

**ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF ARTS AND
SOCIAL SCIENCES**

**AUDITORY DISTANCE PERCEPTION:
INTENSITY AND DIRECT-TO-REVERBERANT ENERGY RATIO CUES**

M.A. THESIS

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Department of Music

Master Programme in Music

DECEMBER 2017

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ SOSYAL BİLİMLER ENSTİTÜSÜ

**DUYUMSAL UZAKLIK ALGISI: SES YOĞUNLUĞU VE DOĞRUDAN
YANKILIYA GENLİK ORANI GÖSTERGELERİ**

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To my family and friends,

FOREWORD

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December 2017

Bartu  ankaya
(Sound Engineer & Designer)

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ABBREVIATIONS

DRR	: Direct-to-Reverberant Energy Ratio
HDD	: Hard Disk Drive
HRTF	: Head Related Transfer Function
IEC	: International Electrotechnical Commission
ILD	: Interaural Level Difference
ITD	: Interaural Time Difference
LTI	: Linear Time-Invariant
RMS	: Root-mean-square
USB	: Universal Serial Bus

SYMBOLS

dB	: Decibel
Hz	: Hertz
kHz	: Kilohertz
ms	: Millisecond
Pa	: Pascal

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AUDITORY DISTANCE PERCEPTION: INTENSITY AND DIRECT-TO-REVERBERANT RATIO CUES

SUMMARY

Spatial hearing can be studied in several aspects such as directionality, localization, elevation and distance. This study investigated the auditory distance perception in particular significance. The term auditory distance perception is generally used to describe the listeners distance estimation. The distance estimation might not be the same with the actual sound source distance in the auditory space. There are several sound source attributes which are considered as distance cues for a given distance discrimination task. Main focus of the study was particularly the most effective relative and absolute distance cues. These are considered to be the intensity and the direct-to-reverberant energy ratio cues. Both of the cues were examined in separate experiments by isolating each cue in a given experiment. Other than the isolation of the cues the condition of having multiple cues were also examined in relative and absolute distance perception. However, the distance perception of the sound sources in the median plane without elevation was the consideration of the study here.

In the first section of the study a literature review had been done prior to the present study. Understanding the fundamentals of acoustics and the human hearing system is crucial for the distance perception phenomenon. This provided several benefits such as the design considerations of the experimental procedure.

The next chapter basically constructed of the methodology used in this study including experimental design and procedure. This study is consisted of six auditory experiments conducted with 12 participants. The stimuli used for the experiments was an impulse sound with varying distances between 1 metre and 6 metres. A total of 18 stimuli were used in the experiments and participants were made to judge either the distance change or the absolute distance of the sound source in scientific units. The results provided that the intensity of the sound source is a robust relative distance cue while the DRR is exclusively effective for absolute distance perception.

DUYUMSAL UZAKLIK ALGISI: SES YOĞUNLUĞU VE DOĞRUDAN YANKILIYA GENLİK ORANI GÖSTERGELERİ

ÖZET

Mekansal işitme, yönelilik, lokalizasyon, yükseklik ve uzaklık gibi çeşitli yönlerden incelenebilir. Bu çalışmada, duyumsal uzaklık algısı ağırlıklı olarak araştırılmıştır. İşitsel uzaklık algılaması terimi, genellikle, dinleyicilerin uzaklık tahminini tanımlamak için kullanılır. Uzaklık tahmini, duyumsal alanda gerçek ses kaynağı uzaklığıyla örtüşür durumda olmayabilir. Belirli bir uzaklık tahmini için uzaklık ipuçları olarak kabul edilen birkaç ses kaynağı niteliği vardır. Bu çalışmanın ana odak noktası, özellikle en etkili göreceli ve mutlak uzaklık ipuçlarıdır. Bunlar yoğunluk ve yankılanan enerji oranı ipuçları olarak düşünülür. Her iki ipucu da belirli bir deneyde her ipucunu izole ederek ayrı deneylerde incelendi. İpuçlarının izolasyonundan başka, çoklu işaretlere sahip olma şartı da göreceli ve mutlak uzaklık algılamasında incelendi. Bununla birlikte, yükseltelerin bulunmadığı medyan düzlemdeki ses kaynaklarının uzaktan algılanışı burada yapılan araştırmanın dikkate alınması idi.

Çalışmanın ilk bölümünde, son araştırmadan önce bir literatür taraması yapılmıştır. Akustik ve insan işitme sisteminin temellerini anlamak uzaklık algılama olgusu için önemlidir. Bu, deney prosedürünün tasarım hususları gibi çeşitli faydalar sağlamıştır.

Bir sonraki bölüm temel olarak deneysel tasarım ve prosedür de dahil olmak üzere bu çalışmada kullanılan metodolojiden oluşturulmuştur. Bu çalışma 12 katılımcı ile yapılan altı duyumsal deneyden oluşmaktadır. Deneyler için kullanılan uyarılar 1 metreden 6 metreye kadar değişen uzaklıklara sahip bir Impulse sesiydi. Deneylerde toplam 18 uyarı kullanıldı ve katılımcılardan, uzaklık değişimini veya ses kaynağının mutlak uzaklığını bilimsel birimler halinde değerlendirmeleri beklendi. Sonuçlar, ses kaynağının yoğunluğunun güçlü bir göreceli uzaklık göstergesi olduğunu buna karşılık mutlak uzaklık algısı için yalnız doğrudan yankılıya genlik oranı göstergesinin etkili olduğunu göstermiştir.

1. INTRODUCTION

Many aspects of the human auditory system had been investigated and observed extensively. Most of the studies spanned around aspects such as; psychoacoustics and psychophysics of human auditory system, human sound localization and spatial hearing. Auditory distance perception is commonly studied under the spatial hearing researches. The topic has been examined under several conditions. While most researches experimented with both echoic and anechoic environments, some of them studied the topic individually, either in echoic semi-reverberant or anechoic environments. Along with the acoustical and non-acoustical cues (Zahorik et al., 2005) for distance perception, the accuracy of these cues (Larsen et al., 2008) on distance perception got attention by the other researchers. Larsen et al. conducted a research specifically on DRR (Direct-to-Reverberant Energy Ratio) to reveal the just noticeable difference for DRR cue on human hearing.

Due to its complex nature, the topic cannot be handled only in terms of acoustic science but also in a psychological level. Zahorik et al. discussed acoustical and non-acoustical cues, including intensity, DRR, frequency spectrum, binaural differences, dynamic cues, vision, familiarity and their combinations. The present study here is focused on two specific distance perception cues instead of all known cues available for the human auditory system. It is suggested that the primary acoustic cues are intensity and direct-to-reverberant energy ratio, especially in enclosed environments such as semi reverberant rooms (Zahorik, 2002). The present study focuses on the intensity, DRR cue and their effects on auditory distance perception.

Handling the subject only as a matter of acoustic principles can be problematic in many ways since the distance perception is a much more complex phenomenon which is directly related to some fundamentals of the psychology of hearing. In order to comprehensively investigate the essence of the subject, psychological aspects of human hearing and the studies such as loudness and spatial perception are somehow complementary to the topic. On the other hand, reviewing such studies that are done

prior to this study is not only helpful for grasping the core elements of the topic, but also useful to develop a set of guidelines for the experimental design of this study.

While conducting an experiment on the human auditory system in such manner, the study should clearly identify the cues that are being tested are absolute (egocentric) or relative (exocentric) cues. The methodological considerations of an experiment design are key elements towards this concern (Mershon and King, 1975). Mershon and King describe the two different approaches in terms of the experiment setup (observer and the sound source positions) and draws attention to the distinction between absolute and relative cues. Furthermore, in some cases relative and absolute cues can be used to determine the perceived depth or distance.

Distance or depth perception is mostly studied under spatial hearing practice. Although it has quite the similar importance in comparison to other aspects of spatial hearing such as; sound source localization, elevation and lateralization of sound sources, it somehow has gained a little attention by the researchers in the field. In that sense, a little is known about the topic relative to the other aspects of spatial hearing (Blauert, 1997, p. 117; Zahorik, 2002). On the other hand, some of the studies or books on spatial hearing include brief explanations of the distance perception which in most cases handful to understand the topic by drawing the similarities in both areas. Most of them bring attention to the cognitive issues, especially in the sound space perception due to complete such task (Rumsey, 2001, pp.35, 36). Furthermore, Rumsey contributes with several temporal changes in sound as distance perception cues where others mostly lie heavy on intensity, DRR, and frequency spectrum cues. Combining and gathering relevant elements and results of the aforementioned studies primarily based on acoustics, psychophysics, psychoacoustics and psychology areas might help the phenomenon to be internalized in a greater extent since it is a multidisciplinary research area. Providing this, it is aimed to design the first chapter of this study as a literature review, thus enabling to make adequate preparation for a theoretical background of the current investigation.

Since the topic involves physics of the sound, its characteristics and its reproduction over sound sources (such as speakers or headphones) that are also relevant to the topic thus should be determined excessively when constructing a hypothesis for the rest of the research. In that regard, constructing the first chapter in a manner mentioned before

is yielding. Furthermore, it is necessary to conceptualize how sound waves propagate in different environments separately.

In the next chapter, I conducted an experiment designed in order to investigate the effectiveness of the cues in question on the human auditory system for distance discrimination. To do so, an experiment for each cue and another experiment on its own for the combination of both cues (intensity and DRR) were performed on participants that required to have normal hearing levels without major hearing loss. Digitally created test signals were fed into a loudspeaker from digital to analogue converter, in varying distances for each test point in the range of one to six metres (1, 2, 3, ... ,6) and then recorded back with a microphone to the computer's hard disk drive through analogue to digital converter signal path. Participants received the test signals over closed back reference headphones in a separate session. They were provided with a spreadsheet to lay their answers. Recorded test sounds were analysed with the basic functions of Octave GNU which is a free software for scientific programming, an alternative to MATLAB[®], using mostly the same coding style and language. The analysis that ran on the test signals mostly remained in the time domain since the spectral domain is somehow irrelevant to the test methodology used here. Responses from the participants will serve as the data set to the research expecting that the evaluation of the data set yields similar results to the relating studies in the field was performed prior to this present study.

This study is an attempt to test the auditory perceived distance in several conditions. The outcome of the study might be used in the innovative designs for the interactive sound applications. Since the interaction of human with sound is crucial for these types of settings, conceptualization of the phenomenon is noteworthy. In this study, main hypotheses were the effect and accuracy of the intensity and the DRR cues on auditory perceived distance. Yet the perceptual weighting of these cues and others was not studied here.

The last chapter of the project, I will discuss the findings from the study in the light of collected data from the participants. The comparison between the actual sound event in the corresponding distance in the field is expected to match with the participant's answer. Although it had been reported that in most situation humans constantly tend to underestimate the farther sources and overestimate the closer sources in the near (closer than one metre) ranges (Zahorik, 2002), yet these distance discrimination cues

studied here still are taken into account as reliable in most compelling discrimination task, namely where no visual information available in the auditory scene.

2. THEORETICAL BACKGROUND

2.1 Fundamentals of Acoustics

The sound is considered as a wave phenomenon in a certain medium such as air, fluids or solid material. However, the behaviour in a fluid medium (air) is more relevant to the topic in this study. It is basically the interaction of the sound waves which we perceive as the sound with the medium itself. In that regard, the elastic properties of the medium, namely pressure variations through compression and rarefaction in the molecules of the medium and oscillations are resulting as the sound. These compressions and rarefactions are accumulated due to sound's propagation as longitudinal waves. In longitudinal waveforms, the displacement axis of the medium is parallel to the propagation of the wave.

These compressions and rarefactions are resulting in a successive low, high-pressure pattern in the propagation direction as illustrated in Figure 2.1 spread out from the point of the sound source. In the area with increased pressure (due to compression), air molecule density is greater than the nominal value and vice versa for the decreased.

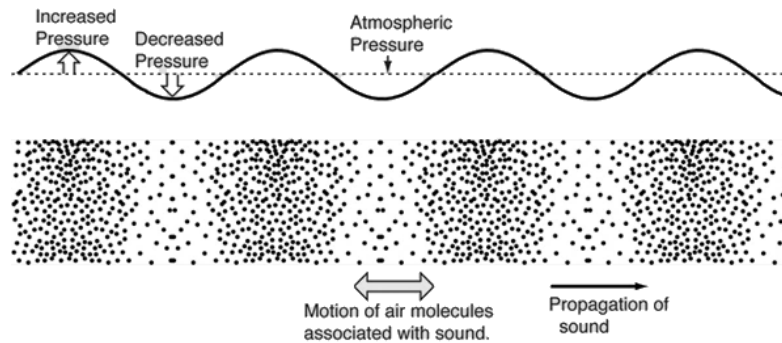


Figure 2.1: Propagation of longitudinal sound waves in air (URL-1)

These pressure amplitudes are expressed in Pascal (Pa) in most cases. On the other hand, in many instances root-mean-square (RMS) of the total pressure is more helpful in terms of loudness perception. It can be derived from the following equation;

$$p_{rms} = 0.707 p_T,$$

where p_T is the total pressure.

