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Investigation of Subjective Perception & Objective Metrics of Acoustic Room Diffusion

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INVESTIGATION OF SUBJECTIVE PERCEPTION & OBJECTIVE METRICS OF ACOUSTIC ROOM DIFFUSION

by

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INVESTIGATION OF SUBJECTIVE PERCEPTION & OBJECTIVE METRICS OF ACOUSTIC ROOM DIFFUSION

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While a variety of assessment methodologies have been proposed to quantify acoustic diffusivity within rooms, a link between these and the perception of diffusion has not been fully established. This study investigated various ways of analyzing diffusion, through both human perception and objective metrics. Numerous impulse response measurements were collected from a physical acoustics testing facility designed for diffusion research. This space featured reversible absorptive/diffusive/reflective wall panels, which allowed numerous testing configurations. One such setup investigated how changing the diffusivity of an isolated wall surface impacted diffusive room conditions. Alternatively, the effects diffuser configurations had on diffusive room conditions were also explored.

The collected room impulse response measurements were utilized in subjective trials and an objective metric analysis. In the subjective testing, room auralizations were presented to subjects in audio comparison trials to determine how well diffusive room conditions could be discerned. It was found that a significant quantity of diffusive surface area was required for the average subject to discriminate between the presented diffusive and absorptive wall conditions. Subjects were even less capable of discerning between the diffusive and reflective wall conditions presented. In addition, Male Speech was found to be more distinguishable than Violin Music, and musicians identified diffusive room conditions more effectively than non-musicians. The objective metric analysis identified the Number of Peaks as the most effective diffusive quantification methodology. Also, two metrics designed to measure reflection strengths within impulse responses were identified: Slope Ratio and the Degree of Time Series Fluctuations.

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University of Nebraska – Lincoln

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Chapter 1

Introduction

1.1.1 Background & Motivation

Acoustic room diffusion has long been a topic of much debate in the architectural acoustics community. It has been known for some time that irregular surfaces (which are the basis of surface diffusion) reflect sound in a manner different than planar surfaces, causing waves to scatter in all directions, as opposed to reflecting solely based on the angle of incidence. It has also been common to regard diffusion with providing positive acoustical effects when installed, especially in musical venues. For example, in regards to concert halls, Beranek (2004) stated, "(surface) irregularities scatter sound waves during each reflection, so that, after many reflections, they add a homogenizing effect to the reverberant sound. This homogenizing effect is called 'diffusivity of the sound field'…These irregularities give the music a mellow (non-glary) tone." [10] The problem remains that there is a lack of information quantifying the effects of diffusive room conditions, other than of through anecdotal observations.

This study aimed to address this situation by researching two separate aspects in the assessment of diffusion: human perception and objective analysis. How capable are people at discriminating diffusive room conditions? This question was addressed in the subjective perception phase of this study. Can diffusive room conditions be calculated using 'normal' measurement procedures? This topic was investigated during the objective analysis phase of the study. The intent of this research was to provide insight into these two different diffusion assessment methodologies, which could be applied in future acoustic room analyses.

1.1.2 Study Outline

The primary purpose of this study was to investigate various assessments of diffusion, through both human perception and objective analysis. By testing the subjective perception of diffusion, it was possible to determine the average person's ability to distinguish between diffusive room conditions under numerous testing configurations. The objective analysis concentrated on assessing the diffusive conditions within a room, utilizing standard measurement procedures and the implementation of previously proposed diffusion quantification methods. There has been a dearth of information regarding either of these topics, particularly as it relates to the analysis of real rooms. Therefore, it was the goal of this study to address this testing deficiency and further the research conducted on the assessment of diffusion.

It was determined at the outset of the study that all testing should be conducted in a real, physical room so that all potential effects of diffusion would be represented in the measurements. It would have been possible to complete some form of analysis utilizing acoustical modelling software, but as this would have created a digital representation by which all subsequent analysis would be estimated from, the idea was quickly dismissed. Thankfully, an acoustics testing facility designed to perform large-scale diffusion research was located and procured for the study. The space itself was designed with three full walls covered in reversible diffusive/absorptive/reflective acoustical panels which could be configured in any way. This allowed many room measurements to be collected under different diffuser configurations, which were subsequently used in both the subjective perception and objective metric analyses.

To implement the human perception testing, the collected measurement data was used to create aural simulations (or auralizations) of the test room using pre-recorded source material (speech and music selections). Each auralization represented the source as if it were being played within the tested room under the specific measurement conditions. These auralizations were presented to subjects in comparative listening trials for a wide variety condition pairings, allowing for numerous questions to be answered regarding the perception of diffusion. For example, the Just Noticeable Difference (JND) between different diffusive wall conditions was investigated along with whether diffuser configurations affected discrimination performance. By completing subject testing on 25 individuals, statistically significant conclusions were generated indicating how well (or poor) subjects were at discerning the tested diffusive room conditions.

The same measurement data utilized in the subjective perception testing was also implemented in the objective metric analysis. Instead of creating auralizations, however, the data was analyzed numerically by studying the fine detail of the collected measurements. Numerous objective diffusion quantification metrics have been proposed by multiple authors in an attempt to accurately assess diffusive room conditions. Some metrics have been developed using multi-channel microphones or specialized testing designs, but there have been several specifically designed to quantify diffusive room conditions by performing a numeric analysis of monaural impulse responses (which quantifies the resulting acoustic conditions from a broadband audio signal that has been generated within a space). As room diffusion is a three-dimensional phenomenon, directional information (generated by using a multi-channel microphone) could be very useful in its assessment. However, because of the ubiquity of monaural impulse response measurements in acoustics, it is also important, perhaps more so, to be able to quantify diffusive room conditions using a monaural microphone, as multi-channel receiver capabilities are not widely available.

All measurement data collected in this study were monaural impulse responses based on specific, known diffuser configurations. It was possible to use this room setup information to investigate the efficacy of several of the proposed diffusion quantification metrics. Specifically, three metrics were selected for comparison because they satisfied all desired assessment parameters: they were designed to assess diffuse room conditions utilizing a monaural receiver, they could all be computed numerically using standard software, and they all produced single number ratings which evaluated diffusive room conditions. The three selected metrics were calculated for all collected diffuser configurations, upon which statistical analyses were conducted to determine correlations between room diffusion and the proposed metrics. Through this process, a single methodology was identified which strongly correlated with the tested diffusive room conditions, permitting its use as an assessment tool of diffusion in future research.

This study investigated the subjective perception and objective metric analyses of diffusion, two sides of a whole in the assessment of diffusion. Both analysis methods are important in understanding the effects of diffusion, although no consensus has yet to be determined for either. It was the goal of this study to further the research in this area by producing data from a physical testing facility to investigate the human perception of diffusion and objective acoustical metrics designed to assess diffusive room conditions.

This Master's Thesis has been divided into six chapters which address all aspects of the study. Chapter 1 has been an introduction to this research and a layout of the remainder of the document. Chapter 2 is a literature review of all prior research regarding the analysis of diffusive room conditions. Chapter 3 details the physical testing conducted to collect all measurement data in the study. Chapter 4 discusses the subjective perception testing setup, study design, auralization process, generated data, and analysis of the subjective perception of diffusion. Chapter 5 covers the objective metric analyses, including the specific details of each methodology, the data produced, and the comparative analysis between the three tested metrics. Chapter 6 summarizes the information that is presented in the preceding chapters and offers conclusions, future testing considerations, and general thoughts concerning the research. Figure, table, and equation lists can be found before Chapter 1 with the references utilized in this study included after Chapter 6. The Thesis is concluded with Appendices A, B, and C which include the subjective perception testing data, the objective metric analysis data, and the Visual Basic code written to compute the objective metrics, respectively.

