reality.
Pavel Zahorik [2002] examines the effect of different weightings of cues on distance perception.
Kearney et al. [2012] examine distance perception in Ambisonic virtual auditory environments.

4.6 Gaps in Current Knowledge.

The human perception of sound source distance is not comprehensively understood. It is difficult to pin-point gaps in distance perception knowledge as the entire subject matter is in need of further exploration. The absence of knowledge in this field has led to crude ineffective methods of creating the distance illusion.

5. Implementation

5.1 Chapter Introduction.

In this chapter, a thorough examination of the distance algorithm is presented. In addition, the mathematical techniques used to design the early reflection simulator are explained. The algorithm and the mathematical techniques were then implemented with the Csound programming language. An explanation of how this was achieved is also given.

5.2 The Distance Pan-pot Algorithm.

The source sound is used to generate a predetermined pattern of early reflections. As the distance pan-pot is rotated, the source sound is attenuated and delayed. This delay and attenuation always complies with the Craven Hypothesis. *Figure 5.1* illustrates this with a signal flow diagram. The delay and gain factor is in the *direct* signal path. The indirect (early reflection) signal path remains unchanged.

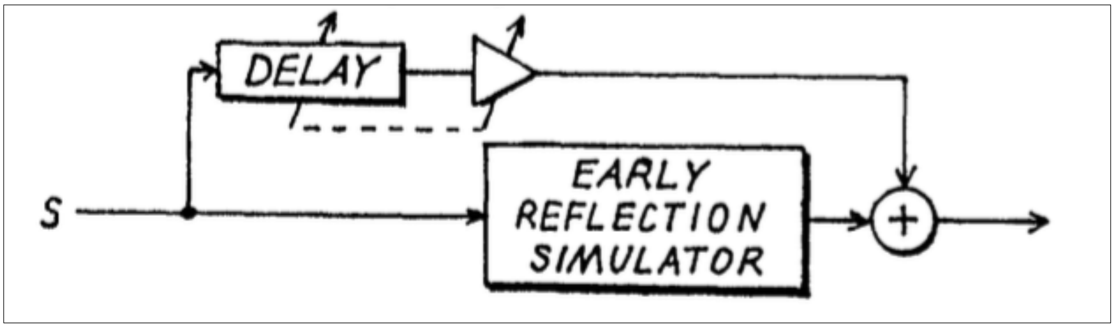

Figure 5.1: Signal Flow of the Distance Algorithm [Gerzon, 1992]

The algorithm simulates a real world scenario. As a real source sound becomes more distant, its gain decreases, and the time delay between direct and reflected sound (pre-delay) also decreases. For compliance with the Craven Hypothesis, Gerzon has calculated that the direct signal path should be delayed by:

$$(d' - d)/c \quad \text{or} \quad \delta / c$$

where d is the original distance of the sound source, d' is the desired virtual distance of the sound source, and c is the speed of sound. Delta (δ) represents the change in distance and is equal to $d' - d$. For compliance with the Craven Hypothesis, Gerzon has calculated the direct signal path gain to be implemented with the following formula:

$$\left[d/\left(d+\delta\right)\right].\left[exp\left(-r.\delta/c\right)\right]$$

See [Gerzon, 1992: p10] for an explanation as to how Gerzon arrived at this formula for calculation of the direct signal path amplitude.

Note that delta is common to both formulas. The equations are linked. The distance pan-pot knob generates values for delta, and the direct signal path is delayed and gained accordingly. When there is an increase in delta, the direct signal is attenuated, and delayed so there is a shorter pre-delay time. When there is a decrease in delta's value, the opposite happens. *Figure 5.2* illustrates this for an increase in delta.

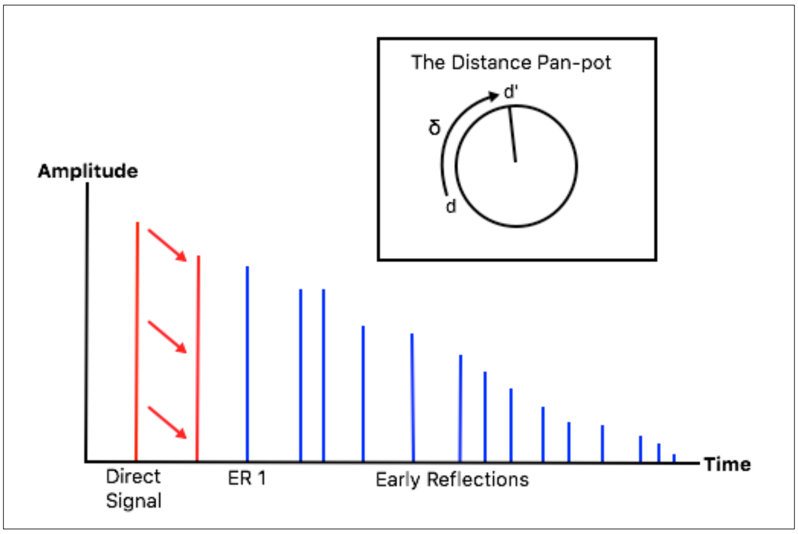

Figure 5.2: The Distance Pan-pot – Delta

The above algorithm demonstrates good computational efficiency as the early reflection pattern is predetermined. The early reflection times and amplitudes are calculated once, and remain unchanged for the duration of the distance pan-pot's operation. During operation, computations occur on the direct signal path only. An alternative *inefficient* approach would be to generate an entirely new early reflection pattern for each new simulated distance.

Gerzon [1992] provides a number of variations to this algorithm, each variation suited to a different application. For example, one variation allows for a distance illusion that does not alter the amplitude of the direct sound source. This approach is useful if the direct sound's level has already been decided. Gerzon also provides an algorithm for the processing of a pre-mixed stereo signal. This algorithm allows for separate distance manipulation of the left, right, and centre portions of the stereo image. The above algorithm, described and illustrated, is the foundation for all succeeding variations and it was the algorithm subject to survey testing.

5.3 The Early Reflection Simulator Design.

This section provides a summary of the most important considerations to make in the design of an early reflection simulator. Gerzon provides the *technique* for designing an early reflection simulator, but the pattern that results depends on decisions made by the designer. In the design of an early reflection simulator there are too many subjective variables to explore empirically. The designer, through trial and error, must explore different early reflection patterns and decide on the pattern to be used. The designer should take into consideration the effectiveness of the distance illusion, and excessive coloration of the source sound when choosing an early reflection pattern.

A reflection, as explained in chapter 2, can be thought of as a duplicate sound source arriving after the original direct sound. For the simulation of reflections, a delay-tap effect is used. A delay-tap effect is one that repeats the source sound after a specified period of time. Any number of repeats (taps) can be generated.

Ergodic mathematical formulas, provided by Gerzon [1992], generate an incrementing set of numbers. These numbers are used for the times of each delay tap. The resulting early reflection pattern is somewhat uniformly distributed, but not to the extent that the interval between each reflection is equal. See *Figure 5.2* again for an illustration of this somewhat-uniform temporal distribution of early reflections. As is the case in real rooms, the number of early reflections occurring increases with time. The generated early reflection times undergo a transformation that increases the early reflection density per unit time. For details on these Ergodic and transformation techniques, see [Gerzon, 1992: p15].

The amplitude of each early reflection (delay tap) depends on its delay time. The later a reflection arrives, the lower its amplitude will be. For more realistic results, Gerzon also suggests taking into account the attenuating (absorbing) properties of room surfaces and air. He provides a method that simulates the uniform frequency attenuation of a reflection at a boundary. From the formula below it can be seen that as the early reflection delay time ($\boldsymbol{T}$) increases, the absorption factor ($\boldsymbol{rT}$)

increases, and the overall early reflection gain ($\boldsymbol{g}$) decreases. This equation is applied to each individual early reflection (delay tap). The speed of sound is represented by $\boldsymbol{c}$ and the initial sound source distance by $\boldsymbol{d}$.

$$\boldsymbol{g} = (\exp(-\boldsymbol{rT})) / (1 + \boldsymbol{cT} / \boldsymbol{d})$$

This model of absorption is an oversimplification, as sound is not usually attenuated uniformly when it meets a boundary. Often, the higher frequencies of the reflecting sound are attenuated more severely than the middle or lower frequencies of the sound. However, when a sound undergoes many reflections, it approaches uniform attenuation. Gerzon's method is a "mathematically simple way of incorporating something approximating a realistic absorption situation" [Gerzon, 1992].

To reduce chances of excessive sound source coloration, each early reflection is uniquely positioned on the stereo stage. Directional diversity of early reflections reduces the chance of comb-filtering and adds a pleasant quality of spaciousness to the sound. The early reflections are also positioned evenly across the stereo stage so there is no tendency towards one side of the stereo image. This particular early reflection simulator design has a very even spatial distribution. It can be said that the sound presented results in a low binaural dissimilarity, i.e. that the sound presented to both ears is quite similar. Binaural dissimilarity is measured with a value termed as *Interaural Cross Correlation* (IACC). This early reflection simulator presents a sound that would have a very high IACC because of the very evenly spaced early reflections. As a result, the sense of spaciousness is not that strong.

Constant power amplitude panning was used to position each early reflection. This form of amplitude panning refers to that which does not alter the perceived loudness of the sound as it changes horizontal position. With standard *linear* amplitude panning (as explained in chapter 2), a sound's loudness will change as it moves from one horizontal position to another. With linear panning, a sound's loudness will be higher in the centre of the stereo image than its loudness when panned hard-left or hard-right. This is due to both speakers outputting the signal. The presented signals sum at the listener's head and loudness is increased. Constant power panning compensates for this increase in loudness by attenuating the sound if its horizontal position is centred. For every early reflection to comply with the Craven

Hypothesis regardless of horizontal position, constant power panning must be employed.