Another characteristic of the sound is the frequency which in most cases referred as the pitch of a sound. In order to avoid any misconception, perceived pitch concept is not mentioned here. Rather, the term pitch used here is basically related to the frequency of the sound wave. Under normal conditions, the sound has been considered to have a fixed speed when travelling in a certain medium. What specifies the speed of the sound is the certain properties of the medium which sound wave travels through. Thermal properties such as temperature have the most significant importance on the sound speed. Humidity is also considered as a parameter, but somehow it has less effect on sound speed than the medium's temperature. To conclude the speed of sound (in air) is temperature dependent. The sound speed under 1-atmosphere pressure can be calculated as such;

$$c = 332 + 0.6 T_c,$$

where c (m/s) is the speed of sound in air and T_c is the temperature expressed in Celsius ($^{\circ}\text{C}$). For example, if we calculate the speed of sound at 20°C according to this formula, we get 344 m/s.

The distance required to complete a cycle of oscillation is called *wavelength* and commonly denoted by λ . Similar to that, a number of cycles produced per unit time (one second when expressed in Hertz) is called *frequency*. On the other, the amount of time for a complete oscillation is called *period* and it is directly related to the frequency of the wave. The period is denoted with T . In conclusion, below equation relates to speed, frequency, and wavelength; excluding period, which can be derived when f is exchanged with $1/T$ since $T = 1/f$.

$$c = f\lambda$$

It is equally important to understand the sound field as it is crucial to realize the propagation of sound waves. International Electrotechnical Commission (IEC) define the *sound field* term as the region of an elastic medium that contains sound waves. According to IEC categorization of the sound fields are active, anechoic, diffuse, direct, far, free, near and reverberant due to sound source position, properties of the medium and physical properties of the environment. In the active sound field, particle velocity and the sound pressure are in phase, whereas in other conditions they might not be, such as in near sound field where the sound pressure does not satisfy the inverse square law. An anechoic sound field is used to describe the environment that is sound

reflection free in theory. On the other hand, a diffuse sound field is related to the energy density uniformity. It is the region where the sound pressure level is uniform. Direct fields are associated with the sound source alone without any reflection from the surfaces. As opposed to near field, sound obeys the inverse square law in the far field. In other words, any point exceeding near field can be described as far field where the source is distant. In the far field, every doubling of the distance from the source translates as 6 dB decrease of pressure level. Similar to an active field, particle velocity and sound pressure are in phase in the far field. IEC explains free field as, sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on the sound waves. Anechoic chambers are a good example of this definition. In that sense, a reverberant field is the opposite of the anechoic and free field since multiple instances of the source are reflected from the boundary surfaces of the room.

So far, the sound phenomenon discussed without the regard of human perception in this chapter. Yet, the human auditory system and brain work together to analyse these surrounding stimuli (noises, music) and conclude to some final judgements about the sound event (Vorländer, 2008, p.80). Many designer and programmer benefitted from the advantage of psychoacoustics and human auditory perception when modelling immersive acoustic virtual reality applications. Vorländer reports that grasping the core elements of human hearing leads the way of designing such virtual acoustic models. He includes that this knowledge is crucial while extracting some characteristics of sound (loudness, spaciousness) from the physical data.

To conclude, psychoacoustics and peripheral hearing mechanisms cannot be neglected in order to fully understand the distance discrimination phenomenon.

2.2 Human Hearing System

In a sense, the human hearing system is a group of collectors, transmitters, and receptors in the aforementioned sound field. It is constructed of two ears on both side of the head and consist of three section which are; external ear, middle ear and lastly inner ear. Each section consists of several elements. Figure 2.2 shows the distinction between the sections as outer (external), middle and inner ear including the elements of each section.

The outer section which is called external ear is constructed of the pinna and the external ear canal (meatus). The middle ear is composed of a membrane at the entrance (eardrum) followed by the middle ear bones (malleus, incus, and stapes) commonly known as hammer, anvil and stirrup. Middle ear has an opening to the throat called eustachian tube. Following section is called inner ear and consists of more complex elements in terms of their function. It consists of the cochlea (which includes the organ Corti), semi-circular canals and other receptors related to the sense of balance. The balance related parts are known to have no particular effects on human hearing in terms of auditory sense.

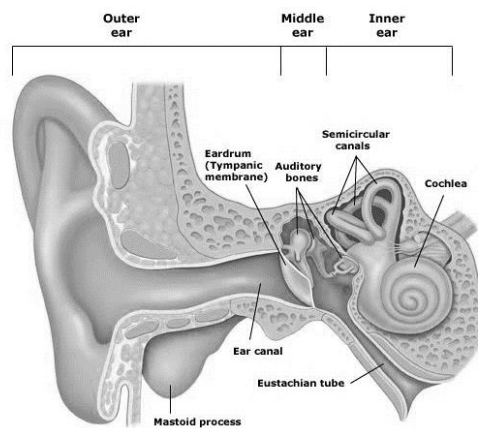


Figure 2.2: Cross section of human ear (URL-2)

In most cases, pinna is likened to fingerprints since it is individual for each person. Pinna is known to have a major importance on the phenomenon called spatial hearing (Blauert, 1997, p.53) and also sound localization (Batteau, 1967). Another important phenomenon is the Head Related Transfer Function (HRTF) for spatial hearing. HRTF can be summarized as the alteration made by the torso, pinna, ear canal and head to the input signal in terms of sound spectrum and localization. Similar to pinna, HRTF is identical due to the differentiation of the shape and size variables. HRTF is important when judging the azimuth (position on the horizontal plane), elevation (position on the vertical plane) and distance of the sound sources in the sound field. For example, binaural recordings benefited from the HRTF principles (applied for both left and right ear) for reproducing sounds that perceived as if they are coming from a point in space when reproduced over headphones.

Certain properties of the human hearing system are defined by the specific elements of the system. For example, cochlea providing the frequency selectivity by its

frequency selective regions. Another property of the system is the frequency range which is from as low as 20 Hz to high as 20 kHz. Although it is known that this range decreases due to ageing and mostly resulting in a hearing loss in the high-frequency range region (16-20 kHz). Yet the system is not equally sensitive to all frequencies due to the uneven loudness perception of human listeners. This concept is widely known as equal loudness curves or contours (Fletcher and Munson, 1933; Robinson and Dadson, 1956). Similar to the frequency range of the system, a dynamic range of the system also exist in terms of amplitude. This range is considered as 120 dB with respect to the softest detectable and the loudest sound just below the threshold of pain. Both ranges described as logarithmic scale because of the relatively huge dynamic range.

HRTF was mentioned briefly without respect to differences might occur between the left and right ear channels. These differences introduced by the sound source positions are known as interaural time differences (ITD) and interaural level differences (ILD) and they are efficient cues for sound localization. When a source is shifted to either left or right side of the centre, it introduces a time difference in terms of arrival time. For example, a sound source on the right side of a listener arrives earlier to the right ear than the left due to the fact that there is less distance for it to travel and vice versa. This incident is known as ITD. Similar to the example used before, sounds on the side of listener introduces interaural level differences on each ear. The main reason for this differentiation is the so-called *acoustical shadow* of the head. High frequencies tend to attenuate by the *acoustical shadow* more than the low frequencies. Both are effective cues for the sound sources that are on the sides. When a listener is exposed to a sound source lay on the median plane, especially with 0° azimuth at ear level (without elevation), both ITD and ILD are minimum, thus making them insufficient for the localization task. In these situations, these are called monaural cues; meaning that they introduce nearly the same influence in both ears. Monaural cues are useful at distance discrimination on the median plane; similar yet another task in many ways than the localization.

However, if the sound source is present in a reverberant environment there is a certain amount of interaction with the source and the room. This interaction translates to the listeners' impression, thus making room acoustics essential. Reverberation is a result of the mentioned interaction. When an enclosed space such as a room is excited by an

impulse, the reflected signals from the surfaces forms reverberation. In other words, reverberation is the impulse response to an impulse. It is referred as the most prominent effects hearing in rooms (Vorländer, 2008, p.92). In contrast to hearing in free field, listeners are exposed to the response of the room other than the direct sound. The response to an impulse as such is generally considered to have early reflections and a late reverberation (like the decay of a reverb tail) period. Impulse and impulse response can be described in mathematical terms, yet another description might follow as such. If we consider the impulse as an input signal to a linear time-invariant (LTI) system, then the impulse response is the yielding output signal. For example, this calculation methodology is used as a core element in convolution reverb algorithms. In order to measure the response, a sine tone sweep excitation is applied to the acoustical space as an impulse; then this response is applied to the input signal by convolution to create a sonic illusion of the sound source being in the sampled space.

2.3 Auditory Space Perception

Humans are in close relationship with the environment in terms of taking advantage of the cues from surrounding while locating sound sources like most animals. An extreme example might be bats navigating with the use of sound without vision. Similar to that humans utilize from directional sounds in order to judge distance and directionality. Most of the times, a direct comparison of the sound reaching two ears is needed to perceive localization. However, in some cases, monaural processing of these, results as the auditory space perception (Moore, 1997). On the other hand, Moore makes a distinction between localization and lateralization and clearly describe each term. In his terminology, Moore refers localization as the judgement of the direction and distance of a sound source while describing lateralization as the apparent location of the source within the head as in situations when sounds presented over headphones, and hence defining the head as the point of origin. The space around the point of origin can be explained in a sphere model so that any point around the head can be described as a coordinate on the vertical and horizontal planes.

Although the terms ITD and ILD are mentioned previously, how they work together (Rayleigh, 1907) was not a concern in the context. Here, Rayleigh provides an explanation about the functionality of them depending on the frequency spectrum mostly known as the *duplex theory*. Although this theory explains the localization task

for simple sounds such as pure tones, it does not have a solid explanation for complex sounds. Especially, ITD is reported to be frequency dependent (Benichoux et al., 2016). At certain frequency ranges one mechanism is more stable than the other one. Rayleigh states that listeners benefit from ITD when localizing low-frequency sounds. On the other hand, high-frequency stimuli are mostly related with ILD in terms of localization. The *acoustical shadow* created by the head is not effective on low-frequencies. In another word, human head cannot serve as an obstacle for low-frequency sounds due to its dimensions and the low-frequency sound waves manage to reach the opposite (to the source) ear by bending around the head. Thus, making ITD the primary cue for these sounds. Surely, it is enough large to act as an obstacle for high-frequency sounds which basically explains ILD being the primary cue for the high frequencies.

However, hearing sound sources in a reflective environment, cannot be considered by means of the direct path only, rather consideration must include the reflections also as a part of the auditory event since there might be hundreds of reflections caused by the excitation of the room (Wallach et al., 1949). In many cases, each of these reflections introduces different cues than the actual sound source offers since they are coming from different directions which are causing confusion about the cues received. Yet, it is reported that even though the localization task is more demanding in highly reverberated environments, it still remains solid to some extent by Wallach et al. in their 1949 study. In this study, they conduct a set of experiments with click signals routed to two loudspeakers directly in front of the listener. As a result, they report that as long as the signals (transient sound or click) are closely sequenced (1 millisecond) in terms of onset time while produced over two separate loudspeakers, the listener perceives the sound as one sound. Furthermore, the arrival time difference caused by onset provides information for localization and the whole sound perceived as coming towards the earlier sound. This phenomenon is called precedence effect later in their study. Similar to They found that the time difference is somehow dependent on signal character. Namely, for short sound 5 ms is enough for sound to be perceived as whole but for speech, this interval is considered to be 40 ms.

In some cases, ITD is not sufficient enough to define the source point, especially on the vertical plane. Since multiple locations on the vertical plane might introduce the same ITD and ILD. This is known as the cone of confusion in the literature. Head

movements such as tilting side to side might be used to resolve the related ambiguities on the vertical plane (Wallach, 1940; Perrett and Noble, 1997). Wallach highlights that binaural cues, ITD and ILD might only be useful to judge the angular distance of the presented sound direction from the axis of ears regardless of its elevation and whether if it is in front or rear with respect to the listener. Tilting the head side to side locates the sound source on the horizontal plane. For example, if the source is below the horizontal plane on the left side of a listener, tilting the head towards the left shoulder locates the source on the horizontal plane since there is a certain amount of shift due to the head movement.