Chapter 2

Literature Review

2.1.1 Introduction

For nearly as long as architectural acoustics has been researched, acousticians have been interested in identifying the properties and effects of acoustic diffusion, which can refer to either the quality of reflections coming off of a surface or the acoustic conditions within a room. *Surface* diffusion is created by irregularities of reflecting surfaces, which scatter sound energy in many directions as opposed to only one direction. For example, incident sound that is reflected off of a surface in all directions would be considered a diffuse reflection (analogous to Lambertian lighting reflections). Conversely, if an incident sound wave is reflected back at the angle of incidence, a specular (non-diffuse) reflection would occur. Many types of diffuse surfaces have been developed, each designed in specific ways to provide various levels of diffuser performance. Figure 2.1.1 displays three diffuser examples (of the hundreds that are commercially available), two common and the third not so much. The left diffuser is a 1-Dimensional Quadratic Residue Diffuser (QRD) which scatters sound in one plane (the X-Dimension) across a specified frequency range, determined by the well configurations. The middle diffuser is also a QRD, though designed to operate in two dimensions (X & Y). The diffuser on the right features a custom configuration, designed to provide both performance and an interesting appearance.

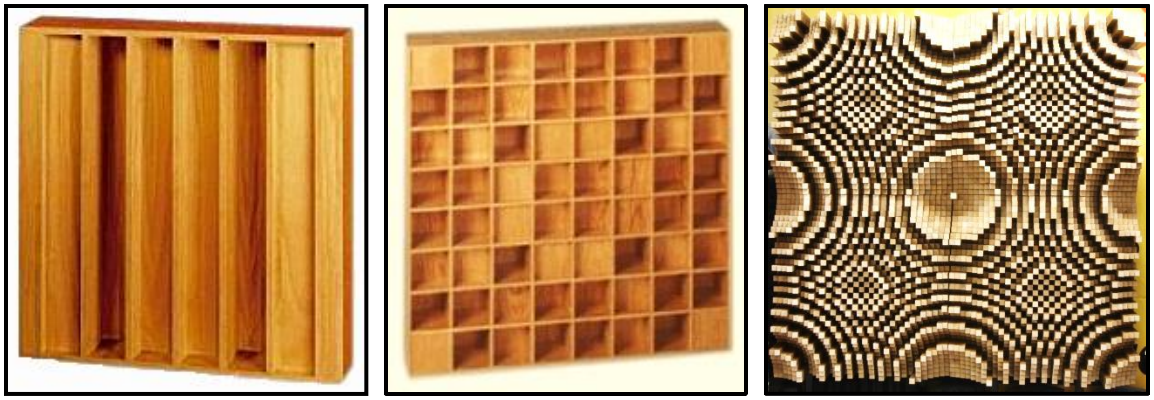


Figure 2.1.1: Available types of diffusers – (a) 1-D Quadratic Residue Diffuser (Source: RPG Inc.), (b) 2-D QRD (Source: RPG Inc.), & (c) 2-D Proprietary diffuser design (Source: RD Acoustic)

Room Diffusion, on the other hand is associated with the acoustical properties of a space as a whole. While these qualities can be influenced by surface diffusion, diffuse room conditions are specifically determined by two acoustic properties: the homogeneity and the isotropy of a sound field. Homogeneity refers to the uniformity of the acoustic conditions throughout the tested space, whereas isotropy indicates the probability of sound arriving at a receiver from any direction. Therefore, a 'fully diffuse room' would have identical acoustic conditions at all locations in the space with an equal directional probability of incoming sound waves. However, a 'fully diffuse room' is a theoretical construct, as uniform acoustical conditions are never entirely met.

Surface diffusion and diffuse room conditions are generally considered to provide positive effects on the sound field, which makes the use of wall diffusers in recording studios and other music venues understandable. They serve to eliminate unwanted reflections within a space without introducing additional absorption, which would impact Reverberation Times and other acoustical metrics. Diffusers have also been reported to add 'life' and 'airiness' to the sound field by scattering waves throughout a space. Look at the newly redesigned NBC Tonight Show studio in Figure 2.1.2, which features diffusion above the host's desk, beside the entrance curtains, and also behind the band.

Figure 2.1.2: The newly redesigned Tonight Show studio features significant wall diffusion (Source: NBC)

Diffusion has been a topic of research in the acoustics community for more than 70 years, with the first published article appearing in the Journal of the Acoustical Society of America written by John Volkmann in 1941, entitled ‘Polycylindrical Diffusers in Room Acoustic Design’. [35] Since that time, significant effort has been spent in defining the properties and effects of both surface diffusion and diffuse room conditions so that each may be better understood. The following sections detail the metrics that have been developed to define surface diffusion, the methodologies utilized to describe room diffusion, and the impact these quantifiers have had on this study.

2.1.2 Quantifying Surface Diffusion

In an attempt to quantify the properties of surface diffusion, two metrics have been developed: Scattering Coefficient and Diffusion Coefficient. These metrics aim to assess the diffusive properties of tested surfaces, producing numerical values to measure their effectiveness. One point that must be remembered about these two metrics is that neither perfectly assesses the diffusive properties of a test surface: they each generate useful information which must be used in combination to produce an accurate evaluation.

The Scattering Coefficient is defined as the ratio of the non-specularly reflected sound energy to the total reflected energy. [2] To visualize this quantity, imagine an incoming sound wave striking a surface. If the surface is very smooth, specular reflections occur, sending the sound energy back at the incoming angle of incidence. If the surface is rough (i.e. diffuse), reflected sound will be scattered in multiple directions. The Scattering Coefficient compares the reflected sound energy not directed in the specular direction against the total reflected energy. The metric values range from 0 to 1 with 0 representing fully specular reflections and 1 representing fully diffuse reflections. These values are determined for 1/3 octave band frequencies between 100 Hz and 5000 Hz, allowing for scattering analysis to be conducted across a wide frequency range.

There are limitations to the Scattering Coefficient, as it does not determine the quality of reflections (direction and the amount of actual sound scattering), only the ratio of non-specular to total reflected energy. This means that if an incoming sound wave is reflected specularly but not at the incoming angle of incidence (i.e. if a flat surface were steeply slanted), the reflecting surface would generate a high Scattering Coefficient, although true scattering would not have occurred. This makes the metric difficult to use in determining the performance of diffusers, especially when comparing different models. However, the Scattering Coefficient is well adapted for use in geometric room prediction methods involving high frequency modelling and scattered energy following probability functions. Because these acoustic modeling programs generally perform calculations over thousands of iterations, Scattering Coefficients applied to modeled surfaces provide the proper amount of reflection variability, which when averaged over the total number of modeled reflections, adds accuracy to the resulting room condition computations.