The technique Gerzon provides for the design of an early reflection simulator does not replicate real room conditions. For a distance illusion, simulating real room conditions may not be the most effective approach. As discussed in chapter 2, if interference between two reflections occurs and the reflection amplitude changes by more than 1dB, a distance cue will not be provided. By departing from a real room simulation, early reflection overlap can be avoided. The Ergodic techniques previously mentioned ensure the early reflections are sufficiently spaced in time so as not to overlap. Also, in a real room, reflection density increases rapidly over time. By reducing the rate at which reflection density growth occurs, the chance of early reflection overlap is reduced.

5.4 CSound.

CSound is a text based digital audio workstation in which users can code virtual instruments and effects. It is a computer programming language designed specifically for audio synthesis. CSound was used to build the distance pan-pot software. The distance pan-pot software code is printed in *Appendix A* of this thesis. The code mirrors the mathematical formulas of Gerzon's distance pan-pot paper. Labels in the code (e.g. ***;(12a)***) refer to the formulas of Gerzon's AES paper.

0.0

Volume 1.2

Width 1.0

ER No. 20

/Volumes/Nifty Drive/Trinity College/Term 3 (Trinity - Thesis)/

Figure 5.3: CSound GUI

Aside from a large distance control, the software allows for manipulation of the output volume, the early reflection stereo width, and number of early reflections sounding. The stereo width control makes use of constant power panning to reposition the early reflections. As the control is reduced, all the uniquely positioned early reflections converge towards the centre of the stereo image. There is also a method for loading user audio files, and a facility for rendering processed audio files to disk. A screen grab of the distance pan-pot graphic user interface is shown in *Figure 5.3*. The software designed was not intended for commercial release, but rather as a tool to process audio files for the collection of data.

CSound comes equipped with a plethora of objects known as *Opcodes*. Opcodes are pre-compiled chunks of computer code that perform various tasks. Opcodes give CSound its power. Implementation of very complex processes is made simple through the use of Opcodes. For example, implementing constant power panning with a more basic coding language would have been a heavily involved process. The *pan2* Opcode makes difficult panning implementations easily achievable.

The *Global Variables* portion of the code (*Appendix A*) is worth noting. The *Global Variables* section holds the changeable values for the subjective tailoring of the early reflection simulator. The amount of uniform absorption is set with the ***gir*** coefficient. Early reflection density per unit time is changed with the ***gip*** coefficient. The Ergodic techniques for early reflection delay time generation can be manipulated with the ***gik*** and ***gix0*** coefficients. Commented next to all of these global variables are other values the author found to be timbrally pleasing and effective in implementing the distance illusion.

The submitted code makes use of arrays. An array is a tool that allows software programmers to organize large amounts of programming objects, such as numbers or strings. Arrays have only recently been added to the CSound programming language, so CSound version 6 (or later) must be used to compile the code.

5.5 Chapter Conclusion.

This chapter explains the distance algorithm. It provides a description of the distance pan-pot implementation. The software development process was only achievable because of CSound. The author would not have successfully implemented the distance algorithm and early reflection simulator were it not for powerful Opcodes.

6. Research Findings and Discussion

6.1 Chapter Introduction.

This chapter presents the research findings. The findings are presented in sections. Each section addresses a specific research question, as stated in chapter 3. After the findings are presented, a discussion of the results is made.

6.2.1 Section 1 (Question 1).

Can the distance pan-pot successfully create a distance illusion? Indisputable survey results prove the distance pan-pot can successfully create a distance illusion. *Table 1* below illustrates this.

Click_01.wav	Click_08.wav	No Change in Perceived Distance
2	28	0

Organ_03.wav	Organ_08.wav	No Change in Perceived Distance
0	13	0

Speech_03.wav	Speech_10.wav	No Change in Perceived Distance
0	25	0

Table 1: Data for Answering Research Question 1

To understand the above table, the names of the compared samples must first be explained. *Click_01.wav* refers to the click sound processed with the distance control at value 1 (its minimum position) i.e. the click sample was lightly processed. *Click_08.wav* refers to the click sound that was processed with the distance control at value 8 i.e. it was heavily processed. *Click_01.wav* was compared to *Click_08.wav.* 28 listeners found *Click_08.wav* to be more distant than *Click_01.wav.*

Almost every listener found the more heavily processed samples to be the more distant sounding samples. An increase of the distance control resulted in an increased perceived distance. The further the distance control was turned, the farther the perceived sound source would migrate.

The previous table (*Table 1*) presents the results of paired samples that differed *significantly* in processing extent. Some of the survey questions compared samples that differed only *slightly* in processing extent. The results are less compelling, but still favour the distance pan-pot's ability.

6.2.2 Section 2 (Question 2).

Does a change in the number of early reflections generated cause a change in perceived distance? This research suggests that perceived distance *is* affected by the number of early reflections generated during a distance effect. For speech sound, more early reflections produced a greater perceived distance. For the other synthesized sounds, fewer reflections produced a greater perceived distance.

Table 2 illustrates these findings. In this table, *ER no.* refers to *early reflection number*. For these investigations, the distance pan-pot control was positioned at value 7. Both the direct and indirect signal is easily heard when the distance control is at this position.

Click_07.wav ER no: 5	Click_07.wav ER no: 30	No Change in Perceived Distance
24	4	1

Organ_07.wav ER no: 5	Organ_07.wav ER no: 30	No Change in Perceived Distance
8	2	3

Speech_07.wav ER no: 5	Speech_07.wav ER no: 30	No Change in Perceived Distance
4	17	3

Table 2: Data for Answering Research Question 2

6.2.3 Section 3 (Question 3).

What is the minimum number of early reflections needed for a distance effect? For speech sound, 3 early reflections are a sufficient amount for the creation of a distance illusion. Listeners heard a difference in distance between the wet and dry samples when the wet speech sample was processed with 3 or more early reflections.

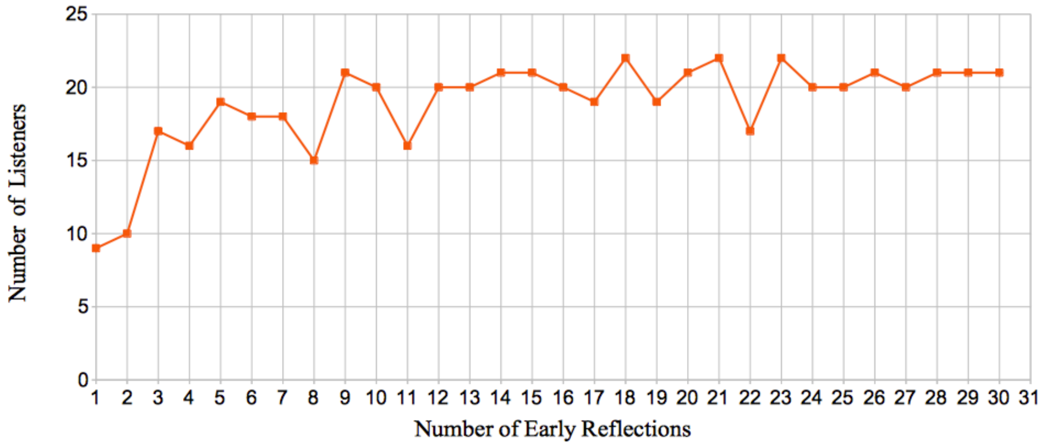

Figure 6.1: 3 Early Reflections for Speech Distance

Figure 6.1 illustrates how the amount of listeners perceiving the wet sample as the more distant sample rapidly increased when 3 early reflections were generated.

This was only the case for the speech sample. The other synthesized samples demonstrated different trends. Most listeners found the dry click sample to be more distant than the wet click sample, regardless of early reflection number. The organ sound's data did not provide for an interpretation of any conclusive results. The data collected did not favour any of the options available to the survey participants.

6.2.4 Section 4 (Question 4).

Does a change in the early reflection stereo width cause a change in perceived sound source distance? Data from the survey shows that perceived distance is *not* affected by early reflection stereo width. There is no change in perceived distance as the spatial distribution of early reflections changes. A mono effect produces the same perceived distance as a stereo effect. The following table (*Table 3*) illustrates this.

Click_00.wav Mono	Click_05.wav Stereo	No Change in Perceived Distance
2	1	24

Organ_00.wav Mono	Organ_05.wav Stereo	No Change in Perceived Distance
1	0	11

Speech_00.wav Mono	Speech_05.wav Stereo	No Change in Perceived Distance
5	2	18

Table 3: Data for Answering Research Question 4

Samples that contained uniquely positioned early reflections (stereo) were compared to samples in which all reflections arrived from the stereo-centre (mono). Most listeners could not hear a difference in distance between these samples. This was also true for compared samples that differed only slightly in stereo width.

6.3 Summary of Findings.

1. The distance pan-pot *can* successfully create a distance illusion. For samples that differed significantly in processing extent, a difference in distance was easily heard. For samples that differed only slightly in processing extent, a difference in distance was more difficultly heard, but the results still favoured the pan-pot's ability. These findings were true for all source samples tested.
2. Perceived distance *is* affected by the number of early reflections generated. For the speech sample, *more* reflections provided a greater perceived distance. For the synthesized click and organ samples, *fewer* reflections provided a greater perceived distance.
3. For speech sound, 3 early reflections were sufficient in producing a distance effect. Dry click samples were consistently perceived as more distant than the wet click samples. No findings could be drawn from the organ sample's data.
4. Changes in early reflection spatial distribution does not affect perceived distance. This was consistently shown to be the case for all source samples tested.

6.4 Discussion.

Undeniable results from the survey show that the distance pan-pot can successfully create a distance illusion. These results can only support the Craven Hypothesis, they cannot validate it. Even though the distance pan-pot adheres to the Craven Hypothesis, it quite possible that the distance illusion created results because of the direct signal level attenuation (a distance gain loss cue). This direct signal level attenuation also occurs in the presence of a reflection signal, which would provide a D/R ratio cue. The Craven Hypothesis is supported by the distance pan-pot's ability in the creation of a distance illusion, but the hypothesis is not validated by this ability.