The localization of virtual sources, somehow, tends to be more vulnerable to suffer from these ambiguities such as the cone of confusion (Bronkhorst, 1994). Yet the localization of the real and virtual sources similar in terms of accuracy for stimuli without high frequency (above 7 kHz) content. Bronkhorst stated that the presence of high frequency lowers the localization performance of virtual sound sources. Virtual sound sources are obtained using HRTF. In such studies, individualized HRTF is applied to the signal in order to improve localization performance of the subject. There are also some studies that present stimuli over headphone with non-individualized HRTF. This kind of experimental design will certainly decrease the observers' ability of localization to some degree. Individualized HRTF is measured with probe microphones from inside the ear canal. It is probably the most efficient stimuli method for an experiment conducted over headphones since the role of pinnae is crucial in some cases for localization task. Similar to that, occlusion of pinnae lessens the ability of localization (Gardner and Gardener, 1973).

It is known that vision has a certain amount of importance for supporting auditory system and vice versa. In other words, the senses are connected to some degree. Thereof, some experiments on auditory system preferably make the vision out of order by simply darkening the room or blindfolding the subjects in order to isolate the senses from each other (Mershon and Bowers, 1979). This influence of vision is mostly studied in distance hearing experiments but there are similar studies established on the directional hearing also. This phenomenon is commonly known as *ventriloquist effect* in psychology literature. The *ventriloquist effect* conceptualized the direction confliction about speech sounds affected by visual stimuli. In this case, vision overrides the auditory cues and observer perceive sound location due to the visual cue.

As a conclusion, the human auditory system is qualified for using the actual cues collected from surrounding environment when a localization task is demanded. These cues can be the differences arriving two ears in terms of time, intensity or phase. Moreover, human pinnae have great influence on sound localization as well. The spectral distortion caused by the outer ear cavities are very effective especially when locating the sources that contain high frequencies. In spite, there might be some situations (such as in the cone of confusion term) ambiguities may arise about the sound location. Yet the system is still durable to a great extent. For instance, the use of head movement to determine the direction is a valuable example for resolving ambiguities about source location. Although, the auditory system takes advantage of a variety of physical, temporal and spectral cues specialized for the task, in some cases using single or two of the cues are yet prospering in terms of accuracy. The perceptual weighting of the localization cues may vary in different circumstances, but apparently, localization efficiency is improved when multiple cues are available to the auditory system.

2.4 Auditory Distance Perception

Distance discrimination based on auditory system relies on acoustical cue processing as well as localization. The intensity of sound might help observer to relate the source distance according to the output level especially if they stimuli are familiar to the observers (Kolarik et al., 2016). It is a well-established research interest, despite the relatively small number of researchers and studies. Most of the studies lay emphasis on acoustic and non-acoustic distance cues, but non-acoustic cues are studied less in that sense, compared to acoustic distance cues. On the other hand, many studies bring the attention to whether these cues are absolute or relative (Mershon and Bowers, 1979).

Another sensitivity of auditory system on distance discrimination is the frequency content of stimuli. It is known that complex stimuli over farther distances tend to change in terms of spectral content due to absorbing properties of air. The degradation in high frequencies is more significant than in the lower frequency range (Little et al., 1992). In that sense, this degradation over distance might be useful by means of distance perception of the observer. However, normally room dimensions are very small for this kind of degradation. In order to effectively attenuate high frequencies

greater distance is needed. Thus, spectrum cue for distance discrimination is exclusive for free field stimuli rather than hearing in rooms.

In comparison to the free field, direct to reverberated sound ratio cue is available in the room environments. Room echoes and the time differences between direct and reflected sounds contribute auditory distance perception. Availability of multiple cues at a given sound event definitely increase the accuracy of the judgement. However, distance discrimination is far from being perfect in terms of accuracy and it is reported that the errors exist. In the case of unfamiliarity to stimuli, these errors tend to increase (Coleman, 1962).

Fortunately, after being overwhelmed by directional hearing, distance perception studies gained importance in the literature recently. There are possible cues for distance perception that are thought to be more influential than others. In this case, some cues are studied more frequently than others. The weighting of these cues on final distance judgement is dependent on the source type. Most of the studies use wideband noises, impulse and speech as stimuli. Yet, changes related to source distance commonly result as changes in the acoustic properties of the received signal at the observers' ears. Frequently, these changes are related to the interaction of acoustical environment and the sound source itself. This complex nature of distance cues, makes the accuracy of the task less reliable and more often the quality of distance perception is found to be poor (Nielsen, 1993). In his study, Nielsen states that listening stimuli in normal rooms preserved the observers' distance perception. In other words, the answers of the observers resembled the physical distance. On the other hand, observers could not provide consistent answers with respect to perceived and physical distance in an anechoic room. In the same study, Nielsen states that experimental results from the normal room condition were independent of the sound level.

There are four prominent acoustic cues for distance discrimination in the case of steady source and observer position; these are, intensity, direct-to-reverberant energy ratio, spectrum and binaural differences.

Normally, sound intensity of a fixed power source is decreased as the distance between the observer and source is increased. This was discussed earlier as the "inverse square law" theory in this chapter. The inverse square law offers 6 dB reduction for per

doubling of distance. However, the assumption is that there is no further reflection due to the radiation pattern. So, in cases of possible reflections are available, this theory does not ensure 6 dB reduction for doubling of distance. Thus, making the intensity loss lesser than it would be in a free field. In room environments associated with highly reflective surfaces might decrease the rate even more. In any case, increased level of intensity would be perceived as if the source moved closer and vice versa.

Direct-to-reverberant energy ratio is also a criterion for the human auditory system for distance perception. This cue is mostly effective in reverberant environments. Increasing the distance with respect to the observer will introduce a greater amount of reflected sounds from reflective surfaces such as floor, walls and ceiling. On the other hand, there is a direct path to the observer without any obstacle between the source and observer. The energy ratio between direct and reflected (later arriving) sound is used to judge the distance from a sound source. If the ratio is referring to a high level of reflected sound, then observer might conclude that the sound is coming from a certain distance rather than being close to him/herself. In room acoustics, the reverberation amount of the room is considered by the acoustic properties of the surface materials. Mentioned acoustic properties are, namely absorption and diffusion properties of the surface. A majority of reflective environments are considered indoors but in some cases, reverberation might also occur at outdoors such as in forest (Richards and Wiley, 1980).

The distance that the sound travel in the air may arise spectral changes to the sound source. However, it is known that the distance for such reduction (3- 4 dB loss) in high frequencies considered as 100 metres for 4 kHz (Ingard, 1953). This kind of reduction is generally helpful for distance discriminations in outdoors. Another spectrum change occurs in the opposite condition, namely in rooms. The spectrum of the reflected sound might experience spectral degradation due to acoustical properties of the reflective surfaces. This translates as a direct change in terms of the spectrum at the observers' ear. Similar to DRR cue, increasing the distance might change the frequency composition since it introduces more reflections. Spectrum cue is accounted as a relative cue for distance perception.

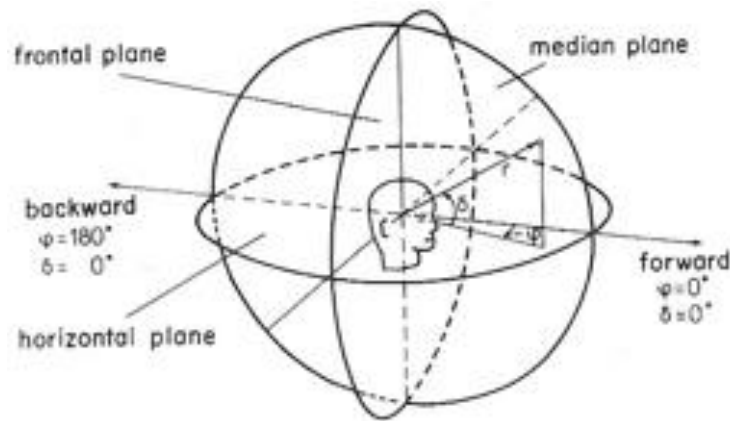


Figure 2.3: Median, frontal and horizontal planes (URL-3)

In the case of the sources apparent in the near field, ITD and IID are no longer independent of radial distance. These differences due to acoustical parallax tend to be maximum at the interaural axis. There are no such differences in the median plane. Figure 2.3 shows the angles of the sound sources (azimuth and elevation) and the auditory planes.

The consideration of aforementioned cues being egocentric or exocentric factors is a conceptual distinction for most of the researchers (Mershon and King, 1975; Mershon and Bowers, 1979; Strybel and Perrott, 1984). Factors directly influence the perception of apparent distance are defined as egocentric (absolute) factors in the terminology. Conversely, cues that are related to relative distance discrimination are called exocentric factors. To illustrate, egocentric factors are the basis to judge the distance in terms of actual distance values. In the meantime, relative factors are closely related with assumptions that require reference distances in order to describe distance. In a sense, it might be likened to the perspective concept in the visual sense. That is to say, auditory depth most commonly has significant similarities with visual perspective. Mershon and King state that their experiment resulted in intensity cue being relative and the reverberant cue being absolute. The main distinction between absolute and relative cues is the functionality of them. Observers should be able to describe distances in scientific units (metre, feet, inch) when absolute cues are present. On the other hand, the distinction of distances should remain as comparisons for the relative distance cues.

2.5 Hypotheses

The scope of the study is to investigate auditory distance perception phenomenon by means of effective absolute and relative cues. More specifically, intensity and DRR cues. As a matter of fact, similar researches had been done in terms of categorization and the accuracy of these cues. Moreover, these studies indicate that some of these cues are dominant in some situations. Thus, making some of them primary and robust in a sense in certain conditions. These circumstances are determined regarding to the type of stimuli (noise, impulse or speech are commonly used in the experiment), hearing environment (anechoic, reverberant, free field) and the reproduction techniques (loudspeakers, headphones, virtual acoustic techniques) used for stimuli. In addition, the specification for experiment subjects in detail was not observed in the previous researches. Despite this, some studies mention the qualification of the experiment subjects. Even so, the information is no further than the naivety (Ashmead et al., 1990) of the subject to the test and hearing properties (with or without hearing loss) of the subject.

Besides, there is the perceptual weighting issue about the cues in question. This issue is not considered here since the topic is not directly related with this problem. Rather, the combination of both cues had been studied here instead of individual weighting of the cues. On the other hand, the priority of these cues has not been neglected while designing the experiments.

The experiment conditions are designed to have two main variables. Other properties such as the spectral content and binaural differences of the sound source are kept constant unless otherwise specified. That is to say, the design limitations of the experiment support the purpose of the study. Varying distances of the sound event introduces a change in intensity as mentioned before. However, it is possible to maintain consistency of intensity at the measurement point. That is to say, if the source intensity is increased correspondingly to the increased distance then the intensity at the measurement point might be kept constant by compensating the level change in negative direction (at measurement point) by incrementing the source intensity. In contrast, if the intensity of source is kept constant, then the intensity at measurement point might decrease with respect to increasing distance.

The first hypothesis is constructed due to this level/intensity change principle over distance and expected to effectively influence distance perception. It is closely related to the inverse square law. Sound obeys the inverse square law when the environment is reflection free. Following equation is used to calculate intensity at surface of a sphere;

$$I = P / 4\pi r^2$$

where; I , P and r described as intensity, source power and distance to the centre of the sphere (radius). Consequently, doubling the distance will result as one-fourth of the previous intensity. Similarly, if the distance is changed from r to $3r$, the intensity will be one-ninth of the previous. Perhaps it is better explained with the surface area of the sphere. Since the source power remains constant, further increase of distance spread the same amount of power over a larger surface and this results as a reduction in the intensity. Furthermore, the relative intensity of two sounds can be expressed in dB. The decibel scale reflects the logarithmic response of the human ear to changes in sound intensity. Intensity in dB is calculated by below equation;

$$I(\text{dB}) = 10\log [I / I_0]$$

If the distance is doubled from the source, the intensity ratio between previous and new position will be 4 (I / I_0). If we apply the ratio to the above equation we will get 6 dB.