The Diffusion Coefficient, on the other hand, was designed to be a measure of diffuser quality, found by determining the uniformity of the sound scattered from a test surface. [6] The metric is found by first measuring the energy reflected from a surface as a free field polar response, which is then used to calculate a single number gauging the uniformity of the polar response. The Diffusion Coefficient also spans from 0 to 1, with a value of 0 indicating fully specular reflections and value of 1 signifying energy being scattered equally in all directions, defining a completely diffusive surface. As before, Diffusion Coefficients are evaluated at 1/3 octave band frequencies ranging between 100 Hz and 5000 Hz, meaning the metric is frequency dependent. The primary advantage of this metric is the capability to assess the quality of diffuse reflections, and thus the efficacy of diffusers, very valuable in the manufacturing of diffusive products. They cannot, however, be implemented in computer modeling software due to the incompatible geometrical calculation methods currently employed.

The Scattering Coefficient and Diffusion Coefficient can each be used to analyze the diffusive properties of a given surface each in their own way, which allows implementation across acoustical applications, from computer modeling to diffuser assessment. However, these coefficients cannot judge the diffusiveness of the resulting sound field once diffusers are installed within a room. This can only be accomplished through analyzing the acoustical response of rooms, either physically or computationally, using metrics specifically designed to assess diffuse room conditions.

2.1.3 Quantifying In-Room Diffusion

In response to the lack of an in-room measure of acoustic diffusion, many authors have proposed methods for quantifying diffusive room conditions. To date, however, no consensus has been formed as to which metric or specific type of analysis is most appropriate and applicable to assessing acoustic room diffusion. The proposed analysis methodologies may generally be divided into two main categories: direct methods and indirect methods.

Direct methods of diffusion analysis measure how closely sound fields are to exhibiting either homogenous or isotropic acoustic conditions, properties necessary for a diffusive room state. Analyzing the homogeneity of a space requires collecting numerous measurements in many locations to determine the uniformity of the response throughout a room. For example, these tests are utilized to assess the homogeneity within testing chambers for multiple acoustical standards, specifically ASTM C423: Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method (utilizing Relative Standard Deviation of Sound Decay). [4] Also, ASTM E90 (Standard Test Method for Laboratory Measurement of Air-Borne Sound Transmission Loss of Building Partitions and Elements) [5] uses the Total Confidence Interval (CI_{Tot}) in its methodology. While the homogeneity of a sound field can be an indicator of the diffusive conditions within a room, the effects are not fully correlated. Acoustic homogeneity can be influenced by the presence of diffusion, true, but it is also possible to create (near) uniform conditions within a space without the use of diffusion, using carefully selected geometry and surface materials. Therefore, another acoustic property is needed for diffuse room conditions, isotropy, and must be addressed as well.

Analyzing the isotropy of a sound field involves measuring the directionality of the incoming sound, specifically whether waves are arriving uniformly from all directions. To measure sound field isotropy within a room using direct methods, directional sound information is required. This necessitates the use of multi-channel measurement techniques, which provide not only pressure and time data but also directional information. These measurement techniques allow a three dimensional analysis of acoustic room conditions to be conducted, as both time and arrival direction of incoming waves are known. So for instance, a multi-channel room measurement could identify strong wall reflections and the direction of origin, allowing for easy acoustic treatment if necessary. Monaural receivers (Omni-directional measurement microphones, for example) are far more common and provide pressure data over the tested time period. This data can be processed to compute many standard acoustic metrics, but it cannot provide any directional information of the recorded pressure waves. Therefore, when analyzing a room measurement, a monaural receiver would be able to identify when a strong wall reflection occurred but not the direction of arrival.

There are a limited number of multi-channel measurement devices commercially available; Figure 2.1.1 displays some common examples on the market. Clearly, each of the three measurement devices shown below are different form factors, designed with different numbers of receiver inputs, and therefore provide different measurement data. In addition to these manufactured multi-channel receivers, it is even possible to design arrays of linked monaural receivers (generally configured in a spherical design), and using some signal processing techniques, generate directional acoustical information.

Looking specifically at the devices in Figure 2.1.1, moving from left to right is a (a) B-Format microphone, (b) an Eigenmike, and (c) an acoustic intensity probe. The B-Format microphone is comprised of four closely spaced cardioid or subcardioid microphone capsules in a tetrahedral orientation. It outputs four channels of data: the monaural response, the X-directional response, the Y-directional response, and the Z-directional response. The signals from each channel of data are time aligned, allowing for directional information to be extrapolated in the form of pressure values with specific directional vectors. In contrast, the Eigenmike is comprised of 32 microphone capsules arranged in a spherical array, as shown below. It operates on the principle of Ambisonics which is a signal processing technique that allows for full three dimensional analysis of sound within a space. With 32 receivers, 4th order Ambisonic measurement techniques are possible with the Eigenmike, providing ‘good’ resolution of directional acoustic information. The final device displayed is an acoustic intensity probe from Brüel & Kjaer (these devices are available from numerous companies). Intensity probes measure the acoustic intensity of incoming waves, determining pressure and particle velocity, the product of which is acoustic intensity. Many times these devices are used in multiples and arranged in three dimensional configurations so that sound intensity can be measured in all dimensions, allowing for directional sound information to be gathered.

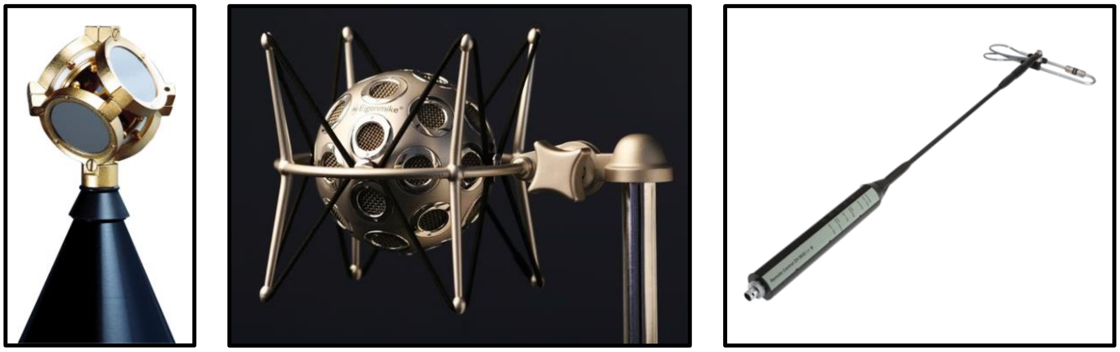


Figure 2.1.3: Multi-channel measurement devices – (a) B-Format microphone (Source: SoundField), (b) Eigenmike (Source: MH Acoustics), & (c) Intensity Probe (Source: Brüel & Kjaer)

Each of the above multi-channel measurement devices (and those not detailed as well) provide significant information on sound fields, and specifically directional room response information. However, this directional information alone is not enough to assess diffuse room conditions. To actually utilize this information requires the implementation of measurement analysis methodologies designed to assess diffuse room conditions. Several of these proposed diffusion assessment methods are detailed in the following sections. As one would expect, though, due to the cost of the needed equipment and/or the complexity of the tests, direct isotropic testing methods are not prevalent.

Alternately, a number of indirect methods have been proposed that extract information from monaural room impulse responses (using standard Omni-directional measurement microphones) to quantify the diffusive properties of sound fields. These monaural impulse responses do not provide directional sound information, and therefore by definition provide less detail on acoustic conditions than the multi-channel measurement devices. However, if a reliable method of evaluating in-room diffusivity could be developed, the widespread acceptance of this form impulse response analysis would allow any acoustician to perform diffusive room analyses. The efficacies of these indirect diffusion quantification methodologies have yet to be established, which is in part what this study aimed to address.