The results from section 2 *suggest* that for natural familiar sounds, more reflections produce a greater perceived distance. For synthesized unfamiliar sounds, fewer reflections produce a greater perceived distance. Before the survey conduction process, the author was aware that different source sounds yielded different effects from the distance pan-pot. However, such dramatic differences in results were not expected.

It would be bold to explicitly declare from this research alone, that for a greater perceived distance, natural sounds require more early reflections, and unnatural sounds require fewer early reflections. However, it is not bold to state that a change in early reflection number received by a listener *will* affect perceived sound source distance. It is also fair to proclaim that an increase in early reflection number may not always lead to an increase in perceived distance.

Section 3 of the findings showed that for speech sound, 3 early reflections are sufficient in number for a distance effect. In some cases, 1 reflection was enough to create a perceived distance greater than the dry sound. The author also found 1 reflection to be sufficient for a distance illusion. These findings are reinforced by James A. Moorer, Facebook, and Two Big Ears who all, as discussed in chapter 4, make use of just 5 early reflections for distance illusions.

The natural familiar speech sample was the only source sound that demonstrated these results. As discussed in chapter 2, changes in sound source level can be used for distance deduction if the source is *familiar* to the listener. Coleman [1962] stated that sound source *familiarity* is also required for effective use of the high frequency attenuation distance cue. It may be the case that sound source familiarity is important to the deduction of distance with early reflections.

According to section 4 of the findings, differences in early reflection spatial distribution do not affect the perceived sound source distance. These results are supported by the fact that older monophonic recordings, where all sound arrives at the listener from one position, can demonstrate strong impressions of distance.

The early reflection simulator was designed with very evenly spatially distributed reflections so there would be no tendency towards one side of the stereo image. As a result, the impression of spaciousness is more subtle than one might expect. If a more uneven distribution of early reflections was employed, changes in early reflection stereo width would be more noticeable. Perhaps differences in distance would arise if a more spacious distribution of early reflections was provided.

There were no significant differences in data trends between listeners using speakers, listeners using headphones, or between listeners from different geographical locations. The same was true for expert and non-expert listeners. See *Appendix B* for a more detailed look at the survey results. These results can also be found in a spreadsheet on the CD-ROM submitted with this thesis.

Chapter 7 Conclusion

7.1 Conclusion.

This research contributes to the knowledge of distance hearing. It furthers the understanding of auditory distance perception, particularly in relation to early reflections. With a better understanding of human distance hearing, more effective illusory distance software can be designed.

7.2 Evaluation of the Research Approach.

The author's approach to the research was focused and methodical. The software was designed precisely to Michael Gerzon's specifications, and online surveys were conducted in a manner that minimised the potential compromise of the data collected.

An interpretation of the data was made with the help of an experienced data analyst. Although statistical procedures were not employed when the data was interpreted, it was thought that such procedures would not alter the outcome of the findings. Also given the timeframe, the attempt at data analysis would have been rushed. Such an attempt would not have validated the research. However, the survey results would still benefit from proper statistical analysis so inference and conclusions can more safely extend from the sample to the population. A more comprehensive review of the data would further validate the findings of this research.

7.3 Recommended Further Research.

There is a drought in the amount of research that explores the effect of early reflection fine structure alteration on distance perception. In particular, the author would like to see research that investigates how spaciousness affects perceived distance. The results of this research indicate that the spatial distribution of early reflections is not important to distance perception. However, the early reflection pattern used was very evenly distributed across the stereo stage. The early reflection pattern used was of a high IACC value. It might be the case that a change in the spatial distribution of a more spacious early reflection pattern causes a change in the perceived distance.

The author also recommends further research examining the impact of early reflection number on perceived distance be carried out. This research found that the data changed dramatically with the source sound (see Chapter 6, question 2). Such investigations are worth conducting again, perhaps in a controlled listening environment to see if such dramatic trends in collected data are repeated. This research can only *suggest* that natural familiar sounds are perceived as more distant with more early reflections sounding, while unnatural unfamiliar sounds are perceived as more distant with fewer early reflections sounding.

Although somewhat unrelated to this research, the author noticed the need for further investigation into the affect of changes in angular sound source size on perceived distance. Michael Gerzon [1992] briefly states that angular size can be used to discern the relative distance of a sound source. However, Gerzon does not formally reference this information, and the author when conducting background research could not find any related research on the subject.

Bibliography

Alexander, R. C., “Beyond Psychoacoustics”, Dora Media Productions, pp. 427-439, 2008

Allen, J. and Berkley, D., “Image Method for Efficiently Simulating Small Room Acoustics”, The Journal of the Acoustical Society of America, Vol. 65, pp. 943-950, 1979

Ashmead et al, “Contribution of listeners' approaching motion to auditory distance perception”, Journal of Experimental Psychology - Human Perception and Performance, Vol. 21, p239-256, 1995

Begault, D., “3-D Sound for Virtual Reality and Multimedia”, Academic Press Professional, pp. 53-56, 2000

Blauert, J., “Spatial Hearing: The Psychophysics of Human Sound Localization”, MIT Press, pp. 93-137, 1983

Blumlein, A., “Improvements in and relating to Sound-transmission, Sound-recording and Sound-reproducing Systems”, Patent Specification 394325, pp. 1-22, 1933

Bronkhorst, A., “Modelling Auditory Distance Perception in Rooms”, TNO Human Factors, 2002

Brungart, D. and Rabinowitz, W., “Auditory localization of nearby sources. Head-related transfer functions”, The Journal of the Acoustical Society of America. Vol. 106, pp. 1465-1579, 1999

Coleman, P., “Failure to Localize the Source Distance of an Unfamiliar Sound”, The Journal of the Acoustical Society of America. Vol. 34, pp. 345-346, 1962

Everest, A., “Master Handbook of Acoustics”, McGraw Hill Education, p1-62, 2015

Gerzon, M., “Recording Techniques for Multichannel Stereo”, British Kinematography Sound and Television, pp. 274-279, 1971

Gerzon, M., “The Design of Distance Pan-pots”, Audio Engineering Society, pp. 1-33, 1992

Haas, H., “The Influence of a Single Echo on the Audibility of Speech”, JAES, Vol. 20, pp. 146-159, 1972

Handel, S., “Listening”, MIT Press, pp. 99-108, 1989

Hirsh, I., “Masking of Speech and Auditory Localization”, Audiology, Vol. 10, pp. 110-114, 1971

Kearney *et al.*, “Distance Perception in Interactive Virtual Acoustic Environments using First and Higher Order Ambisonic Sound Fields”, Acta Acustica united with Acustica, Vol. 98, pp. 61-71, 2012

Mershon, D. and Bowers, J. “Absolute and relative cues for the auditory perception of egocentric distance”, Perception, Vol. 8, pp. 311-322, 1979

Mershon, D. and King, L., “Intensity and reverberation as factors in the auditory perception of egocentric distance”, Perception & Psychophysics, Vol. 18, pp. 409-415, 1975

Michelsen, J. and Rubak, P., “Parameters of Distance Perception in Stereo Loudspeaker Scenario”, DSP Research Group Aalborg University, pp. 1-14, 1997

Mullins, E., “Statistics for the Quality Control Chemistry Laboratory”, Royal Society of Chemistry, pp.87-95, 2003

Oh, J. and Wang, G., “Evaluating Crowdsourcing through Amazon Mechanical Turk as a Technique for Conducting Music Perception Experiments”, Center for Computer Research in Music and Acoustics. Vol. 1, pp. 1-62, 2012

Schoenherr, E., “Stereo”, 2001, Available: http://www.aes.org/aeshc/docs/recording.technology.history/stereo.html. Last accessed 12th Sep 2016

Steinberg, J., and Snow, W., “Auditory Perspective - Physical Factors”, Symposium on Auditory Perspective, Vol., pp. 12-16, 1933

White, P., “Creating A Sense Of Depth In Your Mix”, 2009, Available: http://www.soundonsound.com/techniques/creating-sense-depth-your-mix. Last accessed 12th Sep 2016

Zahorik, P., “Assessing auditory distance perception using virtual acoustics”, Acoustical Society of America, Vol. 111, pp. 183-1846, 2002

Figure References

Bech, S., 2006, *Psychological Acoustics, Psychoacoustics and Perception*, digital image, Available:
http://www.tonmeister.ca/main/textbook/intro_to_sound_recordingch6.html
Last accessed 12th Sep 2016

Broadbridge, 2015, *What are the cones of confusion?*, digital image, Available:
https://www.studyblue.com/notes/note/n/chapter-10-11-perception/deck/15888571
Last accessed 12th Sep 2016

Clip Art, 2016, *Processing Stereo Audio Files*, digital image, Available:
http://www.clipartbest.com/clipart-yTk79ExTE
Last accessed 12th Sep 2016

Gerzon, M., “The Design of Distance Pan-pots”, Audio Engineering Society, pp. 1-33, 1992

Lipshitz, S. P., “Stereo Microphone Techniques…Are the Purists Wrong?”, Audio Engineering Society, Vol. 34, pp. 716-744, 1986 [Note: These figures are not actually from the referenced Lipshitz paper, but based on information found in this paper. The actual original source of the figures is unknown.]