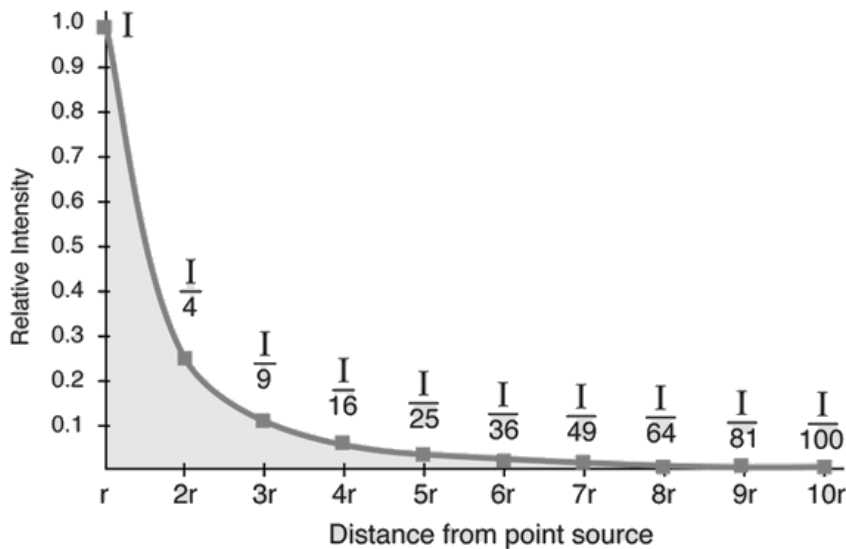


Figure 2.4: Relative intensities with varying distance from a point source (URL-4)

Figure 2.4 illustrates relative intensities with respect to distance change. Even so, sound obeys this law in free field, it does not obey the law in rooms due to reflection properties of the room.

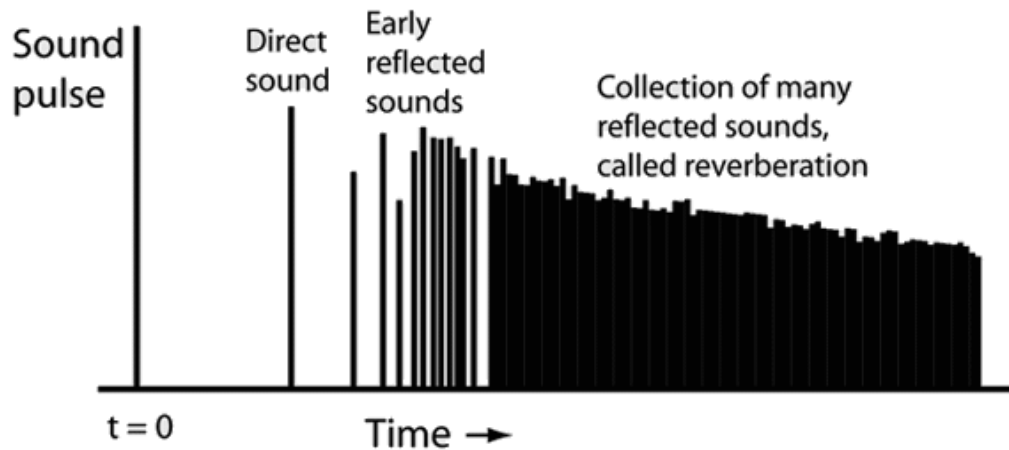


Figure 2.5: A recorded signal of an impulse sound source in distance (URL-5)

The energy proportion of the direct sound to reverberant sound is in close relationship with distance. In Figure 2.5, the sound source -an impulse signal- is shown with the first vertical line at $t = 0$. The time difference between the pulse and direct sound is a matter of distance. After the initial arrival of the sound, first set of reflections arrive at the microphone with a slight delay. This first set of reflections are called *early reflections*. The portion after the *early reflections* is what we generally perceived and call the *reverberation* of the sound. This energy ratio between the direct sound and the rest (reverberation) is related to distance. The second hypothesis is constructed by determining the interaction between source and room. As the distance increases, energy ratio between direct and reflected sound is expected to decrease. As mentioned before, this cue is expected to effect distance judgements of observers. However, in the condition of both cues available to the listener should improve distance judgements further. The energy proportion of the direct sound to reverberant sound is in close relationship with distance.

3. METHODOLOGY

3.1 General Overview

This study interrogated how acoustical cues change the judgement of perceived egocentric and relative distance. Distance judgements required from participants systematically. Furthermore, separate experiments were done for each perceived distance judgement (absolute and relative) and each distance judgement was tested three different conditions. That is to say, intensity cue, DRR cue and both cues were tested separately in each condition. Total of 6 experiments was conducted for this purpose. Although, the stimulation type used for experiments was the same. Stimuli were ordered in pairs in the *relative* distance experiment. Namely, each pair consisted of a reference and comparison sound. These comparison sounds vary in two aspects. Firstly, each comparison sound had different values of intensity. Secondly, the DRR was changed systematically.

The first experiment was done in order to investigate the intensity cue. Thus, DRR was kept constant in between comparison and reference sounds for this experiment. On the other hand, intensity had been changed systematically. Six different intensity values were made available to observers. In other words, each comparison pair consisted of two sounds and participants were expected to report if the sound moved farther, closer or did not move at all. The reply of the participant was recorded on the spreadsheet by him/herself during the experiment.

Next experiment questioned the DRR cue and its effect on *relative* distance judgement. In contrast, the intensity of the stimuli had been kept constant for six different DRR stimuli. Similar to intensity experiment, direct-to-reverberant energy ratio was varied between the reference and comparison sound in DRR experiment. Participants were asked for distance judgements in the same manner (farther, closer or static). Results were recorded in the same fashion.

The third experiment made both cues available for *relative* distance perception. The expected result was further improvement of distance judgement due to use of more

than one cue. In other words, increasing distance of the sound source causes a decrease in intensity and DRR at the same time. Since DRR is the ratio of direct-to-reverberant signal, as the reverberant signal becomes greater, the ratio decreases systematically because the source intensity kept constant for this condition.

Fourth, fifth and sixth experiments are related to the egocentric (*absolute*) distance perception. In these experiments, participants were required to answer in actual physical distances such as metres or centimetres as opposed to relative judgements. Although, the stimuli were the same with the previous experiments (1st, 2nd and 3rd). Participants were provided with 100 cm and 600 cm reference distances. However, in fourth, fifth and sixth experiment participants were not making comparison anymore. They were reporting the distance in scientific units directly to the corresponding stimuli.

Every experiment consisted of randomly chosen stimuli. In the first three experiment, there were 10 random pairs including the static condition also. A total of 30 trials were accomplished for the relative distance judgement experiments (intensity, DRR, both cues). Similarly, 10 trials were done for each cue in the *absolute* distance experiments. To conclude, a total of 60 trails were done in six experiments for each participant. Table 3.1 explains the experimental conditions in detail.

Table 3.1: Characteristics and conditions of the experiments.

#	Available Cue	Response	Trial #	Stimuli	Order
1 st	Intensity	Comparison	10	Impulse	Random
2 nd	DRR	(<i>Farther,</i>			
3 rd	Both Cues	<i>Closer, Static</i>)			
4 th	Intensity	SI units (<i>metres</i> <i>or centimetres</i>)			
5 th	DRR				
6 th	Both Cues				

3.2 Participant Profile and Experiment Environment

A total of 12 participants attended to experiments. They were all participated in all six experiments in two sessions. The first session of experiments consisted of experiments one two and three where *relative* distance perception was tested. The second half of the experiments composed of experiment four, five and six. In this set of experiments, *absolute* distance perception was tested. Five of the participants were female and seven of them were male. The median age of the group was 24 years. Seven participants were Music Master's degree students at Centre for Advanced Studies in Music (MIAM) and the rest was chosen randomly amongst other academic disciplines (all Bachelor's Degree students and graduates). Although no further hearing test was accomplished in order to provide that participants have no considerable hearing loss, they all verbally reported that they are not suffering from hearing loss. Regarding that, they were all accepted to have normal hearing. All of the subjects were naive to the experiments except two of the female and 3 of the male subjects attended similar auditory experiments but not specifically designed for distance perception.

Experiments took place in two different environments. However, the mobility of the apparatus and the reproduction method for stimuli provided a stable presentation of the stimuli between two environments. The main consideration for the selection of test environment was the background noise. In order to provide proper stimuli and unbiased response from the participant, silence was crucial. Both environments provided this property successfully. The first set of experiments were done in the control room of the MIAM recording studio. The control room has medium dimensions except the ceiling is relatively high compared to most rooms. The facility offers an acoustically isolated control room which makes the environment suitable for experiment requirements. Thus, ignoring outside sounds and noise to bleed into experiment environment. The other environment was similar in physical dimensions except for the height of the room. In the meantime, the acoustic isolation of the other room was far less than the MIAM control room. In that sense, the second half of the experiments was chosen to be complete at silent times during the day. Stimuli have been presented over closed back headphones to observers in both environments. Using closed back headphones provided further isolation especially in the second environment since the isolation is less good in that room. Participants reported that

they had not been disturbed by background or equipment noise since the experiment environment was very quiet compared to most cases.

3.3 Generation and Properties of Stimuli

All of the stimuli were generated from a single impulse sound. This impulse was created digitally in a software and it had 5 ms of envelope (contour) time in total. Generated impulse was used to create the actual stimuli. This impulse has been fed into Mackie SRM 450 loudspeaker and a microphone was placed in front of the loudspeaker to record the impulse sound propagated from the loudspeaker in order to generate the stimuli files. The signal was amplified with Grace Design model 801 eight channel preamplifier and sent to the recording equipment. The analogue signal from the microphone was converted to a digital signal with Apogee Symphony I/O converter and the digital audio files (WAV files) were stored on the HDD (Hard Disk Drive) of the computer. The sampling rate of 192 kHz was chosen for precise recording. All recordings for stimuli generation were done with Pro Tools 10 software DAW. This procedure had been followed for creating 18 different stimuli. Six stimuli were used for each experimental condition (intensity, DRR and both). Table 3.2 systematically orders stimuli with respect to the experiment number and recording setup.

The graph in Figure 3.1 shows the analysis results of the intensity cue stimuli files. The analysis and graph were done in Octave GNU. The vertical axis shows the amplitude of the sound (impulse) and the horizontal axis represents the time axis. The signal shown in red belongs to stimulus 1001 (left). Since it was recorded from 1 metre distance, the arrival time of the impulse to the microphone is 3 ms. Moreover, it also has the highest amplitude compared to other signals. The figure clearly represents the intensity decrease with respect to 1 metre iteration of the loudspeaker position. On the other hand, DRR values can be judged with the proportion of the direct part and the later arriving part of the signal for each stimulus. The DRR values of the intensity cue experiments are very close to each other for every stimulus used in this condition which makes the DRR parameter constant between stimuli. In the Figure 3.1, top right corner includes a legend for stimuli numbers. The stimuli shown in this figure was used in experiment number 1 and 4.