Table 2.1.1 summarizes the direct and indirect methods that have been previously proposed for analyzing diffusive room conditions. Included are the various metric names, the author(s) who proposed the methodology, the measurement technique, and a brief description of the metric. The most relevant metrics of those listed have been described in detail in the following sections.

Table 2.1.1: Proposed methods for quantifying acoustic room diffusion

Category	Name	Author	Measurement	Brief Description
Direct-Homogeneity	Relative standard deviation of sound decay (S_{rel})	ASTM C423	Omni-directional mics at multiple locations	Lower values of deviations across locations mean higher diffusivity in terms of homogeneity
	Total confidence interval (CI_{tot})	ASTM E90		
	Standard deviation of Early Decay	Jeon (2013)		
Direct-Isotropy	Directional Diffusivity	Thiele (1953)	Rotating directional mic(10°) at specific location	Calculate ratio of average and deviation value of the levels
	Diffuseness	Furduev (1960)		Calculate how directivity plot is close to perfect circle
	Ratio of low lateral versus high lateral energy(LH) Ratio of front lateral versus rear lateral	Bassett (2011a, 2011b)	B-format measurement	Calculate sound energy arrived to human ear to certain direction range until 150 ms by decomposing spatial intensity
	Steady State Diffusivity(D_{ss})	Christensen and Rindel (2011)	Three dimensional intensity probes or (figure-of eight)	Difference between sound energy level and integrated intensity levels (x,y,z)
	Diffusion Levels			Difference between Schroeder decay curve and intensity
	Diffuseness	Lokki (2008)	Microphone array intensity probes	Ratio between sound intensity and energy density
Indirect	Mixing time	Defrance and Polack (2008)	Omni-directional mics at specific location	Calculate time until phase of IR become random by observing STFT
	Number of peaks(Np)	Jeon(2013)		Counting number of reflections until 80 ms
	Degree of time series fluctuation	Hanyu (2013)		Quantifying fluctuations from ideal exponential decay
	Mixing time	Prislan et al (2014)		Compare impulse responses in a room differing only in the sound source position, using cross-correlation
Visual	Sound Diffusivity Index (SDI)	Haan and Fricke (1993)	Visual inspection of diffusivity of room wall surfaces	Values of 0, .5, or 1 are assigned to all interior surfaces, which are averaged by area for the entire space

2.1.4 Objective Diffusion Quantification Metrics

Direct Measures of Sound Field Homogeneity

The homogeneity of a sound field is determined by the uniformity of the acoustic conditions throughout the tested space. This property of diffuse room conditions is most applicable to testing chambers, where consistent acoustic conditions are necessary to achieve reproducible testing results. Sound field homogeneity can also impact other room types (i.e. performance venues), though only in testing chambers are measurement results affected. Therefore, measures of sound field homogeneity have primarily concentrated on determining the acoustic conditions within testing chambers where measurements for acoustic standards are conducted.

Bradley et al. (2014) [12] analyzed three quantifiers of sound field diffusivity in work conducted on 1:5 scale models of reverberation chambers, implementing both hanging diffusers and boundary (wall) diffusers. The first quantifier studied, Maximum Absorption Coefficient (α_{Max}), was used in two acoustic standards, ASTM C423 and ISO 354 (Measurement of Sound Absorption in a Reverberation Room). [1] This metric works on the principle that increasing the sound field diffusivity raises the associated absorption coefficients within the space. In theory, as the number of diffusers grows within a reverberation chamber, the absorption values will continue to increase until a maximum absorption coefficient is reached. This in turn signifies diffuse room conditions, thus determining the number of diffusers necessary to achieve this state. Unfortunately, this metric was found to not be a reliable quantifier because computed values cannot be compared between different sound fields or reverberation chambers.

The Relative Standard Deviation of Sound Decay (S_{Rel}) from ASTM C423 and Total Confidence Interval (CI_{Tot}) of sound pressure level and absorption area from ASTM

E90 were the other two sound field homogeneity quantifiers analyzed by Bradley et al. Both metrics are calculated by determining acoustic variations between measurement positions throughout a room. Smaller deviations between tested locations indicate higher sound field homogeneity, as well as diffuse room conditions. In analyzing the efficacy of the two metrics, however, discrepancies were found, especially in the low frequencies, due to the inconsistent qualification procedures.

Investigating sound field homogeneity is conceptually straight-forward and uses a fairly simple methodology: conduct numerous measurements throughout a space and analyze the uniformity. Unfortunately, as Bradley found, the calculable metrics do not show good reproducibility, primarily due to room-specific testing conditions such as microphone positioning, the number of collected measurements, the particular chamber tested, etc. Increasing the accuracy of these metrics necessitates additional measurements within the tested space, which makes the procedure more time consuming but also no more comparable with results from other facilities. Therefore, there is still room for the improvement regarding direct measures of sound field homogeneity.

Direct Measures of Sound Field Isotropy

Sound field isotropy is the other acoustic property which defines diffuse room conditions. Attempts have been made to define and calculate acoustic isotropy for more than 60 years, as far back as by Theile in 1953. [33] His proposed metric, Directional Diffusivity, ranged between 0 and 1 and measured sound energy using a turning rod-shaped directional microphone, calculated as follows:

$$DD = 1 - \frac{m}{m_o} \qquad m = \frac{deviation\ of\ sound\ energy}{mean\ of\ sound\ energy} \tag{1}$$

where m_o represents the value when there is only direct sound.

Christensen and Rindel (2011) [13] developed the Steady State Diffusivity and Dynamic Diffusion Curve metrics which compare Omni-directional measurement data with directional measurements by using three intensity probes or figure-of-eight microphone (X, Y, & Z axes). Steady State Diffusivity (D_{SS}) in dB is calculated directly by subtracting the integrated sound intensity level from the sound energy level. To determine diffuse room conditions, the Dynamic Diffusion Curve is derived by computing differences between the Schroeder reverse integrated decay curve and the X, Y, & Z-directional intensity curves. Preliminary results of the research showed positive signs of metric performance, though as stated before, the complex measurement setup makes this testing configuration difficult to implement.

Ahonen and Galdo (2013) [18] developed a quantifier of diffuseness which implements an energetic analysis using an intensity probe with a 10 millisecond time window. The estimator offers the advantage of providing accurate results in 2D and 3D analysis as long as the average plane wave power remains constant over the time window. However, this condition presents drawbacks in applications which involve strength-varying sound fields, such as speech processing.

Basset (2012) [7] also defined a diffusion quantification metric, Spatial Diffusivity, which utilized Ambisonic sound recordings. This metric is derived by decomposing the spatial intensity from sound energy arriving at the human ear within a specific directional range and a time window of 150 milliseconds. It was found that the ratio of low lateral to high lateral energy (LH) as well as the ratio of front lateral to rear lateral energy (FR) are both related to diffuseness perception.

Lokki et al. (2008) [27] have investigated diffuse room conditions as well, implementing a unique measurement configuration. A microphone array consisting of 12 Omni-directional measurement microphones was used, configured in a spherical X, Y, & Z orientation. This allowed the formation of six intensity probe pairings (one in each direction, at both 1 cm spacing and 10 cm spacing). This device was used to study the spatial impulse response of six concert halls, the results of which indicated that diffuse room conditions were similar within halls but differed between them. As could be expected from a complex methodology such as this, in the author's words, "Analysis results of the multi-dimensional data are hard to visualize." Thankfully, work continued in this regard, resulting in the analyses conducted by Patynen et al. (2013) [28] which produced very coherent visualizations of three dimensional sound field conditions.