Thompson, 2007, *Sound Localization and the Auditory Scene*, Thompson Higher Education, digital image, Available:
http://courses.washington.edu/psy333/lecture_pdfs/Week9_Day2.pdf
Last accessed 12th Sep 2016

Oculus VR, LLC., 2016, *Introduction to Virtual Reality Audio*, digital image, Available:
https://developer3.oculus.com/documentation/audiosdk/latest/concepts/book-audio-intro/
Last accessed 12th Sep 2016

Ottewill, M., 1999, *Reverberation Devices and Methods*, digital image, Available:
http://www.planetoftunes.com/sound-recording/reverb.html#.V7x9GWViCV5
Last accessed 12th Sep 2016

Steinberg, J., and Snow, W., “Auditory Perspective - Physical Factors”, Symposium on Auditory Perspective, Vol., pp. 12-16, 1933

Tyrrell, E., “The Distance Pan-pot: An Alternative Approach to the Distance Effect”, Trinity College Dublin, pp. 1-70, 2016

Appendix A – CSound Code

```
<CsoundSynthesizer>
<CsOptions>
</CsOptions>
<CsInstruments>
;=========================================================================;
;=============================== Header ==================================;
;=========================================================================;
sr = 44100                                                                ;
ksmps = 4                                                                 ;
nchnls = 2                                                                ;
0dbfs = 1.0                                                               ;
;=========================================================================;
;========================== Global Variables =============================;
;=========================================================================;
giD = 1                                                                   ;
gic = 340                                                                 ;
gir = 0.93                   ;0.99       ;0.80                            ;
gik = 0.61803                ;0.70711  ;0.57735  ;0.60653  ;0.91287  ;0.61803 ;
gix0 = 0.5                   ;0.1       ;  0.6        ;0.5                ;
gip = 1                      ;0.5                                         ;
giTimeScaler = 0.1           ;0.09                                        ;
gkMaxPreDelayTime init 0                                                  ;
;=========================================================================;
;========================= Score Length Setup ============================;
;=========================================================================;
instr 1                                                                   ;
gSAudioFile invalue "_Browse1"                                            ;
iDuration filelen gSAudioFile                                             ;
event_i "i", 100, 0, iDuration+1                                          ;
event_i "i", 200, 0, iDuration+1                                          ;
event_i "i", 300, 0, iDuration+1                                          ;
turnoff                                                                   ;
endin                                                                     ;
;=========================================================================;
;========================= Direct Signal Path ============================;
;=========================================================================;
instr 100                                                                 ;
gkPotValue invalue "Panpot"                                               ;
kPotValueScaled1 scale gkPotValue, 7, giD                                 ;
kDelta = kPotValueScaled1 - giD                                           ;
kDirectDelayTime = kDelta / gic                                  ;(12a)   ;
kDirectDelayTimeLmt limit kDirectDelayTime, 0, gkMaxPreDelayTime          ;
kDirectDelayTimeLmtSmooth port kDirectDelayTimeLmt, 0.01                  ;
aDirectDelayTimeLmtSmooth upsamp kDirectDelayTimeLmtSmooth                ;
printk2 kDirectDelayTimeLmt                                               ;
                                                                          ;
aDirectSignal diskin gSAudioFile                                          ;
gaDirectToERSimulator = aDirectSignal                                     ;
                                                                          ;
aDirectSignalDelayed vdelayx aDirectSignal, aDirectDelayTimeLmtSmooth, 1, 128 ;
                                                                          ;
gkDeltaLmt = kDirectDelayTimeLmt*gic                                      ;
                                                                          ;
gaDirectToMasterBus = \                                                   ;
aDirectSignalDelayed*(giD / (giD+gkDeltaLmt))*exp(-gir*gkDeltaLmt/gic)  ;(12b) ;
endin                                                                     ;
;=========================================================================;
;=========================================================================;
;=========================================================================;
```

```
;==================================================================================================;
;================================= Early Reflection Simulator =====================================;
;==================================================================================================;
instr 200                                                                                          ;
                                                                                                   ;
iY0 = (gix0 + (0*gik)) % 1                                                              ;(19)      ;
iY1 = (gix0 + (1*gik)) % 1                                                                         ;
iY2 = (gix0 + (2*gik)) % 1                                                                         ;
iY3 = (gix0 + (3*gik)) % 1                                                                         ;
iY4 = (gix0 + (4*gik)) % 1                                                                         ;
iY5 = (gix0 + (5*gik)) % 1                                                                         ;
iY6 = (gix0 + (6*gik)) % 1                                                                         ;
iY7 = (gix0 + (7*gik)) % 1                                                                         ;
iY8 = (gix0 + (8*gik)) % 1                                                                         ;
iY9 = (gix0 + (9*gik)) % 1                                                                         ;
iY10 = (gix0 + (10*gik)) % 1                                                                       ;
iY11 = (gix0 + (11*gik)) % 1                                                                       ;
iY12 = (gix0 + (12*gik)) % 1                                                                       ;
iY13 = (gix0 + (13*gik)) % 1                                                                       ;
iY14 = (gix0 + (14*gik)) % 1                                                                       ;
iY15 = (gix0 + (15*gik)) % 1                                                                       ;
iY16 = (gix0 + (16*gik)) % 1                                                                       ;
iY17 = (gix0 + (17*gik)) % 1                                                                       ;
iY18 = (gix0 + (18*gik)) % 1                                                                       ;
iY19 = (gix0 + (19*gik)) % 1                                                                       ;
iY20 = (gix0 + (20*gik)) % 1                                                                       ;
iY21 = (gix0 + (21*gik)) % 1                                                                       ;
iY22 = (gix0 + (22*gik)) % 1                                                                       ;
iY23 = (gix0 + (23*gik)) % 1                                                                       ;
iY24 = (gix0 + (24*gik)) % 1                                                                       ;
iY25 = (gix0 + (25*gik)) % 1                                                                       ;
iY26 = (gix0 + (26*gik)) % 1                                                                       ;
iY27 = (gix0 + (27*gik)) % 1                                                                       ;
iY28 = (gix0 + (28*gik)) % 1                                                                       ;
iY29 = (gix0 + (29*gik)) % 1                                                                       ;
                                                                                                   ;
iArray1[] fillarray iY0, iY1, iY2, iY3, iY4, iY5, iY6, iY7, iY8, iY9, iY10, iY11, iY12, \          ;
iY13, iY14 ,iY15, iY16, iY17, iY18, iY19, iY20, iY21, iY22, iY23, iY24, iY25, iY26, iY27, \        ;
iY28, iY29                                                                                         ;
iTmin minarray iArray1                                                                             ;
iTmax maxarray iArray1                                                                             ;
                                                                                                   ;
ib = iTmin^(1+gip)                                                                      ;(20b)     ;
ia = ((iTmax + iTmin)^(1+gip)) - ib                                                     ;(20c)     ;
                                                                                                   ;
iTimeTap0 pow ((ia*iY0) + ib), 1 / (1+gip)                                              ;(20a)     ;
iTimeTap1 pow ((ia*iY1) + ib), 1 / (1+gip)                                                         ;
iTimeTap2 pow ((ia*iY2) + ib), 1 / (1+gip)                                                         ;
iTimeTap3 pow ((ia*iY3) + ib), 1 / (1+gip)                                                         ;
iTimeTap4 pow ((ia*iY4) + ib), 1 / (1+gip)                                                         ;
iTimeTap5 pow ((ia*iY5) + ib), 1 / (1+gip)                                                         ;
iTimeTap6 pow ((ia*iY6) + ib), 1 / (1+gip)                                                         ;
iTimeTap7 pow ((ia*iY7) + ib), 1 / (1+gip)                                                         ;
iTimeTap8 pow ((ia*iY8) + ib), 1 / (1+gip)                                                         ;
iTimeTap9 pow ((ia*iY9) + ib), 1 / (1+gip)                                                         ;
iTimeTap10 pow ((ia*iY10) + ib), 1 / (1+gip)                                                       ;
iTimeTap11 pow ((ia*iY11) + ib), 1 / (1+gip)                                                       ;
iTimeTap12 pow ((ia*iY12) + ib), 1 / (1+gip)                                                       ;
iTimeTap13 pow ((ia*iY13) + ib), 1 / (1+gip)                                                       ;
iTimeTap14 pow ((ia*iY14) + ib), 1 / (1+gip)                                                       ;
```

```
iTimeTap15 pow ((ia*iY15) + ib), 1 / (1+gip)                                              ;
iTimeTap16 pow ((ia*iY16) + ib), 1 / (1+gip)                                              ;
iTimeTap17 pow ((ia*iY17) + ib), 1 / (1+gip)                                              ;
iTimeTap18 pow ((ia*iY18) + ib), 1 / (1+gip)                                              ;
iTimeTap19 pow ((ia*iY19) + ib), 1 / (1+gip)                                              ;
iTimeTap20 pow ((ia*iY20) + ib), 1 / (1+gip)                                              ;
iTimeTap21 pow ((ia*iY21) + ib), 1 / (1+gip)                                              ;
iTimeTap22 pow ((ia*iY22) + ib), 1 / (1+gip)                                              ;
iTimeTap23 pow ((ia*iY23) + ib), 1 / (1+gip)                                              ;
iTimeTap24 pow ((ia*iY24) + ib), 1 / (1+gip)                                              ;
iTimeTap25 pow ((ia*iY25) + ib), 1 / (1+gip)                                              ;
iTimeTap26 pow ((ia*iY26) + ib), 1 / (1+gip)                                              ;
iTimeTap27 pow ((ia*iY27) + ib), 1 / (1+gip)                                              ;
iTimeTap28 pow ((ia*iY28) + ib), 1 / (1+gip)                                              ;
iTimeTap29 pow ((ia*iY29) + ib), 1 / (1+gip)                                              ;
                                                                                          ;
kArray2[] fillarray iTimeTap0, iTimeTap1, iTimeTap2, iTimeTap3, iTimeTap4, iTimeTap5, \   ;
iTimeTap6, iTimeTap7, iTimeTap8, iTimeTap9,iTimeTap10, iTimeTap11, iTimeTap12, \          ;
iTimeTap13, iTimeTap14, iTimeTap15, iTimeTap16, iTimeTap17, iTimeTap18, iTimeTap19, \     ;
iTimeTap20, iTimeTap21, iTimeTap22, iTimeTap23, iTimeTap24, iTimeTap25, iTimeTap26, \     ;
iTimeTap27, iTimeTap28, iTimeTap29                                                        ;
                                                                                          ;
kTemp init 0                                                                              ;
kIndxj = 0                                                                                ;
                                                                                          ;
loop1:                                                                                    ;
        if (kArray2[kIndxj+1] < kArray2[kIndxj]) then                                     ;
        kTemp = kArray2[kIndxj]                                                           ;
        kArray2[kIndxj] = kArray2[kIndxj+1]                                               ;
        kArray2[kIndxj+1] = kTemp                                                         ;
        endif                                                                             ;
loop_lt kIndxj, 1, 29, loop1                                                              ;
                                                                                          ;
kTimeTap0 = kArray2[0]*giTimeScaler                                                       ;
kTimeTap1 = kArray2[1]*giTimeScaler                                                       ;
kTimeTap2 = kArray2[2]*giTimeScaler                                                       ;
kTimeTap3 = kArray2[3]*giTimeScaler                                                       ;
kTimeTap4 = kArray2[4]*giTimeScaler                                                       ;
kTimeTap5 = kArray2[5]*giTimeScaler                                                       ;
kTimeTap6 = kArray2[6]*giTimeScaler                                                       ;
kTimeTap7 = kArray2[7]*giTimeScaler                                                       ;
kTimeTap8 = kArray2[8]*giTimeScaler                                                       ;
kTimeTap9 = kArray2[9]*giTimeScaler                                                       ;
kTimeTap10 = kArray2[10]*giTimeScaler                                                     ;
kTimeTap11 = kArray2[11]*giTimeScaler                                                     ;
kTimeTap12 = kArray2[12]*giTimeScaler                                                     ;
kTimeTap13 = kArray2[13]*giTimeScaler                                                     ;
kTimeTap14 = kArray2[14]*giTimeScaler                                                     ;
kTimeTap15 = kArray2[15]*giTimeScaler                                                     ;
kTimeTap16 = kArray2[16]*giTimeScaler                                                     ;
kTimeTap17 = kArray2[17]*giTimeScaler                                                     ;
kTimeTap18 = kArray2[18]*giTimeScaler                                                     ;
kTimeTap19 = kArray2[19]*giTimeScaler                                                     ;
kTimeTap20 = kArray2[20]*giTimeScaler                                                     ;
kTimeTap21 = kArray2[21]*giTimeScaler                                                     ;
kTimeTap22 = kArray2[22]*giTimeScaler                                                     ;
kTimeTap23 = kArray2[23]*giTimeScaler                                                     ;
kTimeTap24 = kArray2[24]*giTimeScaler                                                     ;
kTimeTap25 = kArray2[25]*giTimeScaler                                                     ;
kTimeTap26 = kArray2[26]*giTimeScaler                                                     ;
```

```
kTimeTap27 = kArray2[27]*giTimeScaler                                          ;
kTimeTap28 = kArray2[28]*giTimeScaler                                          ;
kTimeTap29 = kArray2[29]*giTimeScaler                                          ;
                                                                               ;
if (kTimeTap0 <= 0.010) then                                                   ;
        gkMaxPreDelayTime = kTimeTap1 - 0.002                                  ;
        kGainTap0 = 0                                                          ;
else                                                                           ;
        gkMaxPreDelayTime = kTimeTap0 - 0.002                                  ;