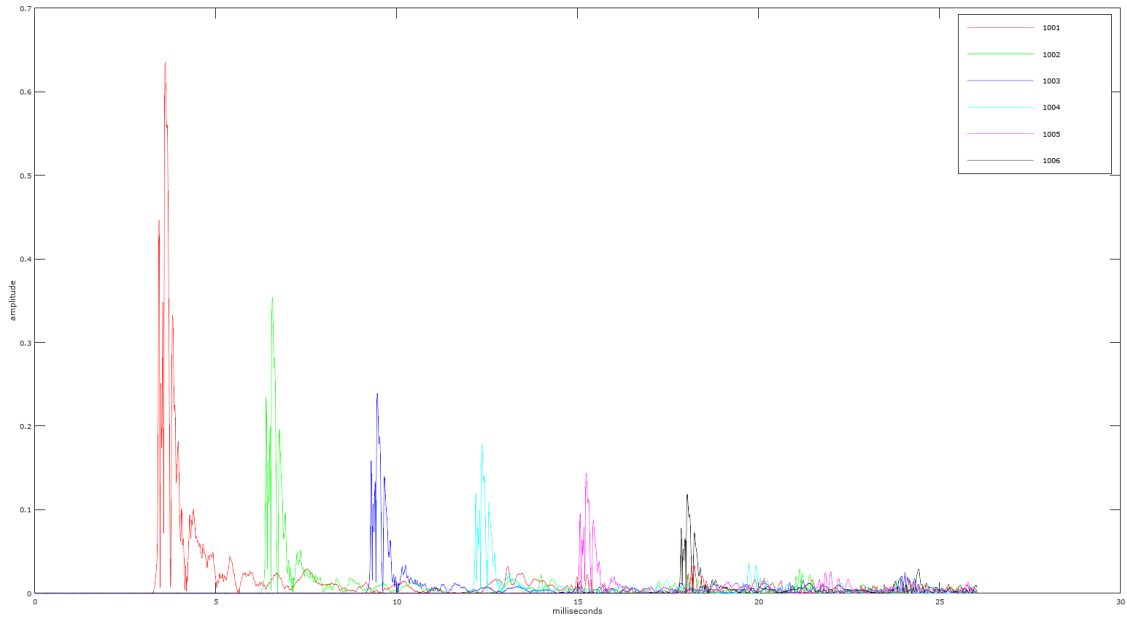


Figure 3.1: Signal analysis of stimulus 1001, 1002, 1003, 1004, 1005 and 1006 (left to right)

To begin, a Neumann U87 condenser microphone -in cardioid polar pattern- was placed in front of the loudspeaker without directionality (0° azimuth) and elevation (same height with the microphone). The cardioid pattern was selected instead of the omnidirectional pattern because using the omnidirectional pattern could increase the reflected sound energy in the recording. The position of the loudspeaker had been changed systematically in order to create six different stimuli. In the meantime, microphone position was kept constant. The height of the microphone was set to 180 cm above the ground which in most experiments considered as “ear level” height. The sound level of the loudspeaker was kept constant so increasing distance between them could decrease the intensity at the microphone position. However, this reduction due to distance did not obey the inverse square law since the recording was done in an enclosed space. Six different recordings were done for each sound source point. In the first recording, the distance between the microphone and the loudspeaker was one metre. For the second measurement point, the distance was set to two metres without moving the microphone position. This one-metre iteration of loudspeaker distance had been followed for third, fourth, fifth and sixth measurements concurrently. The floor and some reflective surfaces on the walls of the recording environment were covered with acoustically absorbent material in order to reduce reflected sound energy. Since this reduction was not sufficient enough, the reverberant energy of the recorded material was reduced further with digital signal processing. This provided the stimuli

to have only one variable (intensity change over distance). As a conclusion, each recorded stimulus had different intensity values. This set of stimuli has been used in the first and fourth experiment.

Figure 3.2 is the signal analysis exclusively for stimulus 2001 and 2006 that are used for the DRR experiments. The signal shown with red colour belongs to stimulus 2001 and the one shown with magenta colour belongs to stimulus 2006. As the figure illustrates, the amplitude values of the direct part of both stimuli are very close to each other. On the other hand, that is not valid for their DRR values. Stimulus 2006 apparently has lower DRR value than stimulus 2001 since, the reverberated energy of it is relatively higher than the stimulus 2001 in spite, they have nearly the same amplitude for their direct parts. Note that the time axis (horizontal) scaling is different from the Figure 3.1.

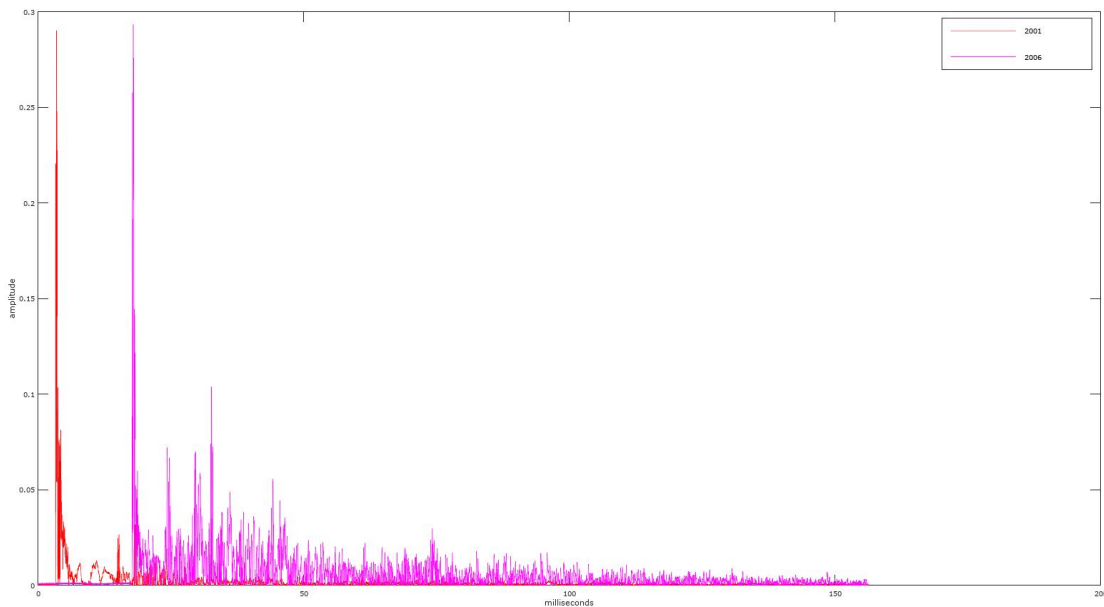


Figure 3.2: Signal analysis of stimulus 2001 (red) and stimulus 2006 (magenta)

Secondly, the recording of DRR stimuli was accomplished. Although the recording procedure was similar, generation of stimuli for DRR experiment required different properties. First of all, the microphone was replaced with a DPA 4006 (omnidirectional) microphone. Figures provided in Appendix D illustrates the recording setup and the positions of the omnidirectional microphone and loudspeaker in detail for recording DRR stimuli. No further change was done in the recording equipment other than the microphone itself. Since DRR cue was tested in this condition, recording with an omnidirectional microphone is much more reliable. In

other words, omnidirectional microphones are more precise than cardioid pattern microphones in terms of collecting reflected sound. That provided a better resolution for this test condition. The placement of the microphone in the room had not been changed. Similar to first recordings, one-metre iteration of the loudspeaker position had been applied for each DRR stimuli. In contrast, the loudspeaker was fed with a greater amount of signal as the distance between microphone and loudspeaker increased. This provided consistent intensity values at the microphone position for different distances. That is to say, the intensity value fluctuated in negligible amounts for every position of sound source regardless of how far they were placed exactly in front of the microphone. The aforementioned sound absorbent material had been completely removed from the floor and walls since the amount of reflected sound is the criterion for this test condition. No further digital signal processing had been applied to the recorded material. Each iteration resulted in decreased values of DRR as the distance increased. In other words, the amount of reflected sound was converging to the direct sound in terms of energy as the distance increased. Thus, it provided a proper set of stimuli for the distance judgement experiments. Mentioned set of stimuli has been used in the second and fifth experiments where DRR cue had been examined.

The analysis of stimuli used in experiments where both cues made available was given in the Figure 3.3. The analysis provided that increasing distance between the loudspeaker and the microphone introduced a systematic decrease in both the intensity and the DRR value of the stimuli. Figure 3.3 provides the analysis of stimulus 3001 (red) and 3006 (magenta).

Lastly, the stimuli for experiment three and six had been recorded. In these experiments, both of the cues were available to the observer. The recording session was relatively similar to the second recording session in terms of microphone selection (same microphone) and the recording setup (loudspeaker and microphone position), except the intensity has not been kept constant for each distance iteration. Loudspeaker power had been kept constant during the recordings for each distance so that the intensity at the microphone position could decrease with the distance iteration. That is to say, the intensity and DRR were decreasing harmoniously as the distance between measurement point (microphone position) and loudspeaker became larger.

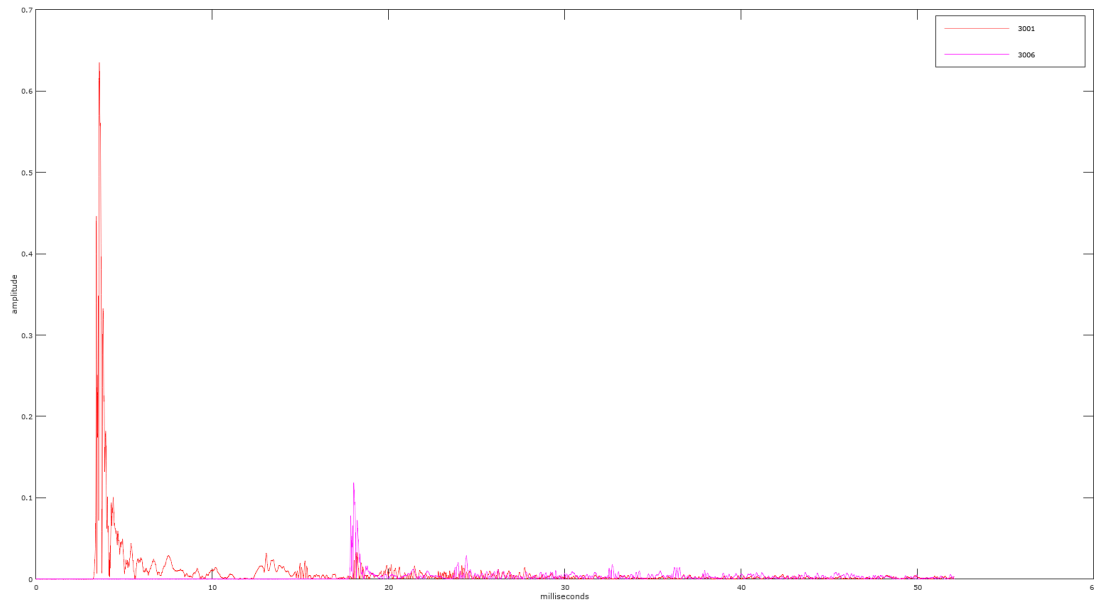


Figure 3.3: Signal analysis of stimulus 3001 (red) and stimulus 3006 (magenta)

Table 3.2: Stimuli used in the experiments and related recording setup

Experiment #	Stimulus #	Distance (cm)	Microphone pattern
1 st & 4 th	1001	100	Cardioid (Neumann U87)
	1002	200	
	1003	300	
	1004	400	
	1005	500	
	1006	600	
2 nd & 5 th	2001	100	Omnidirectional (DPA 4006)
	2002	200	
	2003	300	
	2004	400	
	2005	500	
	2006	600	
3 rd & 6 th	3001	100	Omnidirectional (DPA 4006)
	3002	200	
	3003	300	
	3004	400	
	3005	500	
	3006	600	

Impulse stimuli had been chosen for several reasons. Firstly, the *locatedness* of a sound event might differentiate according to the signal type. In most cases, a click or impulse is more or less robust in terms of spatial attributes of the sound. That is to say, impulse signals can be located explicitly. Secondly, some signal types other than impulse (click) such as; pure tones, wide and narrow band noises and speech tend to introduce so-called localization blur in greater amounts compared to the impulse sounds. The correlation between the sound event location and the distance of the sound source is closer to the linear line when compared to the use of other signal types.

3.4 Experimental Procedure

Participants were met outside the test room and they filled a form that includes some information about themselves such as their age and education. The same form provided the consent of the participants to attend such experiment. Experiment instructions explained to each participant briefly and further questions about the procedure were answered in greater detail in order to avoid any misconception of the experimental procedure. Later, they moved into the experiment environment. Every experiment accomplished with two participants at a time. Each participant received individual headphones for the presentation of the stimuli. The participants were not blindfolded during the experiment. They were seated and were asked to remain silent during the experiment; further brief was given to provide a quiet experiment environment because any noise could potentially interrupt the experimental procedure. The trial was repeated if participants might report any disruption during the trial. In that case, the responses were discarded and the trial was done again before moving to the next trail. Experiment apparatus was placed behind the participants and the operator ensured the quiet operation of the equipment. They were provided with pens and spreadsheets in order to report their responses. The figure in Appendix B includes a copy of the spreadsheet.

A total of six experiment completed with each group of participants in two separate sessions. Participants were provided with two practice trials before moving on to the actual experimental procedure. Each group completed the relative distance perception experiments first. The first session has consisted of experiment 1,2 and 3. Afterwards a brief break was given before moving further to the second session. In the second session, experiments 4, 5 and 6 were completed. These were absolute distance

perception experiments. Each experiment lasted three minutes approximately. Therefore, at least 20 minutes were required to complete the six experiments with each group.