Indirect Measures of Sound Field Isotropy

While direct measures of sound field isotropy can potentially provide significant information on the acoustic conditions of a room, measurement systems to compute the described metrics are not widely available. In response, several metrics have been proposed which parse the pressure and time data of monaural impulse responses to create numerical values which measure diffuse room conditions. No consensus has yet been reached determining the 'best' metric for assessing diffuse conditions, as no one methodology has been found to accurately predict all properties of diffusion.

Polack et al. (1993) [17] proposed the parameter Mixing Time, analogous to the Schroeder frequency (which defines the approximate boundary between modal and geometrical room behavior) but in the time domain. After Mixing Time, a diffuse sound field can be assumed, which indicates that statistical theory can be applied. This metric is defined as the time it takes for adjacent sound rays to spread uniformly across the room.

It uses short time Fourier transforms (STFT) to determine the randomness of phase of the IR using increasing time windows until a diffuse sound field is reached.

Similar in concept to the proceeding metric, Transition Time was proposed by Jeong et al. (2012) [23] which determines the time in milliseconds after the direct sound at which ‘diffuse conditions’ within a room are reached. After the Transition Time, no strong energy peaks, or reflections, remain in the impulse response. Therefore, having fewer strong reflections within an impulse response results in a lower Transition Time. It also indicates higher diffuse room conditions, as the presence of room diffusion generally serves to decrease sound reflection strength. It is therefore possible to rate the diffusive conditions within a room based on the Transition Time, with theoretically more diffuse conditions resulting in a lower Transition Time.

Hanyu (2013) [20] developed the Degree of Time Series Fluctuation, based on how the normalized reflected sound energy fluctuation deviates from the Schroeder reverse integrated decay curve, higher values indicating more diffuser room conditions. It was found that the parameter value increased when diffusers with higher scattering coefficients were used through numerical simulations.

Jeon et al. (2013) [21] introduced Number of Peaks (Np) as an indirect method of analyzing diffuse room conditions. This method counts the number of peaks in an impulse response above a given threshold by using a wavelet transform. The main idea is derived from observation: that acoustic diffusers decrease peak reflection levels and increase the number of reflections in the time domain. It was found that the Number of Peaks parameter is positively correlated to diffuse room conditions generated by surface diffusers. This study also investigated the preference of diffuse room conditions within concert halls thorough subjective tests (which leads into the next section). This study instructed subjects to choose which sample they preferred under different conditions, leaving the possibility of other non-diffusion influences affecting results.

2.1.5 Subjective Perception of Diffusion

While there has been significant research conducted relating objective quantifiers with diffuse room conditions, work has also been directed towards determining human capabilities to perceive the properties of diffusion. The majority of this work has concentrated on the subjective preference of diffusion, asking questions such as ‘Which room condition do you prefer?’ when comparing auralizations of differing diffusive states. This type of research provides useful information as to the types of diffusive room conditions humans prefer, but it does not address the underlying question of how well people can discern diffusion. Only a handful of studies have concentrated on determining diffusion perception limits, which was one of the motivations behind this research.

Damaske (2008) [16] investigated subjective diffuseness perception using the metric, Diffuseness (D). Subjective tests using a 65 speaker array were conducted asking participants to select the perceived directions of sound stimuli. It was found that only signals from lateral directions seemed to affect diffuseness responses. Also, the author argued that a number of proposed objective measures for diffuse sound fields do not relate to subjective diffuseness perception, and instead, subjective diffuseness should be related to directional impressions such as “cloud of sound” and “spaciousness”.

Bassett (2012) studied diffuseness perception (in addition to Spatial Diffusivity described above) using Ambisonic sound recordings. He found that the low to high lateral energy ratio (LH) and the front to rear lateral energy ratio (FR) were related to diffuseness perception. To study the subjective preference of diffuse sound fields for musicians and concert goers, Bassett used computer simulations of three concert halls, each utilizing three levels of diffusion, presented via a 32 channel loudspeaker array. Subjects were asked to choose which room condition they preferred between two presented states. The results showed little significance across all but one testing condition, demonstrating a lack of relation between diffusion level and preference.

The previous studies indicate that subjective preference of diffusion is not uniform across the population. This is in line with other acoustic preference research that indicates how different groups prefer different sound fields (Lokki et al 2008). What has not been thoroughly examined is the ability for humans to perceive diffusion. It can be demonstrated that reflections off diffusing surfaces are different than off hard, flat surfaces, but at what point can this differentiation be made?

Robinson et al. (2013) [31] aimed to determine an associated quantity of diffusion in performance venues: apparent source width. To accomplish this, subjects were asked to discriminate the relative lateral position of two simultaneous sources on stage under various absorptive, diffusive, and reflective room conditions. Measurements from a small theater and simulations of a concert hall, both with sources closely spaced on stage, were used to generate signals for use in the subjective discrimination tests. The tests attempted to gauge the subject’s impression of the blend and the separation of sources. It was found that absorptive, diffusive, or reflective surfaces exhibited different thresholds of discrimination for closely spaced speech sources. The mean threshold separation angles for all subjects in the three tested conditions in the theater were 9.2°, 12°, and 9.8°, respectively. This indicated that reflective and absorptive surfaces allowed for more accurate discrimination between sources than diffusive surfaces in this study.

Diffusion has also received significant attention in acoustic room modeling, specifically scattering coefficients which are commonly utilized on wall surfaces within in modeling programs. Cox (2006) [14] summarized it well, “In recent decades, considerable evidence has been produced to show that incorporating scattering into these models enhances prediction accuracy, and in many cases is an essential ingredient in an accurate model.” It should be stated, though, that these conclusions regarding the efficacy of scattering in room modeling were based on anecdotal evidence only, as until recently no research has specifically addressed the subjective perception properties acoustic modeling programs.

Shtrepi et al. (2015) [32] studied the perceptual limits of scattering coefficients through listening tests in simulated concert halls using three acoustical modeling programs: CATT-Acoustic, Odeon, and Raven. The effects of different scattering coefficients (0.1 – 0.9) applied to the walls and the ceiling of a small simulated concert hall were investigated both objectively and perceptually. The objective evaluation was conducted using ISO 3382-141 [3] standard acoustic parameters. On the other hand, the perceptual evaluation consisted of determining the perception threshold of diffuseness between different surface scattering coefficients. The results showed that the values of the acoustic parameters depended primarily on source-to-receiver distance and the scattering coefficient variation, rather than on the distance from the lateral walls for which no significant differences were found. It was also concluded that a discernable perception of diffusion could be found for only one of the modeling programs, Odeon, indicating a lack of confidence in the effectiveness of the scattering coefficients for the other two programs.

2.1.6 Study Association

While much research has been conducted to quantify room diffusion numerically or identify the limits of human diffusion perception, there still remains a considerable amount of work to be done. Specifically, the largest deficiency of most diffusion research is the use of numerical or computational modeling analysis, as opposed to measuring the effects of physical diffusers. There is an understandable reasoning behind this shortcoming: primarily the cost and complexity associated with testing diffuse room conditions in a physical environment. There are simply very few testing facilities in the world that have been designed for physical diffusion testing which forces most research to turn towards acoustical modeling software.