        kGainTap0 = (exp(-gir*kTimeTap0)) / (1+(gic*kTimeTap0)/giD)            ;
endif                                                                          ;
                                                                               ;
kGainTap1 = (exp (-gir*kTimeTap1)) / (1+(gic*kTimeTap1)/giD)          ;(9)     ;
kGainTap2 = (exp (-gir*kTimeTap2)) / (1+(gic*kTimeTap2)/giD)                   ;
kGainTap3 = (exp (-gir*kTimeTap3)) / (1+(gic*kTimeTap3)/giD)                   ;
kGainTap4 = (exp (-gir*kTimeTap4)) / (1+(gic*kTimeTap4)/giD)                   ;
kGainTap5 = (exp (-gir*kTimeTap5)) / (1+(gic*kTimeTap5)/giD)                   ;
kGainTap6 = (exp (-gir*kTimeTap6)) / (1+(gic*kTimeTap6)/giD)                   ;
kGainTap7 = (exp (-gir*kTimeTap7)) / (1+(gic*kTimeTap7)/giD)                   ;
kGainTap8 = (exp (-gir*kTimeTap8)) / (1+(gic*kTimeTap8)/giD)                   ;
kGainTap9 = (exp (-gir*kTimeTap9)) / (1+(gic*kTimeTap9)/giD)                   ;
kGainTap10 = (exp (-gir*kTimeTap10)) / (1+(gic*kTimeTap10)/giD)                ;
kGainTap11 = (exp (-gir*kTimeTap11)) / (1+(gic*kTimeTap11)/giD)                ;
kGainTap12 = (exp (-gir*kTimeTap12)) / (1+(gic*kTimeTap12)/giD)                ;
kGainTap13 = (exp (-gir*kTimeTap13)) / (1+(gic*kTimeTap13)/giD)                ;
kGainTap14 = (exp (-gir*kTimeTap14)) / (1+(gic*kTimeTap14)/giD)                ;
kGainTap15 = (exp (-gir*kTimeTap15)) / (1+(gic*kTimeTap15)/giD)                ;
kGainTap16 = (exp (-gir*kTimeTap16)) / (1+(gic*kTimeTap16)/giD)                ;
kGainTap17 = (exp (-gir*kTimeTap17)) / (1+(gic*kTimeTap17)/giD)                ;
kGainTap18 = (exp (-gir*kTimeTap18)) / (1+(gic*kTimeTap18)/giD)                ;
kGainTap19 = (exp (-gir*kTimeTap19)) / (1+(gic*kTimeTap19)/giD)                ;
kGainTap20 = (exp (-gir*kTimeTap20)) / (1+(gic*kTimeTap20)/giD)                ;
kGainTap21 = (exp (-gir*kTimeTap21)) / (1+(gic*kTimeTap21)/giD)                ;
kGainTap22 = (exp (-gir*kTimeTap22)) / (1+(gic*kTimeTap22)/giD)                ;
kGainTap23 = (exp (-gir*kTimeTap23)) / (1+(gic*kTimeTap23)/giD)                ;
kGainTap24 = (exp (-gir*kTimeTap24)) / (1+(gic*kTimeTap24)/giD)                ;
kGainTap25 = (exp (-gir*kTimeTap25)) / (1+(gic*kTimeTap25)/giD)                ;
kGainTap26 = (exp (-gir*kTimeTap26)) / (1+(gic*kTimeTap26)/giD)                ;
kGainTap27 = (exp (-gir*kTimeTap27)) / (1+(gic*kTimeTap27)/giD)                ;
kGainTap28 = (exp (-gir*kTimeTap28)) / (1+(gic*kTimeTap28)/giD)                ;
kGainTap29 = (exp (-gir*kTimeTap29)) / (1+(gic*kTimeTap29)/giD)                ;
                                                                               ;
aDump delayr 2                                                                 ;
aTap0 deltapi kTimeTap0                                                        ;
aTap1 deltapi kTimeTap1                                                        ;
aTap2 deltapi kTimeTap2                                                        ;
aTap3 deltapi kTimeTap3                                                        ;
aTap4 deltapi kTimeTap4                                                        ;
aTap5 deltapi kTimeTap5                                                        ;
aTap6 deltapi kTimeTap6                                                        ;
aTap7 deltapi kTimeTap7                                                        ;
aTap8 deltapi kTimeTap8                                                        ;
aTap9 deltapi kTimeTap9                                                        ;
aTap10 deltapi kTimeTap10                                                      ;
aTap11 deltapi kTimeTap11                                                      ;
aTap12 deltapi kTimeTap12                                                      ;
aTap13 deltapi kTimeTap13                                                      ;
aTap14 deltapi kTimeTap14                                                      ;
aTap15 deltapi kTimeTap15                                                      ;
aTap16 deltapi kTimeTap16                                                      ;
```

```
aTap17 deltapi kTimeTap17                                                     ;
aTap18 deltapi kTimeTap18                                                     ;
aTap19 deltapi kTimeTap19                                                     ;
aTap20 deltapi kTimeTap20                                                     ;
aTap21 deltapi kTimeTap21                                                     ;
aTap22 deltapi kTimeTap22                                                     ;
aTap23 deltapi kTimeTap23                                                     ;
aTap24 deltapi kTimeTap24                                                     ;
aTap25 deltapi kTimeTap25                                                     ;
aTap26 deltapi kTimeTap26                                                     ;
aTap27 deltapi kTimeTap27                                                     ;
aTap28 deltapi kTimeTap28                                                     ;
aTap29 deltapi kTimeTap29                                                     ;
delayw gaDirectToERSimulator                                                  ;
                                                                              ;
kERMenu invalue "ERMenu"                                                      ;
if (kERMenu == 0) then                                                        ;
            kERNumber = 5                                                     ;
elseif (kERMenu == 1) then                                                    ;
            kERNumber = 10                                                    ;
elseif (kERMenu == 2) then                                                    ;
            kERNumber = 15                                                    ;
elseif (kERMenu == 3) then                                                    ;
            kERNumber = 20                                                    ;
elseif (kERMenu == 4) then                                                    ;
            kERNumber = 25                                                    ;
elseif (kERMenu == 5) then                                                    ;
            kERNumber = 30                                                    ;
endif                                                                         ;
                                                                              ;
kWidth invalue "Width"                                                        ;
kERSpread port kWidth, 0.1                                                    ;
kERSpread0 scale kERSpread, 0.63333,      0.5                                 ;
kERSpread1 scale kERSpread, 0,            0.5                                 ;
kERSpread2 scale kERSpread, 0.13333,      0.5                                 ;
kERSpread3 scale kERSpread, 1.0,          0.5                                 ;
kERSpread4 scale kERSpread, 0.8,          0.5                                 ;
kERSpread5 scale kERSpread, 0.3,          0.5                                 ;
kERSpread6 scale kERSpread, 0.46667,      0.5                                 ;
kERSpread7 scale kERSpread, 0.9,          0.5                                 ;
kERSpread8 scale kERSpread, 0.2,          0.5                                 ;
kERSpread9 scale kERSpread, 0.73333,      0.5                                 ;
kERSpread10 scale kERSpread, 0.03333,     0.5                                 ;
kERSpread11 scale kERSpread, 0.96667,     0.5                                 ;
kERSpread12 scale kERSpread, 0.06667,     0.5                                 ;
kERSpread13 scale kERSpread, 0.93333,     0.5                                 ;
kERSpread14 scale kERSpread, 0.4,         0.5                                 ;
kERSpread15 scale kERSpread, 0.56667,     0.5                                 ;
kERSpread16 scale kERSpread, 0.16667,     0.5                                 ;
kERSpread17 scale kERSpread, 0.83333,     0.5                                 ;
kERSpread18 scale kERSpread, 0.36667,     0.5                                 ;
kERSpread19 scale kERSpread, 0.6,         0.5                                 ;
kERSpread20 scale kERSpread, 0.76667,     0.5                                 ;
kERSpread21 scale kERSpread, 0.1,         0.5                                 ;
kERSpread22 scale kERSpread, 0.7,         0.5                                 ;
kERSpread23 scale kERSpread, 0.23333,     0.5                                 ;
kERSpread24 scale kERSpread, 0.66667,     0.5                                 ;
kERSpread25 scale kERSpread, 0.26667,     0.5                                 ;
kERSpread26 scale kERSpread, 0.33333,     0.5                                 ;
kERSpread27 scale kERSpread, 0.86667,     0.5                                 ;
```

```
kERSpread28 scale kERSpread, 0.43333,     0.5                                   ;
kERSpread29 scale kERSpread, 0.53333,     0.5                                   ;
                                                                                ;
aER0L, aER0R pan2 aTap0*kGainTap0, kERSpread0,        0                         ;
aER1L, aER1R pan2 aTap1*kGainTap1, kERSpread1,        0                         ;
aER2L, aER2R pan2 aTap2*kGainTap2, kERSpread2,        0                         ;
aER3L, aER3R pan2 aTap3*kGainTap3, kERSpread3,        0                         ;
aER4L, aER4R pan2 aTap4*kGainTap4, kERSpread4,        0                         ;
aER5L, aER5R pan2 aTap5*kGainTap5, kERSpread5,        0                         ;
aER6L, aER6R pan2 aTap6*kGainTap6, kERSpread6,        0                         ;
aER7L, aER7R pan2 aTap7*kGainTap7, kERSpread7,        0                         ;
aER8L, aER8R pan2 aTap8*kGainTap8, kERSpread8,        0                         ;
aER9L, aER9R pan2 aTap9*kGainTap9, kERSpread9,        0                         ;
aER10L, aER10R pan2 aTap10*kGainTap10, kERSpread10,        0                    ;
aER11L, aER11R pan2 aTap11*kGainTap11, kERSpread11,        0                    ;
aER12L, aER12R pan2 aTap12*kGainTap12, kERSpread12,        0                    ;
aER13L, aER13R pan2 aTap13*kGainTap13, kERSpread13,        0                    ;
aER14L, aER14R pan2 aTap14*kGainTap14, kERSpread14,        0                    ;
aER15L, aER15R pan2 aTap15*kGainTap15, kERSpread15,        0                    ;
aER16L, aER16R pan2 aTap16*kGainTap16, kERSpread16,        0                    ;
aER17L, aER17R pan2 aTap17*kGainTap17, kERSpread17,        0                    ;
aER18L, aER18R pan2 aTap18*kGainTap18, kERSpread18,        0                    ;
aER19L, aER19R pan2 aTap19*kGainTap19, kERSpread19,        0                    ;
aER20L, aER20R pan2 aTap20*kGainTap20, kERSpread20,        0                    ;
aER21L, aER21R pan2 aTap21*kGainTap21, kERSpread21,        0                    ;
aER22L, aER22R pan2 aTap22*kGainTap22, kERSpread22,        0                    ;
aER23L, aER23R pan2 aTap23*kGainTap23, kERSpread23,        0                    ;
aER24L, aER24R pan2 aTap24*kGainTap24, kERSpread24,        0                    ;
aER25L, aER25R pan2 aTap25*kGainTap25, kERSpread25,        0                    ;
aER26L, aER26R pan2 aTap26*kGainTap26, kERSpread26,        0                    ;
aER27L, aER27R pan2 aTap27*kGainTap27, kERSpread27,        0                    ;
aER28L, aER28R pan2 aTap28*kGainTap28, kERSpread28,        0                    ;
aER29L, aER29R pan2 aTap29*kGainTap29, kERSpread29,        0                    ;
                                                                                ;
if (kERMenu == 0) then                                                          ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L                                ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R                                ;
                                                                                ;
elseif (kERMenu == 1) then                                                      ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L+aER5L+aER6L+aER7L \            ;
+aER8L+aER9L                                                                    ;
                                                                                ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R+aER5R+aER6R+aER7R \            ;
+aER8R+aER9R                                                                    ;
                                                                                ;
elseif (kERMenu == 2) then                                                      ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L+aER5L+aER6L+aER7L \            ;
+aER8L+aER9L+aER10L+aER11L+aER12L+aER13L+aER14L                                 ;
                                                                                ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R+aER5R+aER6R+aER7R \            ;
+aER8R+aER9R+aER10R+aER11R+aER12R+aER13R+aER14R                                 ;
                                                                                ;
elseif (kERMenu == 3) then                                                      ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L+aER5L+aER6L+aER7L \            ;
+aER8L+aER9L+aER10L+aER11L+aER12L+aER13L+aER14L+aER15L+aER16L \                 ;
+aER17L+aER18L+aER19L                                                           ;
                                                                                ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R+aER5R+aER6R+aER7R \            ;
+aER8R+aER9R+aER10R+aER11R+aER12R+aER13R+aER14R+aER15R+aER16R \                 ;
+aER17R+aER18R+aER19R                                                           ;
```

```
                                                                          ;
elseif (kERMenu == 4) then                                                ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L+aER5L+aER6L+aER7L \      ;
+aER8L+aER9L+aER10L+aER11L+aER12L+aER13L+aER14L+aER15L+aER16L \           ;
+aER17L+aER18L+aER19L+aER20L+aER21L+aER22L+aER23L+aER24L                  ;
                                                                          ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R+aER5R+aER6R+aER7R \      ;
+aER8R+aER9R+aER10R+aER11R+aER12R+aER13R+aER14R+aER15R+aER16R \           ;
+aER17R+aER18R+aER19R+aER20R+aER21R+aER22R+aER23R+aER24R                  ;
                                                                          ;
elseif (kERMenu == 5) then                                                ;
gaERToMasterBusL = aER0L+aER1L+aER2L+aER3L+aER4L+aER5L+aER6L+aER7L \      ;
+aER8L+aER9L+aER10L+aER11L+aER12L+aER13L+aER14L+aER15L+aER16L \           ;
+aER17L+aER18L+aER19L+aER20L+aER21L+aER22L+aER23L+aER24L+aER25L \         ;
+aER26L+aER27L+aER28L+aER29L                                              ;
                                                                          ;
gaERToMasterBusR = aER0R+aER1R+aER2R+aER3R+aER4R+aER5R+aER6R+aER7R \      ;
+aER8R+aER9R+aER10R+aER11R+aER12R+aER13R+aER14R+aER15R+aER16R \           ;
+aER17R+aER18R+aER19R+aER20R+aER21R+aER22R+aER23R+aER24R+aER25R \         ;
+aER26R+aER27R+aER28R+aER29R                                              ;
endif                                                                     ;
endin                                                                     ;
;=========================================================================;
;============================== Master Section ===========================;
;=========================================================================;
instr 300                                                                 ;
kVolume invalue "Volume"                                                  ;
kAutoGain invalue "AutoGain"                                              ;
kPotValueScaled2 scale gkPotValue, 6.6, 1                                 ;
                                                                          ;
aOutLeft = (gaDirectToMasterBus+gaERToMasterBusL)*kVolume                 ;
aOutRight = (gaDirectToMasterBus+gaERToMasterBusR)*kVolume                ;
                                                                          ;
outs aOutLeft, aOutRight                                                  ;
endin                                                                     ;
</CsInstruments>                                                          ;
;=========================================================================;
;================================== Score ================================;
;=========================================================================;
<CsScore>                                                                 ;
i1 0 1                                                                    ;
</CsScore>                                                                ;
</CsoundSynthesizer>                                                      ;
;=========================================================================;
;=========================================================================;
;=========================================================================;
```