In the first session where relative distance perception experiments were completed, participants replied by making perceived distance comparison with respect to reference sounds. Multiple choices were provided with the spreadsheet. These were; a) distance decreased, b) distance increased and c) distance did not change. Responses collected by this manner in the first three experiments. On the other hand, the second session was different in terms of participant responses. They were asked to scale the absolute distance by means of scientific units. None of the participants reported that they felt uncomfortable with the scientific units and most of them preferred to use metres instead of centimetres. However, minimum of two decimal points requested from the participants who used metres to express their responses. On the other hand, participants who used centimetres responded with the same precision; for example, if the perceived distance was 2.5 metres away from the point of the observer, they would report the absolute perceived distance as 250 cm. In both sessions, intensity, DRR and two cues together condition were tested successfully.

3.5 Presentation of Stimuli

Participants had been received the stimulus over Beyerdynamic DT 770 closed back headphones. Regardless of experiment sessions and environments, the same headphones used during all presentations of the stimuli. Aforementioned 18 audio files were transferred to a personal laptop computers' HDD in order to make experiment apparatus portable. No further change was done to audio files in terms of frequency content and signal level. Equipment used for all six experiments basically consisted of a personal computer, two sets of closed back headphones and a USB audio interface (Focusrite Scarlett 6i6 2nd Generation, 6-input 6-output) with multiple headphone outputs. Output levels of the audio interface were kept constant and set to the same level for both outputs during the experiments.

These audio files were ordered (in pairs) in a DAW for each corresponding experiment. There were 10 different pairs for 10 trials in the first three (perceived relative distance) experiment. On the other hand, stimuli were not presented in pairs during the perceived absolute distance experiments (experiment 4, 5 and 6) since participants were not

making a comparison between the distance of auditory events rather reporting the absolute distance. Figure 3.4 summarizes the presentation order of experiment four in terms of trial number and corresponding stimulus. Six different ordering of stimuli files had been arranged in the Pro Tools session, for each corresponding experiment. So that, every trial and presentation consisted of different combinations in every experiment. Although, some pairs were arranged purposefully to have the same audio files in order to provide no distance change condition. A human speech indicator to notify the trial number was placed right before the first pair and between each pair. These digital files were converted to analogue signals at a high sampling rate (192 kHz) with the audio interface, then fed into the headphones and lastly to the ears of the participant.

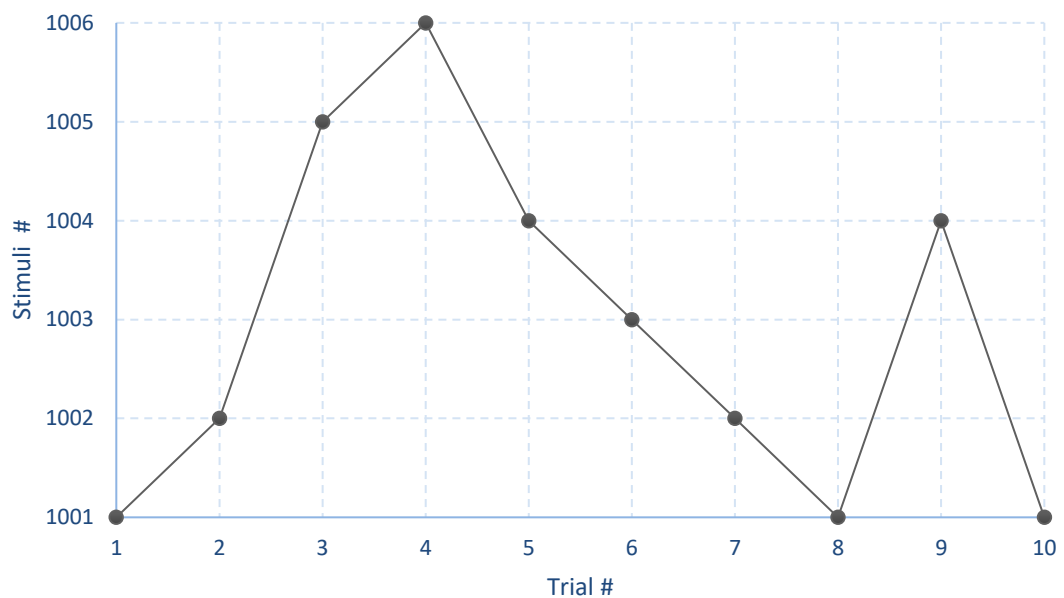


Figure 3.4: Stimuli order of experiment # 4 (absolute distance)

Participants were provided with several practice trials; immediately after that, they moved on to the actual experiment trials. The human voice indicated the number of the trial; one second after that, they heard the first pair of sounds. There were four seconds of duration between the pairs to provide them enough time to record their responses on to the spreadsheet formerly given. Participants were informed at the end of every experiment and then they moved to the next experiment. After the first three experiments, the first session of the experiment was completed and that was followed by a short break. Then, they were moved to the second session which is also consisted

of three other experiments. The presentation of the stimulus was in the same fashion for every experiment.

After 60 successive trials -including all six experiments- were accomplished with the group of participants, they were moved outside the test environment and the procedure was continued with the next group of participants exactly in the same manner.

3.6 Experiment Results

The substantial variables in the experiments were the availability of absolute and relative distance cues. Each condition created its corresponding data set. That is to say, the set of data collected from the first experiment, was evaluated to examine relative distance perception with intensity cue available to the participant. Similarly, the set of data collected from the second experiment was used for relative distance perception with DRR cue in use. Moreover, six different set of data was collected from 12 participants who attended six experiments. Despite the fact that data sets collected from experiment 4, 5 and 6 looked similar, they all correspond to different cues in function for distance perception (intensity, DRR or both).

Before moving on to further evaluation of the experimental data, it is appropriate to report that each stimulus fitted the experimental conditions. Every set of stimuli were analysed by means of their active auditory distance perception cues. Every stimulus was precisely created and designed; analyses were proved that these are suitable to use in corresponding experiments. For example, experiment #1 and #4 required a systematic intensity decrease in the stimulus files over a positive increment of distance. Normally, this systemic decrease is expected to be in an inverse square relationship between intensity and distance. That relationship is only valid if the sound radiates in free field. In contrast, the stimuli used here could not provide such decrease (6 dB) but, relatively less than that amount (4 dB) since the sound was not propagated in free field. On the other hand, stimulus files for experiment #2 and #5 were demanding a different variable factor, which is DRR. Likely, they were also sufficient for the task. Every positive increment of distance was decreasing the ratio (DRR) systematically. Lastly, in experiments #3 and #6, both cues were made variables in the trials. None of the stimulus files was found incorrect or faulty in that sense.

3.6.1 Relative cues to perceived distance

The first experiment was testing the first hypothesis in the relative judgement condition. Participants provided different distance judgements for every stimulus. Although, it has been observed that greater distance differences in the stimulus pairs had a positive influence on relative distance perception. For example, a stimulus pair with greater distance difference immediately influenced the correct choice (on average) in the experiment trial. On the other hand, some of the participants tend to interpret smaller distance differences as in the wrong distance change direction or considered that the source point is static in the stimulus pair. In other words, increasing the distance difference (100 cm to 600 cm vs. 100 cm to 300 cm) reduced the error factor on participants' distance judgement. However, experiments provided that the intensity cue might be sufficient and tactile enough for in such distance discrimination tasks similar to the experimental procedure used in this study.

The second experiment of the present study investigated the DRR cue as a relative cue for distance discrimination task. DRR value of the stimulus varied systematically between stimulus files. This DRR difference between the nearest sound source and farthest was ranged approximately 15 dB. That is to say, the near sound source (100 cm) produced 5 dB DRR, however, the same value was -10 dB for the farthest sound source (600 cm). Since the just noticeable difference for DRR is much smaller than this range (2 dB), stimulus files were qualified enough to perform such experiment. Participants were expected to estimate the direction of distance change by relying upon DRR respectively. Indeed, the difference in DRR provided solid information for distance perception in some distance differences. On the other hand, the performance was better in the first experiment compared to the second experiment. The isolation of the DRR cue might be the primary reason for such decrease in distance judgement performance. In other words, the second experiment could not support the second hypothesis as strong enough as expected.

Lastly, experiment number three was directly related with the aforementioned isolation of the cues issue. The main purpose of the experiment was to determine if there is a correlation between the number of cues available to the listener and perceived relative distance. In the third experiment, both cues were made available to examine if this condition improves the participant's distance judgement. In other words, as the source distance increased, both cues were decreased systematically. This aspect was not

included in the main hypothesis section of this study since it is not directly related to the recent work. On the other hand, it is more likely to encounter similar experiments or investigations in the studies that are interested in the perceptual weighting of the auditory distance cues.

To conclude, results of experiment three suggested an improvement on the relative distance estimation when compared to the results of the second experiment. On the other hand, the performance was not better than the results of the first experiment. This might indicate that intensity difference is a robust cue for the relative distance judgement tasks. On the other hand, availability of the intensity cue together with DRR cue might have resolved some ambiguities in the judgement. Thus, making the results of experiment three relative better than the results of the second experiment. In that sense, DRR might not be the most reliable cue for the relative distance perception.

3.6.2 Absolute cues to perceived distance

The intensity cue for absolute perceived distance had been examined here in the fourth experiment. The experimental results indicated that the use of this cue for the absolute distance judgement is not the ideal choice. The distance discrimination based upon participant responses scattered around the actual distance of the sound source with a larger amount of error. Nonetheless, nearly all participants responded to the distance increase in relation to the intensity decrease or vice versa. Although the fact that the intensity cue provided some sense of the distance between the listener and the sound source, experimental results suggest that the distance estimation can be quite incorrect when the judgement is heavily relied on this cue. Especially in the close distances between 100 cm and 350 cm. Even though the results for this range was incorrect, they provided a linear relationship with the actual distance (approximately 90 cm shifted estimation values compared actual distance) exclusively when the distance was smaller than 200 cm. To conclude, the experiment results could not prove that the intensity is a strong absolute distance cue despite the fact that it is for relative discrimination tasks.

The next experiment consisted of absolute distance judgement trials based on the direct-to-reverberant energy ratio cue. The results showed that the distance estimates of the participants associated with DRR cue provides a substantial amount of improvement for the perceived distance judgement. Even so, this improvement is valid

for relatively close distances namely up to 450 cm. After that distance participants' response were getting systematically lesser than the physical distance. In other words, the responses were quite satisfactory for the closer sound sources compared to the farthest two distances (500 cm and 600 cm). The underestimation of the physical distances started around 400 cm. The systematic change of DRR seems to provide better distance estimates compared to the intensity cue. Although it may look like DRR is the superior cue for absolute distance judgement, the estimates were still scattering around the actual distance. Figure 3.5 shows the linear portion of the distance estimates and the aforementioned underestimation and the dashed line represents the matched estimation of physical and perceived distance. On the other hand, distance estimates might have been improved if the DRR range was greater than used here. That is to say if the amount of reverberation was greater, then the participants' might not have been underestimated the distance after a certain degree of distance. The results of the fifth experiment supported the second hypothesis.

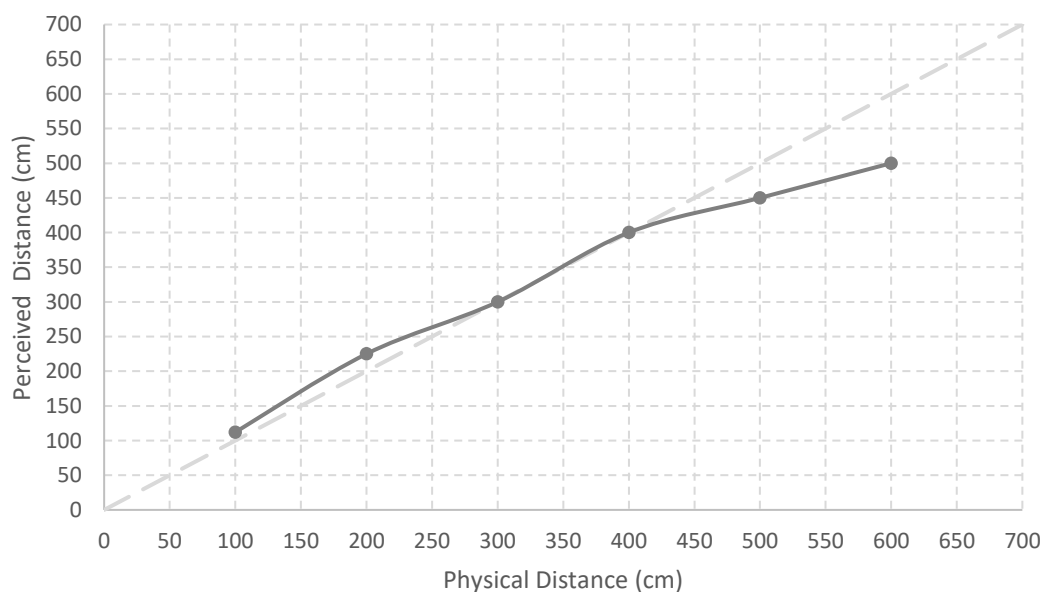


Figure 3.5: Median value of estimated perceived distance in experiment #5
(line in dark grey)

In the last experiment both of the distance discrimination cues provided an improved estimate of the distance judgement compared to the fourth experiment where judgements were done with respect to the intensity cue. The results of the experiment show that the aforementioned estimation ambiguities related encountered in the fourth experiment might have been resolved with the availability of both cues. However, the

change of both cues systematically with respect to source distance did not make the estimations better than that are done in the previous experiments. The only improvement observed was the lesser degree of distance shift for the close sources in comparison to the forth experiment. Moreover, the underestimation of the distance of the sound distant sources was still available.