This study aimed to fill this gap in diffusion research by conducting analyses of both subjective perception and objective metrics of diffuse room conditions utilizing a physical testing facility. Also, while many diffusion quantification methodologies have been proposed, the efficacies of these metrics have not yet been compared. To address this, three indirect sound field isotropy metrics, Transition Time, Degree of Time Series Fluctuations, and Number of Peaks were calculated and analyzed using the collected physical testing data. In the end, this study identified a preferred diffusion quantification metric as well as the limits of the subjective perception of diffusion, making at least a small contribution towards the knowledge pool regarding diffusion.

Chapter 3

Physical Acoustical Testing

3.1.1 Physical Testing Requirements

To investigate the desired properties of diffusion, it was decided at the outset of the study that a physical testing space was needed. Diffusion is a very complicated process and can be influenced by numerous factors when reflecting sound, such as the frequency content of the signal, the angle of incidence, the distances from both source(s) and receiver(s), as well as the number of sources. Also, the type and orientation of the diffusers themselves can have a tremendous effect on the nature of the reflected sound. This fact in particular has encouraged many acoustical product manufacturers to investigate creating the best and most efficient types of diffusive products.

The only way to fully represent the process of diffusion was to utilize real diffusers in a physical testing space, because there would simply be too many variables to account for otherwise. The question became: Where could this testing take place? Fortunately, there was one facility that was already purpose built for diffusion testing, in close proximity to the author, and available for use during the proposed time period. This facility was the MOCAP Variable Acoustics Laboratory, located on the campus of Columbia College Chicago, in Chicago Illinois, where the author earned his Bachelors of Science degree in Acoustics, December 2014.

It should be noted that the analysis could have been conducted solely within acoustical modeling software, but this was decided against early on. If this route would have been chosen, the testing by definition would have been an approximation of the physical effects taking place. Most acoustical modeling programs (Odeon, Ease, CATT, among others) utilize the scattering coefficient alone when accounting for the diffusion process. While utilizing this metric generally produces accurate representations of computed acoustical parameters, such as Reverberation, Clarity, etc. (more so than if the scattering coefficient was not applied) the programs cannot properly model the full effects of diffusion, especially in the nearfield, where the analysis of this study was primarily being conducted. The fact was, if modeling software was utilized to conduct this research, an approximation of diffusive properties would have represented the core of this study, and therefore this option to use computer modeling software was eliminated.

3.1.2 MOCAP Variable Acoustics Laboratory

The MOCAP Variable Acoustics Laboratory was selected as the location to perform the physical testing for this study. The space is a multi-use facility that can be utilized for several types of activities: acoustical testing, musical performances, film and television use, and audio-visual presentations. In fact, MOCAP is short for motion capture, one of the other functions of the space. To accommodate this use, specialized motion capture equipment was installed, such as a fly-rig system which allowed actors to perform flying acrobatics, move in slow-motion, and create other ‘Matrix’ style motion capture effects. While interesting, the rigging system actually had a detrimental impact on the testing in this study, which will be discussed in detail later.

The MOCAP facility is a medium sized rectangular space, with a length of 50 ft. (15.24 m), a width of 40 ft. (12.19 m), and a height of 19.5 ft. (5.94 m). This equates to a volume of 39000 ft^3 (1104 m^3) and an internal surface area of 7510 ft^2 (2275 m^3). The floor is polished concrete on grade and the walls and ceiling are also made from concrete, though featuring a rough texture. The ceiling and upper 6 ft. of the walls are sprayed with a ~3 in. thick layer of K-13 spray-on acoustical insulation, made by International Cellulose Corporation. The Noise Reduction Coefficient (NRC) of this material is 1.02 at the applied thickness with a solid backing, meaning that the ceiling of the MOCAP space theoretically acts as a complete absorber in the mid and high frequencies. Even at 125 Hz, the absorption coefficient is 0.57 under these application conditions, providing effective sound absorption at low frequencies. On the lower concrete wall surfaces, 4 ft. by 8 ft. by 1 in. thick Tectum Interior Wall Panels are installed with the upper edge of the panels reaching 10 ft. These have an NRC of 0.40 and little absorption at low frequencies ($\alpha = 0.06$ at 125 Hz). These were primarily installed to eliminate any potential flutter effects from sound bouncing between the parallel concrete walls, but they also contribute to the overall level of sound absorption within the space.

In two of the room corners, framed interior walls protrude from the rectangular outer walls. In the north-east corner, a 6 ft. by 8 ft. by 9 ft. high closet houses equipment that is used within the facility. In the south-east corner, a 6 ft. by 10 ft. interior ceiling-high wall section includes the primary entry door that leads to the hallway. The room also houses two large computer desks that control the many automated systems, a vocal booth for real-time audio over-dubbing, television monitors, and various other pieces of audio-visual equipment. Figure 3.1.1 shows the MOCAP space as it was before any additional acoustical testing treatments were installed, other than the hanging theater curtains which can be seen in the right figure

Figure 3.1.1: MOCAP Variable Acoustics Laboratory – Before acoustical treatment

3.1.3 MOCAP Acoustical Testing Treatments

During the fall of 2013 and spring of 2014, the MOCAP facility was transformed from strictly a motion capture room into an acoustical laboratory. This involved the creation of 298 reversible acoustical panels, the aluminum support system to hold these panels, and a full-room wall curtain system. A modular 7.2 surround sound system was also installed within the space which included seven full-frequency speakers and two subwoofers. The author was heavily involved in the creation of the reversible acoustical panels, which was the basis of his senior capstone project at Columbia College.

The acoustical panels are 24 in. wide, 24 in. tall, and 12 in. deep, constructed with one diffusive side and one absorptive side. The diffusive sides are seven-well one-dimension Schroeder-style diffusers that were molded from 1/8 in. thick ABS plastic. (Figure 3.1.2) While only six wells are shown in the figure, the seventh well is formed by the edges of two adjacent panels when installed on the walls. Each well is approximately 3.5 in. wide with ½ in. fins dividing the wells. The shallowest well is 1 in. deep (not considering the edges) with the deepest well being 5 in. This results in effective diffusion cutoff frequencies of around 400 Hz at the low end and 800 Hz at the high end, with an effective scattering high frequency cutoff of 2150 Hz. Because the ABS plastic was thin and not completely rigid, backing material was needed to improve the structural stability of the panels to prevent internal vibration. To accomplish this, Handi Flow pour-in-place polyurethane foam (which hardens into a very dense material) was filled into the crevices of the diffusers. Along with a 1 in. thick wooden support board, this provided all the structure required. (Figure 3.1.3) These constructed units comprised of a diffuser, the sprayed foam, and the support board which were then installed into the outer shell of the acoustical panels along with the absorption on the reverse side.

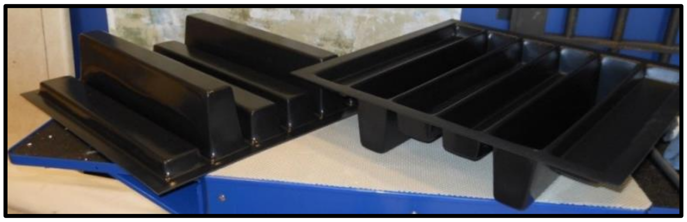


Figure 3.1.2: Acoustical Panels – Schroeder-style diffusers before installation

Figure 3.1.3: Acoustical Panels – Diffuser constructed with foam backing & support board

The absorptive sides of the acoustical panels are comprised of three layers of Roxul stone wool insulation, which is manufactured from volcanic rock and has both excellent acoustical properties and fire resistance. (Figure 3.1.4) Three different densities of Roxul insulation were used for construction: RHT-40 (least dense), RHT-60, and RHT-80 (densest). These densities each have different absorption coefficients across the frequency spectrum, with RHT-40 performing better at high frequencies and RHT-80 better at lower frequencies. Combining the three layers provided the best solution to achieve the highest absorption for the panels. The front of the RHT-40 layer was designed with an acoustically transparent black felt fabric to improve appearance and prevent handling issues, as the Roxul insulation can be itchy when touched.