Appendix B – Survey Results

Section 1 (Question 1): Click

Click_01.wav	Click_08.wav	No Change in Perceived Distance
2	28	0
Click_02.wav	Click_04.wav	No Change in Perceived Distance
1	23	6
Click_03.wav	Click_05.wav	No Change in Perceived Distance
4	15	12
Click_06.wav	Click_09.wav	No Change in Perceived Distance
4	15	11
Click_07.wav	Click_10.wav	No Change in Perceived Distance
0	16	13

Section 1 (Question 1): Organ

Organ_01.wav	Organ _02.wav	No Change in Perceived Distance
0	9	5
Organ _03.wav	Organ _08.wav	No Change in Perceived Distance
0	13	0
Organ _04.wav	Organ _09.wav	No Change in Perceived Distance
1	12	0
Organ _05.wav	Organ _06.wav	No Change in Perceived Distance
2	5	6
Organ _07.wav	Organ _10.wav	No Change in Perceived Distance
2	10	0

Section 1 (Question 1): Speech

Speech_01.wav	Speech _02.wav	No Change in Perceived Distance
0	11	14
Speech _03.wav	Speech _10.wav	No Change in Perceived Distance
0	25	0
Speech _04.wav	Speech _07.wav	No Change in Perceived Distance
0	14	7
Speech _05.wav	Speech _09.wav	No Change in Perceived Distance
1	18	6
Speech _06.wav	Speech _08.wav	No Change in Perceived Distance
3	4	18