As a conclusion, absolute distance judgements of the participants were generally tended to overestimate the closer sound sources while the opposite of it was true for the farther sound sources. This perspective shift of the auditory distance perception was observed in all three conditions. As a matter of fact, these shifts were minimal in DRR based judgements compared to other conditions.

3.6.3 Discussion

The analysis of the experimental results provided that the intensity might be the superior cue for the relative distance discrimination tasks. On the other hand, the DRR cue seems to be sufficient enough to provide close estimation of the actual source distance for absolute perceived distance judgements. The results from the experiment five were more statistically significant than the other experiments (4 and 6) that were done for absolute distance perception. Although it seems like that they provided consistent absolute distance estimation of the physical distance, participants underestimated the physical distance steadily in the 4 to 6 metres range. Indeed, this underestimation was regardless of the cue made available in the stimuli files. That is to say, all three experiments resulted in participants' underestimation of farther sound sources. On the other hand, the nature of the overestimation of close sound sources was differentiating between three absolute distance experiment and participants tended to overestimate the close sources less in the experiment five. The main reason for this underestimation of the farther sound sources might be explained in two different approaches.

First of all, this less rapid change of the distance discrimination than the sound source distance is commonly observed in the auditory distance experiments. It is hypothesized that auditory distance perception has a limit as the sound sources is placed farther in the auditory space. In this case, placing sound sources in the median plane with no elevation might result converging estimates to the distance limit for far distances. This phenomenon is generally called the *auditory horizon* and it has been considered the

main reason of the limited estimation of farther sources. The effect of auditory horizon might be greater for the unfamiliar sound sources such as impulse signals compared to familiar sources.

Similar limiting factor had been found in visual distance perception (Mershon and King,1975) called the *specific distance tendency*. The authors state that the *specific distance tendency* might be a general perceptual tendency rather than being exclusive for visual perception only. Another effort to explain this auditory limit might be the *loudness constancy*. It has been reported that reverberant environments tend to produce a constant loudness after a certain distance as the DRR decreased with respect to the increased source distance. In other words, the reverberant energy might converge to some kind of a limit value. Thus, resulting in limited values of estimated absolute distance. The *specific distance tendency* and the *loudness constancy* concepts are adopted from visual perception field studies in order to explain this phenomenon.

4. CONCLUSION

The analysis of auditory distance perception experiment results suggested that the intensity cue might be mainly effective on the relative distance perception while the direct-to-reverberant energy ratio is sufficient for absolute distance perception. Yet, the efficiency of the DRR cue is not exquisite somehow. The use of this cue could not provide a direct correlation between the distance estimates and the physical source distances; the underestimation of the farther sound sources was present regardless of the active cue for discrimination of distance. Although, it can be considered that the human auditory system is not intricate enough to judge the distance of the sound source without defective conclusions, it is very common to encounter such underestimation or overestimation of the physical distances in the auditory distance experiments. The nature of these underestimations was conceptualized with the auditory horizon phenomenon mentioned earlier in this study. Another impressive finding of this study is the indiscrimination of close sources in the relative distance perception especially when the participants were given the DRR cue for the task. For the relative distance perception experiments participants were asked to choose the matching condition for the distance changes from the multiple choices provided in the spreadsheet. On the other hand, similar distance change ranges (Δd) were distinguishable to some extent in the absolute distance perception experiments.

The stimuli chosen for all six experiments were recorded impulse signals with varying source distances. The familiarity of the stimuli was considered as another cue in some distance perception studies. Nonetheless, one might consider that an impulse sound is a less familiar type of signal compared to others such as noise and speech. In that sense, human voice can be considered as the most familiar signal type to the majority of people. Further improvement of the distance estimates might be achieved with the use of short speech sounds such as syllables. Yet, the impulse signal might not be unfamiliar to some of the participants. That is to say, the explanation and the evaluation of experiment results with respect to familiarity is somehow demanding. On the other hand, this study did not use any speech sound as a stimulus sound since the familiarity issue was not directly related to the research topic.

The presentation method of the stimuli to the participant is closely related to the distance perception. The experimental design here applied headphone presentation of the stimuli. It was chosen for several reasons. The main reason for this selection was simply the lack of an anechoic room. The isolation of the intensity cue required an anechoic environment to examine the sound intensity's effect on the perceived auditory distance. Otherwise the experiment would not have a single variable. The unavailability of an anechoic environment forced the study to present the stimuli over headphones instead of presenting the stimuli files with a loudspeaker in an anechoic environment. The mentioned aspects of the presentation were mainly a consideration for the intensity cue experiments. On the other hand, there are several examples in the previous studies that presented stimuli over headphones instead of using loudspeakers (Zahorik, 2002). The method used in Zahorik's study uses the virtual acoustics method to present the stimulus over headphones. He suggested that the method allows precise measurement and control of the acoustic cues that are important for distance perception.

However, the method requires some additional apparatus and measurements than the apparatus used in this study. The mentioned apparatus (probe microphones for measuring the binaural impulse response at the ear canals of the participant) was unavailable in this study. On the other hand, distance estimates and the control over the experimental variables might be improved if such method used for stimuli presentation. That is not to say that the distance estimates obtained in this study are invalid but the availability of such apparatus might lower the estimate errors.

Another experimental limitation for this study was the distance range tested here since the maximum distance of the recording room has determined the maximum distance used in the experiments. On the other hand, this physical limitation of the recording environment has essentially made one of the auditory distance cue to be left out of interest in this study. The frequency spectrum of the stimuli did not change drastically since the maximal distance difference (five metres) was not large enough to shape (high frequency attenuation) the frequency spectrum over increased distance. Figure 4.1 provides an FFT analysis of the stimulus files recorded at 100 cm and 600 cm distances (3001, 3006) that has been used in experiments 3 and 6. Although, the absolute distance experiments may have given an insight to the nature of the distance underestimations if the distance range was larger than it is used in the experiments.

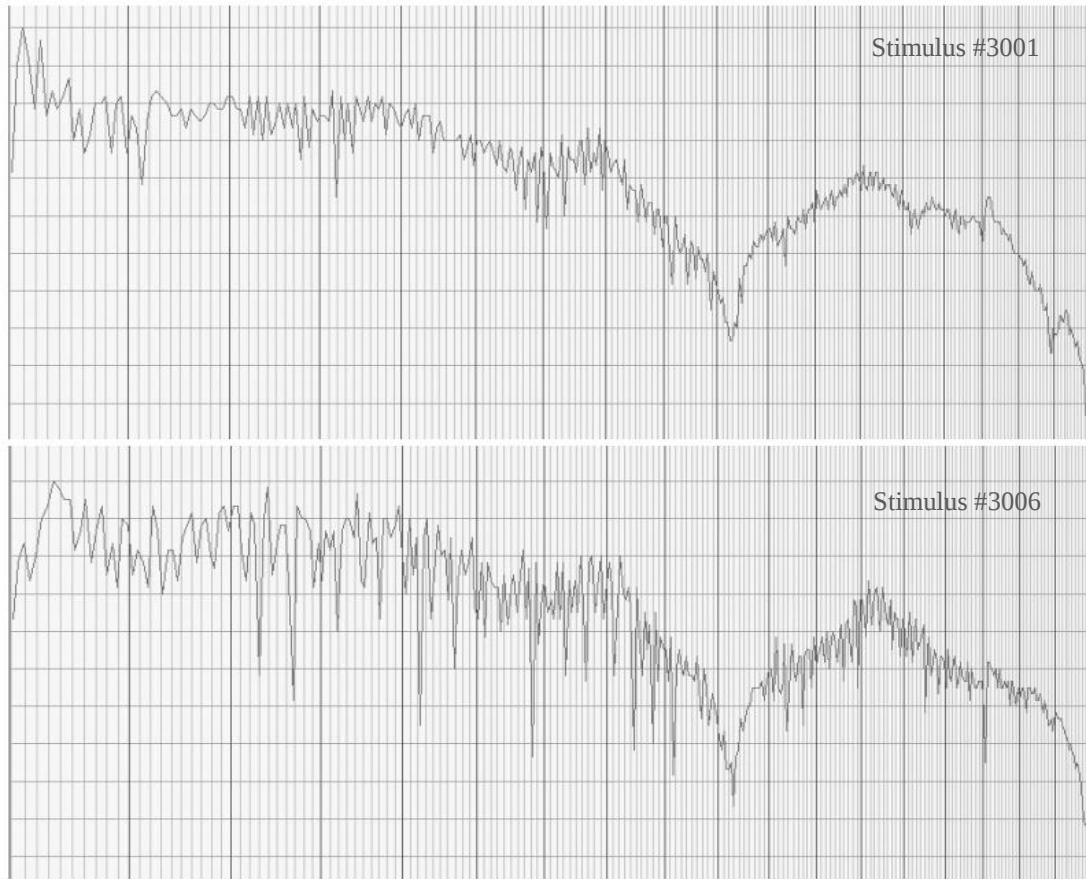


Figure 4.1: FFT analysis of the stimulus 3001 (top) and 3006 (bottom)

The results of the absolute distance experiments showed a significant trend of distance underestimations over 4 metres. However, this study had been tested a limited range of distance. That is to say, including some experiments with greater range might reveal the nature of the participants' distance underestimation. For example, recording the stimulus in a larger room such as an auditorium would provide a larger distance scale. On the other hand, integrating convolution reverb algorithms to the experiments would be also helpful in that sense. Most of the databases includes impulse response recorded from larger distances such as 50 metres. So, working with a modelled virtual space is absolutely beneficial for expanding the distance scale in case there is no available large space for recording the stimulus file. Another improvement for further studies would be decreasing the Δd values between stimuli. The minimum distance difference was 1 metre in the experiments. That is, 0.5 metre iteration for recording the stimuli would yield in much finer resolution and moreover a better sampling of distance estimation.

As far, the focus of the study was the distance perception of the sound sources specifically located in the median plane without elevation. Besides that, it would have

been interesting to introduce the directionality of the sound sources as a variable to the experiments. In this way, the auditory distance perception of humans might be inspected profoundly.

Comprehensive understanding of how humans interacts with the auditory environment and interprets it may arise new possibilities of sound presentation and analysis methods. A hierarchy of the important aspects of the sound and the cues for auditory space perception will definitely help clarifying the design considerations of such interactive models. The findings of this study are only dealt with the sound sources in a specific plane but eventually an integrated model of auditory space perception will be developed. Further studies into such consideration potentially broaden and formulate the outcome of the present study and contribute to the given area of interest.