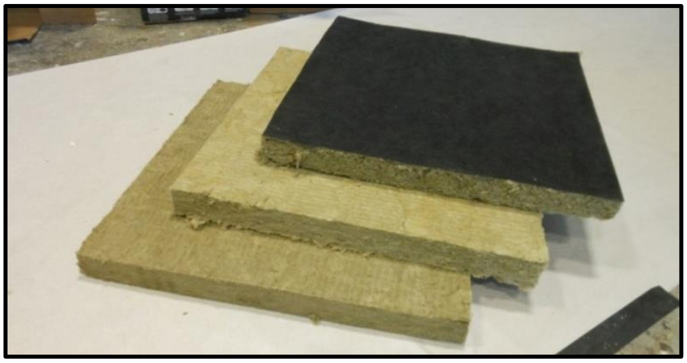


Figure 3.1.4: Acoustical Panels – Three layers of Roxul absorption before installation

The diffusive and absorptive sides of the acoustical panels were installed into exterior shells, manufactured out of 1/8 in. corrugated plastic (similar to mail totes). The edges of each side were sealed with spray adhesive to ensure panel stability and allow for easy installation into the aluminum wall frames. Figure 3.1.5 shows the completed acoustical panels, with both the diffusive and absorptive sides displayed.

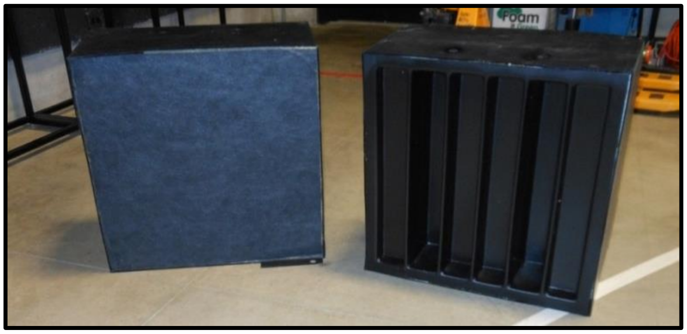


Figure 3.1.5: Acoustical Panels – Constructed units, diffusive and absorptive sides

Once all of the acoustical panels were created, an aluminum support frame was installed on three full walls within the MOCAP facility. The frame was designed to hold four (south wall) or six (north/west walls) rows of panels in a continuous grid. This frame allows each panel to be removed individually and reinstalled with either face showing, absorptive or diffusive. The acoustical panels can be removed from the room completely if desired, although 298 panels of this size take up quite a bit of space. Figure 3.1.6 (a) shows the room in the fully absorptive condition with all panels showing the absorptive sides and Figure 3.1.6 (b) shows the fully diffusive condition with all panels reversed.

The acoustical panels within the MOCAP space allow the ability to create two completely different room states: absorptive and diffusive. The absorptive sides provide an NRC of 0.85 with no diffusion, which simulates a pseudo-anechoic (non-reverberant) environment within the room. With the panels reversed, the diffusive sides introduce a NRC 0.54 surface, while also creating effective diffusive reflections in the mid and high frequencies. With a total surface area of nearly 1200 sq. ft., the acoustical panels can significantly change the sound field within the space. For instance, the Reverberation Times within the decrease from 0.44 s (at 1000 Hz) in the diffusive condition to 0.31 s in the absorptive condition, quite a large change for a space of this size. Aurally, the room change quite a bit as well, with the diffusive room condition sounding much brighter and livelier. Looking at the metrics this might be expected, but the auditory perception between panel states within the room is even greater than the numeric values imply.

The choice to utilize the MOCAP Variable Acoustics Laboratory for this study was very easy to make, as it provided an infinite range of diffusion testing possibilities from a physical testing environment. It allowed for numerous types of tests to be conducted under various conditions to address many issues regarding diffusive room conditions, which are explained in the following sections.

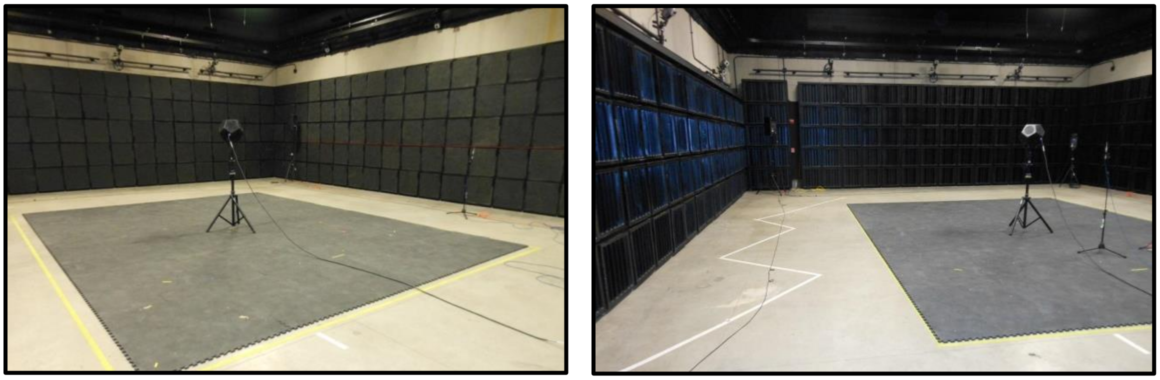


Figure 3.1.6: MOCAP Variable Acoustics Laboratory – After acoustical treatment – (a) Fully absorptive condition & (b) Fully diffusive condition

Physical Testing Setup

3.2.1 Testing Location

After selecting the MOCAP Variable Acoustics Laboratory as the testing space for this study, attention was turned toward defining the research goals, deciding the tests to be conducted, and how they would be undertaken. First, Dr. Dominique Chéenne and Dr. Lauren Ronsse, professors at Columbia College Chicago, were contacted in December of 2015 to gain permission to conduct the study at the MOCAP testing facility. After they both agreed, Frank Sparano (director of the Media Production Center, where the MOCAP is located) was contacted to schedule testing dates. It was agreed that the measurements would take place during the first week of January, 2016 when both the University of Nebraska and Columbia College Chicago were on winter break. The dates scheduled were January 7th and 8th, meaning that all tests were completed in a two day time period. This left little time to waste, as there were many measurements to collect and the sheer physical nature of moving the acoustical panels took a significant amount of time, given the number of setup configurations that were tested. Luckily, the building was free of students and other visitors and no major unforeseen problems arose during the testing days, so all necessary measurements were completed in the time allotted.