Section 2 (Question 2): Click

Click_07.wav ER No: 5	Click_07.wav ER No: 10	No Change in Perceived Distance
13	5	12
Click_07.wav ER No: 5	Click_07.wav ER No: 15	No Change in Perceived Distance
22	1	6
Click_07.wav ER No: 5	Click_07.wav ER No: 20	No Change in Perceived Distance
16	6	7
Click_07.wav ER No: 5	Click_07.wav ER No: 25	No Change in Perceived Distance
22	4	3
Click_07.wav ER No: 5	Click_07.wav ER No: 30	No Change in Perceived Distance
24	4	2
Click_07.wav ER No: 10	Click_07.wav ER No: 15	No Change in Perceived Distance
15	6	8
Click_07.wav ER No: 10	Click_07.wav ER No: 20	No Change in Perceived Distance
14	7	8
Click_07.wav ER No: 10	Click_07.wav ER No: 25	No Change in Perceived Distance
13	3	11
Click_07.wav ER No: 10	Click_07.wav ER No: 30	No Change in Perceived Distance
15	2	10
Click_07.wav ER No: 15	Click_07.wav ER No: 20	No Change in Perceived Distance
5	7	17
Click_07.wav ER No: 15	Click_07.wav ER No: 25	No Change in Perceived Distance
9	4	15
Click_07.wav ER No: 15	Click_07.wav ER No: 30	No Change in Perceived Distance
9	4	16
Click_07.wav ER No: 20	Click_07.wav ER No: 25	No Change in Perceived Distance
5	4	19
Click_07.wav ER No: 20	Click_07.wav ER No: 30	No Change in Perceived Distance
9	3	16
Click_07.wav ER No: 25	Click_07.wav ER No: 30	No Change in Perceived Distance
2	4	20

Section 2 (Question 2): Organ

Organ_07.wav ER No: 5	Organ _07.wav ER No: 10	No Change in Perceived Distance
7	0	6
Organ _07.wav ER No: 5	Organ _07.wav ER No: 15	No Change in Perceived Distance
4	0	7
Organ _07.wav ER No: 5	Organ _07.wav ER No: 20	No Change in Perceived Distance
4	2	7
Organ _07.wav ER No: 5	Organ _07.wav ER No: 25	No Change in Perceived Distance
5	0	8
Organ _07.wav ER No: 5	Organ _07.wav ER No: 30	No Change in Perceived Distance
8	2	3
Organ _07.wav ER No: 10	Organ _07.wav ER No: 15	No Change in Perceived Distance
1	4	8
Organ _07.wav ER No: 10	Organ _07.wav ER No: 20	No Change in Perceived Distance
3	1	9
Organ _07.wav ER No: 10	Organ _07.wav ER No: 25	No Change in Perceived Distance
4	7	8
Organ _07.wav ER No: 10	Organ _07.wav ER No: 30	No Change in Perceived Distance
3	3	6
Organ _07.wav ER No: 15	Organ _07.wav ER No: 20	No Change in Perceived Distance
2	1	10
Organ _07.wav ER No: 15	Organ _07.wav ER No: 25	No Change in Perceived Distance
5	2	6
Organ _07.wav ER No: 15	Organ _07.wav ER No: 30	No Change in Perceived Distance
0	5	13
Organ _07.wav ER No: 20	Organ _07.wav ER No: 25	No Change in Perceived Distance
2	4	7
Organ _07.wav ER No: 20	Organ _07.wav ER No: 30	No Change in Perceived Distance
4	0	9
Organ _07.wav ER No: 25	Organ _07.wav ER No: 30	No Change in Perceived Distance
3	3	7

Section 2 (Question 2): Speech

Speech_07.wav ER No: 5	Speech _07.wav ER No: 10	No Change in Perceived Distance
2	4	19
Speech _07.wav ER No: 5	Speech _07.wav ER No: 15	No Change in Perceived Distance
4	5	16
Speech _07.wav ER No: 5	Speech _07.wav ER No: 20	No Change in Perceived Distance
4	19	1
Speech _07.wav ER No: 5	Speech _07.wav ER No: 25	No Change in Perceived Distance
4	21	1
Speech _07.wav ER No: 5	Speech _07.wav ER No: 30	No Change in Perceived Distance
4	17	4
Speech _07.wav ER No: 10	Speech _07.wav ER No: 15	No Change in Perceived Distance
2	1	22
Speech _07.wav ER No: 10	Speech _07.wav ER No: 20	No Change in Perceived Distance
2	11	12
Speech _07.wav ER No: 10	Speech _07.wav ER No: 25	No Change in Perceived Distance
5	10	10
Speech _07.wav ER No: 10	Speech _07.wav ER No: 30	No Change in Perceived Distance
3	15	7
Speech _07.wav ER No: 15	Speech _07.wav ER No: 20	No Change in Perceived Distance
3	7	15
Speech _07.wav ER No: 15	Speech _07.wav ER No: 25	No Change in Perceived Distance
1	9	15
Speech _07.wav ER No: 15	Speech _07.wav ER No: 30	No Change in Perceived Distance
2	9	14
Speech _07.wav ER No: 20	Speech _07.wav ER No: 25	No Change in Perceived Distance
2	5	18
Speech _07.wav ER No: 20	Speech _07.wav ER No: 30	No Change in Perceived Distance
3	9	13
Speech _07.wav ER No: 25	Speech _07.wav ER No: 30	No Change in Perceived Distance
2	3	20

Section 3 (Question 3): Click

Click_Dry.wav	Click_07.wav ER No: 1	No Change in Perceived Distance
11	2	15
Click_ Dry.wav	Click_07.wav ER No: 2	No Change in Perceived Distance
18	1	9
Click_ Dry.wav	Click_07.wav ER No: 3	No Change in Perceived Distance
17	1	9
Click_ Dry.wav	Click_07.wav ER No: 4	No Change in Perceived Distance
13	4	10
Click_ Dry.wav	Click_07.wav ER No: 5	No Change in Perceived Distance
19	5	4
Click_ Dry.wav	Click_07.wav ER No: 6	No Change in Perceived Distance
19	6	2
Click_ Dry.wav	Click_07.wav ER No: 7	No Change in Perceived Distance
21	6	1
Click_ Dry.wav	Click_07.wav ER No: 8	No Change in Perceived Distance
19	4	5
Click_ Dry.wav	Click_07.wav ER No: 9	No Change in Perceived Distance
21	5	2
Click_ Dry.wav	Click_07.wav ER No: 10	No Change in Perceived Distance
19	6	2
Click_ Dry.wav	Click_07.wav ER No: 11	No Change in Perceived Distance
19	5	2
Click_ Dry.wav	Click_07.wav ER No: 12	No Change in Perceived Distance
20	7	0
Click_ Dry.wav	Click_07.wav ER No: 13	No Change in Perceived Distance
20	7	1
Click_ Dry.wav	Click_07.wav ER No: 14	No Change in Perceived Distance
20	5	2
Click_ Dry.wav	Click_07.wav ER No: 15	No Change in Perceived Distance
21	4	2
Click_ Dry.wav	Click_07.wav ER No: 16	No Change in Perceived Distance
22	5	1
Click_ Dry.wav	Click_07.wav ER No: 17	No Change in Perceived Distance
19	6	3

Click_ Dry.wav	Click_07.wav ER No: 18	No Change in Perceived Distance
22	5	0
Click_ Dry.wav	Click_07.wav ER No: 19	No Change in Perceived Distance
21	2	4
Click_ Dry.wav	Click_07.wav ER No: 20	No Change in Perceived Distance
19	7	1
Click_ Dry.wav	Click_07.wav ER No: 21	No Change in Perceived Distance
20	5	2
Click_ Dry.wav	Click_07.wav ER No: 22	No Change in Perceived Distance
20	6	2
Click_ Dry.wav	Click_07.wav ER No: 23	No Change in Perceived Distance
21	6	0
Click_ Dry.wav	Click_07.wav ER No: 24	No Change in Perceived Distance
18	8	1
Click_ Dry.wav	Click_07.wav ER No: 25	No Change in Perceived Distance
22	4	1
Click_ Dry.wav	Click_07.wav ER No: 26	No Change in Perceived Distance
20	6	2
Click_ Dry.wav	Click_07.wav ER No: 27	No Change in Perceived Distance
20	6	2
Click_ Dry.wav	Click_07.wav ER No: 28	No Change in Perceived Distance
21	6	1
Click_ Dry.wav	Click_07.wav ER No: 29	No Change in Perceived Distance
17	8	2
Click_ Dry.wav	Click_07.wav ER No: 30	No Change in Perceived Distance
19	5	3

Section 3 (Question 3): Organ

Organ_Dry.wav	Organ _07.wav ER No: 1	No Change in Perceived Distance
3	6	4
Organ _ Dry.wav	Organ _07.wav ER No: 2	No Change in Perceived Distance
3	7	3
Organ _ Dry.wav	Organ _07.wav ER No: 3	No Change in Perceived Distance
5	6	2
Organ _ Dry.wav	Organ _07.wav ER No: 4	No Change in Perceived Distance
5	6	2
Organ _ Dry.wav	Organ _07.wav ER No: 5	No Change in Perceived Distance
1	8	3
Organ _ Dry.wav	Organ _07.wav ER No: 6	No Change in Perceived Distance
5	4	4
Organ _ Dry.wav	Organ _07.wav ER No: 7	No Change in Perceived Distance
3	5	5
Organ _ Dry.wav	Organ _07.wav ER No: 8	No Change in Perceived Distance
3	6	4
Organ _ Dry.wav	Organ _07.wav ER No: 9	No Change in Perceived Distance
2	9	2
Organ _ Dry.wav	Organ _07.wav ER No: 10	No Change in Perceived Distance
6	5	2
Organ _ Dry.wav	Organ _07.wav ER No: 11	No Change in Perceived Distance
4	4	5
Organ _ Dry.wav	Organ _07.wav ER No: 12	No Change in Perceived Distance
2	6	4
Organ _ Dry.wav	Organ _07.wav ER No: 13	No Change in Perceived Distance
6	6	1
Organ _ Dry.wav	Organ _07.wav ER No: 14	No Change in Perceived Distance
3	7	3
Organ _ Dry.wav	Organ _07.wav ER No: 15	No Change in Perceived Distance
5	7	2
Organ _ Dry.wav	Organ _07.wav ER No: 16	No Change in Perceived Distance
4	6	3
Organ _ Dry.wav	Organ _07.wav ER No: 17	No Change in Perceived Distance
5	4	4