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APPENDICES

APPENDIX A: Sketch of the recording room

APPENDIX B: Spreadsheet

APPENDIX C: Microphone specifications

APPENDIX D: Recording environment and microphone setup

APPENDIX A

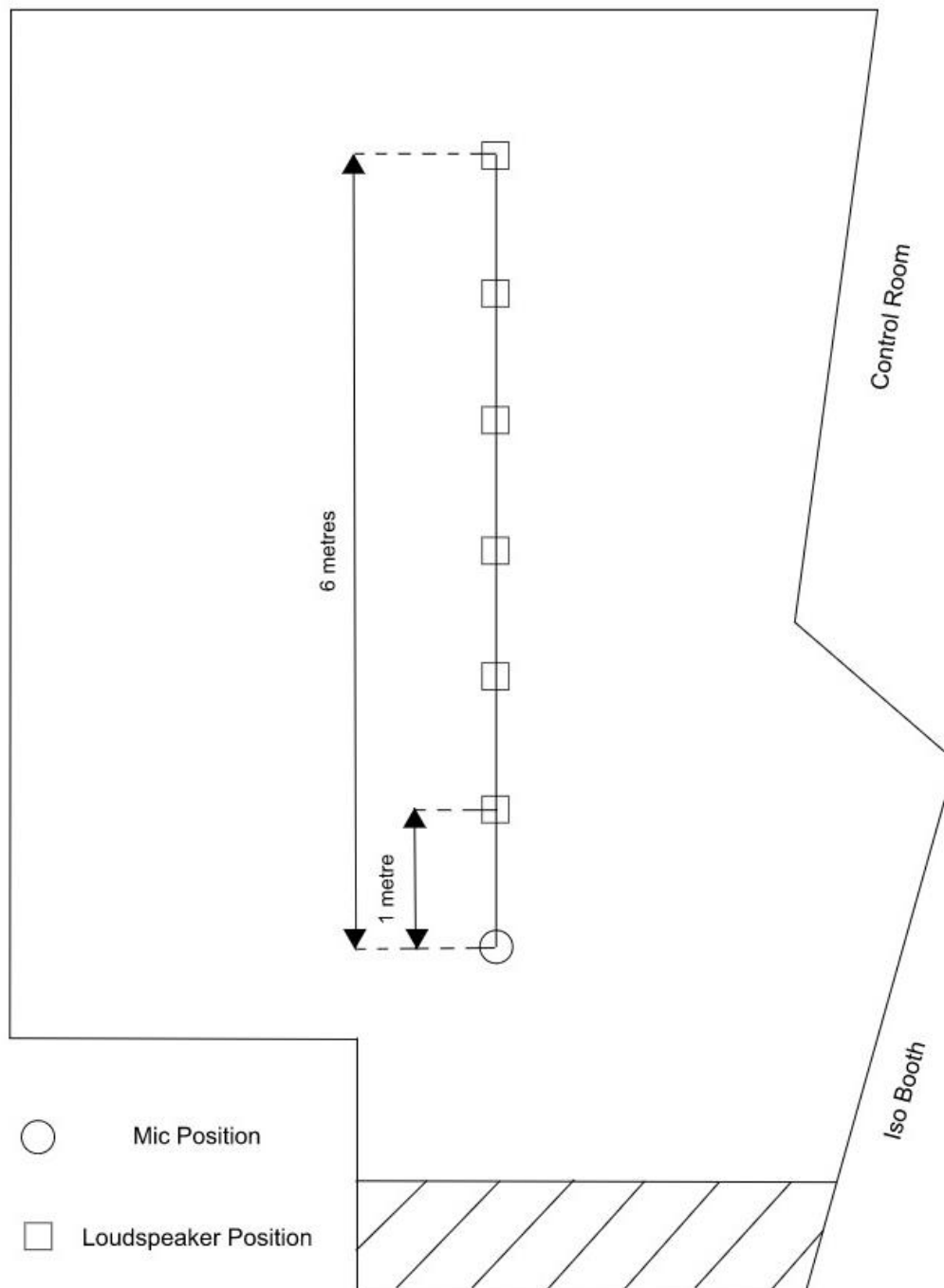


Figure A.1: Loudspeaker and microphone positions for recording stimuli

APPENDIX B

Relative Distance				Absolute Distance	
A				D	
#	Distance Decreased	Distance Increased	Distance did not changed	#	Distance (metre)
1				1	
2				2	
3				3	
4				4	
5				5	
6				6	
7				7	
8				8	
9				9	
10				10	

B				E	
#	Distance Decreased	Distance Increased	Distance did not changed	#	Distance (metre)
1				1	
2				2	
3				3	
4				4	
5				5	
6				6	
7				7	
8				8	
9				9	
10				10	

C				F	
#	Distance Decreased	Distance Increased	Distance did not changed	#	Distance (metre)
1				1	
2				2	
3				3	
4				4	
5				5	
6				6	
7				7	
8				8	
9				9	
10				10	

Figure B.1: Spreadsheet for participants to record the distance judgements

APPENDIX C

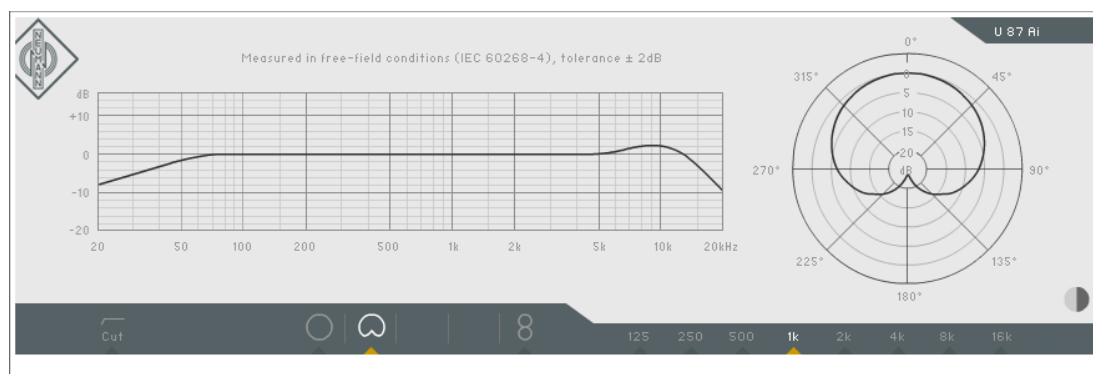


Figure C.1: Neumann U87 Ai frequency response (without cut-off) and polar pattern (cardioid selected, at 1 kHz) (URL-6)

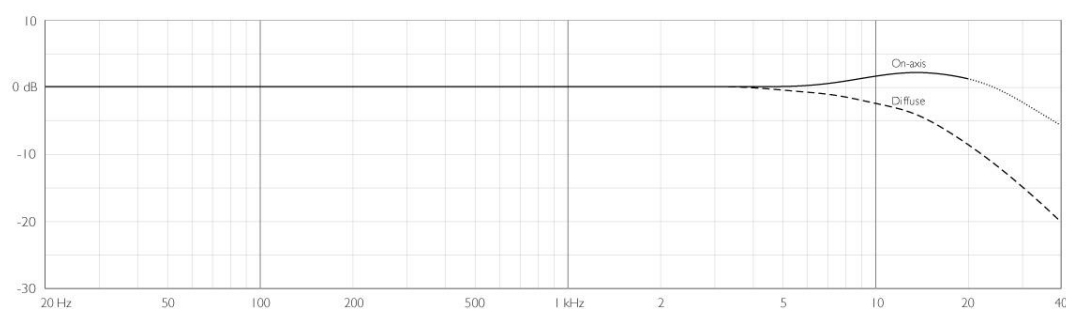


Figure C.2: DPA 4006 Frequency response (with free-field grid attached) (URL-7)

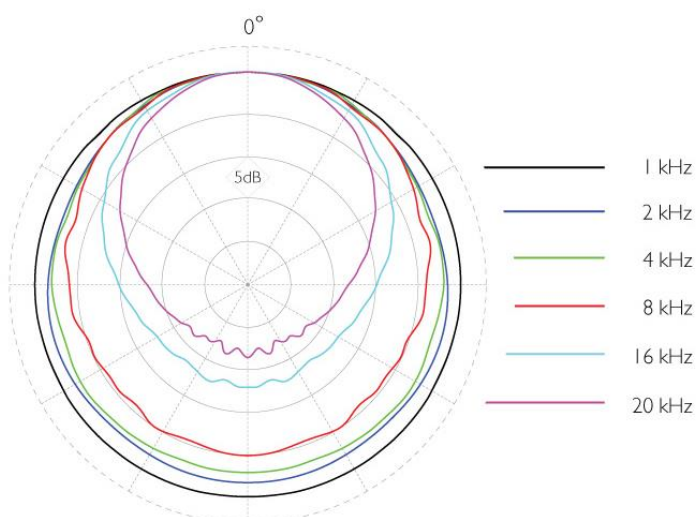


Figure C.3: DPA 4006 Polar pattern at different frequencies (with free-field grid attached) (URL-7)

APPENDIX D



Figure D.1: Loudspeaker and microphone positions for DRR stimuli (# 2006) recording at 6 metres



Figure D.2: Top view for DRR stimuli (# 2006) recording at 6 metres



Figure D.3: Microphone setup (DPA was used for DRR and both cues stimuli recording, Neumann was used for intensity cue stimuli)

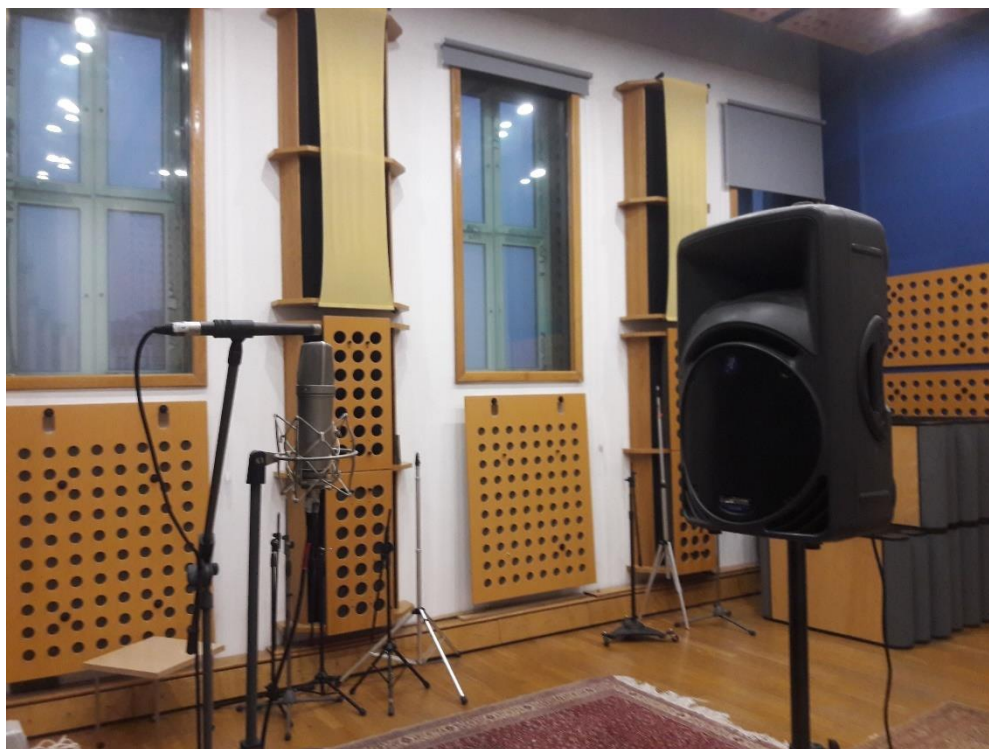


Figure D.4: Side view for DRR stimuli (# 2001) recording at 1 metre

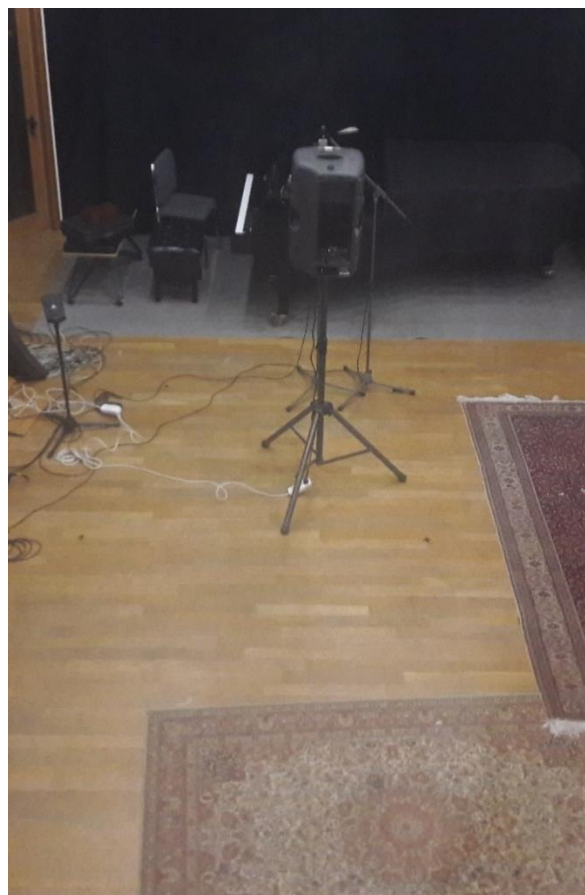


Figure D.5: Top view for DRR stimuli (# 2001) recording at 1 metre

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