Organ _ Dry.wav	Organ _07.wav ER No: 18	No Change in Perceived Distance
4	7	2
Organ _ Dry.wav	Organ _07.wav ER No: 19	No Change in Perceived Distance
4	6	3
Organ _ Dry.wav	Organ _07.wav ER No: 20	No Change in Perceived Distance
4	4	6
Organ _ Dry.wav	Organ _07.wav ER No: 21	No Change in Perceived Distance
3	5	5
Organ _ Dry.wav	Organ _07.wav ER No: 22	No Change in Perceived Distance
2	5	6
Organ _ Dry.wav	Organ _07.wav ER No: 23	No Change in Perceived Distance
3	6	4
Organ _ Dry.wav	Organ _07.wav ER No: 24	No Change in Perceived Distance
5	2	5
Organ _ Dry.wav	Organ _07.wav ER No: 25	No Change in Perceived Distance
4	5	4
Organ _ Dry.wav	Organ _07.wav ER No: 26	No Change in Perceived Distance
5	2	5
Organ _ Dry.wav	Organ _07.wav ER No: 27	No Change in Perceived Distance
5	4	4
Organ _ Dry.wav	Organ _07.wav ER No: 28	No Change in Perceived Distance
2	6	5
Organ _ Dry.wav	Organ _07.wav ER No: 29	No Change in Perceived Distance
4	4	5
Organ _ Dry.wav	Organ _07.wav ER No: 30	No Change in Perceived Distance
6	5	2

Section 3 (Question 3): Speech

Speech_Dry.wav	Speech _07.wav ER No: 1	No Change in Perceived Distance
1	9	11
Speech _ Dry.wav	Speech _07.wav ER No: 2	No Change in Perceived Distance
2	10	12
Speech _ Dry.wav	Speech _07.wav ER No: 3	No Change in Perceived Distance
2	17	6
Speech _ Dry.wav	Speech _07.wav ER No: 4	No Change in Perceived Distance
2	16	7
Speech _ Dry.wav	Speech _07.wav ER No: 5	No Change in Perceived Distance
0	19	6
Speech _ Dry.wav	Speech _07.wav ER No: 6	No Change in Perceived Distance
2	18	5
Speech _ Dry.wav	Speech _07.wav ER No: 7	No Change in Perceived Distance
2	18	5
Speech _ Dry.wav	Speech _07.wav ER No: 8	No Change in Perceived Distance
2	15	8
Speech _ Dry.wav	Speech _07.wav ER No: 9	No Change in Perceived Distance
1	21	3
Speech _ Dry.wav	Speech _07.wav ER No: 10	No Change in Perceived Distance
1	20	4
Speech _ Dry.wav	Speech _07.wav ER No: 11	No Change in Perceived Distance
1	16	8
Speech _ Dry.wav	Speech _07.wav ER No: 12	No Change in Perceived Distance
2	20	3
Speech _ Dry.wav	Speech _07.wav ER No: 13	No Change in Perceived Distance
3	20	2
Speech _ Dry.wav	Speech _07.wav ER No: 14	No Change in Perceived Distance
0	21	4
Speech _ Dry.wav	Speech _07.wav ER No: 15	No Change in Perceived Distance
4	21	0
Speech _ Dry.wav	Speech _07.wav ER No: 16	No Change in Perceived Distance
0	20	4
Speech _ Dry.wav	Speech _07.wav ER No: 17	No Change in Perceived Distance
0	19	6

Speech _ Dry.wav	Speech _07.wav ER No: 18	No Change in Perceived Distance
2	22	2
Speech _ Dry.wav	Speech _07.wav ER No: 19	No Change in Perceived Distance
1	19	5
Speech _ Dry.wav	Speech _07.wav ER No: 20	No Change in Perceived Distance
1	21	3
Speech _ Dry.wav	Speech _07.wav ER No: 21	No Change in Perceived Distance
2	22	0
Speech _ Dry.wav	Speech _07.wav ER No: 22	No Change in Perceived Distance
3	17	5
Speech _ Dry.wav	Speech _07.wav ER No: 23	No Change in Perceived Distance
2	22	1
Speech _ Dry.wav	Speech _07.wav ER No: 24	No Change in Perceived Distance
1	20	4
Speech _ Dry.wav	Speech _07.wav ER No: 25	No Change in Perceived Distance
3	20	2
Speech _ Dry.wav	Speech _07.wav ER No: 26	No Change in Perceived Distance
2	21	2
Speech _ Dry.wav	Speech _07.wav ER No: 27	No Change in Perceived Distance
2	20	3
Speech _ Dry.wav	Speech _07.wav ER No: 28	No Change in Perceived Distance
2	21	2
Speech _ Dry.wav	Speech _07.wav ER No: 29	No Change in Perceived Distance
3	21	1
Speech _ Dry.wav	Speech _07.wav ER No: 30	No Change in Perceived Distance
3	21	1

Section 4 (Question 4): Click

Click_00.wav	Click_01.wav	No Change in Perceived Distance
1	2	24
Click_ 00.wav	Click_02.wav	No Change in Perceived Distance
0	4	23
Click_ 00.wav	Click_03.wav	No Change in Perceived Distance
2	4	22
Click_ 00.wav	Click_04.wav	No Change in Perceived Distance
3	2	22
Click_ 00.wav	Click_05.wav	No Change in Perceived Distance
2	1	24
Click_ 01.wav	Click_02.wav	No Change in Perceived Distance
3	2	22
Click_ 01.wav	Click_03.wav	No Change in Perceived Distance
2	2	23
Click_ 01.wav	Click_04.wav	No Change in Perceived Distance
5	2	20
Click_ 01.wav	Click_05.wav	No Change in Perceived Distance
1	4	22
Click_ 02.wav	Click_03.wav	No Change in Perceived Distance
5	1	21
Click_ 02.wav	Click_04.wav	No Change in Perceived Distance
3	2	22
Click_ 02.wav	Click_05.wav	No Change in Perceived Distance
3	4	20
Click_ 03.wav	Click_04.wav	No Change in Perceived Distance
3	2	22
Click_ 03.wav	Click_05.wav	No Change in Perceived Distance
4	3	20
Click_ 04.wav	Click_05.wav	No Change in Perceived Distance
2	1	24

Section 4 (Question 4): Organ

Organ_00.wav	Organ _01.wav	No Change in Perceived Distance
2	2	11
Organ _ 00.wav	Organ _02.wav	No Change in Perceived Distance
1	0	12
Organ _ 00.wav	Organ _03.wav	No Change in Perceived Distance
0	2	11
Organ _ 00.wav	Organ _04.wav	No Change in Perceived Distance
1	1	11
Organ _ 00.wav	Organ _05.wav	No Change in Perceived Distance
1	0	11
Organ _ 01.wav	Organ _02.wav	No Change in Perceived Distance
1	1	11
Organ _ 01.wav	Organ _03.wav	No Change in Perceived Distance
0	1	12
Organ _ 01.wav	Organ _04.wav	No Change in Perceived Distance
3	1	9
Organ _ 01.wav	Organ _05.wav	No Change in Perceived Distance
1	2	10
Organ _ 02.wav	Organ _03.wav	No Change in Perceived Distance
0	2	11
Organ _ 02.wav	Organ _04.wav	No Change in Perceived Distance
1	0	12
Organ _ 02.wav	Organ _05.wav	No Change in Perceived Distance
3	3	7
Organ _ 03.wav	Organ _04.wav	No Change in Perceived Distance
1	2	10
Organ _ 03.wav	Organ _05.wav	No Change in Perceived Distance
2	0	11
Organ _ 04.wav	Organ _05.wav	No Change in Perceived Distance
0	3	9

Section 4 (Question 4): Speech

Speech_00.wav	Speech _01.wav	No Change in Perceived Distance
1	4	20
Speech _ 00.wav	Speech _02.wav	No Change in Perceived Distance
3	0	21
Speech _ 00.wav	Speech _03.wav	No Change in Perceived Distance
2	1	22
Speech _ 00.wav	Speech _04.wav	No Change in Perceived Distance
4	2	19
Speech _ 00.wav	Speech _05.wav	No Change in Perceived Distance
5	2	18
Speech _ 01.wav	Speech _02.wav	No Change in Perceived Distance
1	2	22
Speech _ 01.wav	Speech _03.wav	No Change in Perceived Distance
4	0	21
Speech _ 01.wav	Speech _04.wav	No Change in Perceived Distance
3	2	20
Speech _ 01.wav	Speech _05.wav	No Change in Perceived Distance
5	1	19
Speech _ 02.wav	Speech _03.wav	No Change in Perceived Distance
1	3	21
Speech _ 02.wav	Speech _04.wav	No Change in Perceived Distance
3	3	21
Speech _ 02.wav	Speech _05.wav	No Change in Perceived Distance
2	0	22
Speech _ 03.wav	Speech _04.wav	No Change in Perceived Distance
2	0	23
Speech _ 03.wav	Speech _05.wav	No Change in Perceived Distance
0	1	23
Speech _ 04.wav	Speech _05.wav	No Change in Perceived Distance
0	1	23