3.2.2 Physical Testing Goals

For the overall study, there were two main components driving the direction of the physical testing: subjective perception testing and objective metric analyses. Both of these goals involved using impulse response measurements from the MOCAP space in various diffuser configurations. The unique nature of the MOCAP facility allowed for any number of testing combinations, so it was desired to try and cover as many scenarios as time would allow generating the largest amount of data possible. The physical testing was divided into two main categories: the Wall Tests and the Room Tests. The Wall Tests were conducted on an isolated wall section within the MOCAP space, with the reversible acoustical panels being set up in different configurations of diffusers, absorbers, and reflectors (which will be discussed in more detail below). These Wall Tests specifically analyzed the first order reflections and early decay times from the selected test wall section. The Room Tests, on the other hand, incorporated the entire complement of 298 acoustical panels within the space in different diffuser configurations and coverage percentages. This test provided information on how the room conditions changed as the number of diffusers within the room increased for three different diffuser configurations. These two main testing categories produced wide amounts of useable data in a very efficient way, allowing both subjective perception testing and objective metric analyses to be completed using the same group of collected impulse responses.

3.2.3 Physical Testing Equipment

The equipment utilized in the physical testing of this study was compiled from four sources: the University of Nebraska, Boys Town National Research Hospital, Columbia College Chicago, and the author. All parties provided necessary pieces of equipment, without which the study could not have been completed as constructed.

Sources

- Larson Davis BAS 001 – Dodecahedron Omni Directional Speaker
- Larson Davis BAS 002 – Omni Directional Power Amplifier
- QSC K12 (4) – Powered Directional Speakers
- Electrovoice SX 100 – Directional Speaker
- Crown XS 700 – Power Amplifier
- Speaker Stands (4)

The Larson Davis Omni-directional speaker and amplifier were used in the initial testing of the MOCAP space and were intended as the primary source used in the Room Tests. This plan changed when it was discovered that the speaker created unwanted resonance issues within the room (discussed in a later section); four powered, directional QSC speakers were used in lieu of the Larson Davis in the Room Tests. A directional Electrovoice speaker was used in all Wall Tests. This speaker was selected from a number of models available for use due to its wide, flat frequency response and highly controlled radiation pattern and was driven by the Crown power amplifier. Speaker stands were used in all configurations to place the speakers at the center height (4 – 5 ft. high) of the acoustical panels to maximize the effect of the reflected energy.

Receivers

- Larson Davis 831 Sound Level Meter
- Earthworks M30BX – Omni Microphone
- G.R.A.S. 45BB-2 Kemar Head & Torso
- Microphone Stand & Chair for Kemar

All three of the above receivers, the Omni-directional Larson Davis sound level meter, the Earthworks Omni-directional measurement microphone, and the G.R.A.S. Kemar Head & Torso simulator, were used in all Wall Test and Room Test setups. The Larson Davis 831 sound level meter was utilized as a Type 1 microphone to collect Omni-directional impulse response data for objective metric analysis. It was connected to the input measurement equipment via an XLR cable through the onboard signal output jack. The Earthworks M30BX, a Type 1 Omni-directional microphone as well, included an onboard battery powered preamp, eliminating the need for phantom power. It was also used to collect impulse response data for the objective metric analysis.

The G.R.A.S. 45BB-2 Kemar Head & Torso was a specialized piece of microphone equipment used to simulate human hearing. It included a plastic head the size and shape of an adult male with two Type 1 microphones installed where human eardrums are located. Left and right ear pieces formed from pliable rubber were installed to accurately represent the reflection patterns created from human pinnae. These rubber ears were removable and could be replaced with molded versions from any person's ears to record perfect reflection patterns for that individual. The Kemar head was installed on top of a male torso complete with a t-shirt covering. All of these components accurately represented the auditory effects and resonances that form the overall response in a human ear. This piece of equipment was used to collect impulse response data that would be convolved with audio source material and presented to subjects in perception testing. The unit was sat upright in a chair with the ears positioned at a typical listening height of 4 ft.

Other Equipment

- University of Nebraska Acoustics Computer
    - EASERA Acoustical Testing Software
- Sound Devices USBPre 2 – USB Preamp
- Speaker/Microphone Cables
- Nicon CoolPix S6200 – Digital Camera
- Camera Stand (2)
- Equipment Cart
- Bosch Laser Measure

The physical testing was conducted using the University of Nebraska acoustics computer, using the installed EASERA testing software. This software package was a sophisticated acoustical testing platform which included numerous functions for analyzing sound. In the testing procedure, the impulse response capabilities were used to produce full-frequency (20 Hz – 20000 Hz) swept sine signals, which were generated by the speaker sources and collected by the receivers. For all tests, the sample rate was set at 48 kHz, the bitrate was set at 16 bit, and the time span of the impulse response was set to 683 ms. This combination of sample rate, bitrate, and time span encompassed the full decay of the MOCAP space in all acoustical panel setups and generated the least amount of unwanted resonance within the space. For each collected impulse response, the acoustical parameters (Reverberation Time, Clarity, etc.) were analyzed, the numeric representation of the impulse response was exported for analysis, and the wave file of the recorded decay was exported for convolution.

To send signals to EASERA, the Sound Devices USBPre 2 USB preamp was connected to the acoustics computer. This piece of equipment allowed the sources and receivers to be connected into the computer with minimal electrical noise or latency. All speakers and microphones transferred signals to/from the USB preamp through XLR cables to minimize any unwanted external interference. The Electrovoice speaker was subsequently sent power from the amplifier using a 1/4 in. to banana plug speaker cable, while the QSC speakers were internally powered, negating the need for speaker cabling. All testing setups and other important information were visually documented using the Nicon CoolPix camera attached to a camera stand for stability. The Bosch laser measure was used to record the exact position of all equipment for each test conducted.

Materials

- Sound Absorption Blankets – Used on the Floor
- 1 in. MDF Reflector Panels – Used in the Wall Test

To mitigate a possible first order reflection from the floor between the speakers and the microphones in the Wall Tests, a 4 in. thick sound absorbing blanket was placed on the floor, centered at the reflection point. The purpose was to reduce the level of the floor reflection so that it would not influence the sound being measured from the test wall. From the data collected, this treatment was effective, as no unwanted reflections in the specified time frame were found in the impulse responses.

To create the reflective condition for the Wall Tests (described in the next section), 24 in. by 24 in. reflector panels were constructed by the author. These were made from 1 in. thick medium density fiberboard (MDF) and cut to fully occlude the reversible acoustical panels. Two metal hangers were installed on each reflector to attach to the aluminum support frame. The reflectors represented a hard surface wall (i.e. plaster or concrete) creating specular reflections, as opposed to diffuse or absorptive reflections. These panels were successful in providing a hard comparative surface, as the impulse responses measured in the reflective wall condition displayed much more distinct reflections off of the test wall than either the diffusive or absorptive testing conditions. It should be noted, however, that because these panels were only 1 in. thick, the low frequency performance was likely to be negligible, due to the wavelengths of sound in that range. It was not possible to know exactly how the panel performance decreased at these frequencies, but as the lowest frequency of interest was around 400 Hz the reflector panels were deemed acceptable for the frequency range of interest.

3.2.4 Initial Testing

Before beginning the primary physical testing of the study, a round of initial tests were undertaken to determine whether acoustical conditions within the space, primarily Reverberation Times, changed as the reversible acoustical panels were flipped from absorptive to diffusive and vice versa during the Wall Tests. The goal of the study was to investigate the effects of diffusion, not changes in Reverberation Time or other acoustical metrics, so it was important to keep these properties consistent throughout the different diffusive configurations that were implemented. This meant maintaining less than 5% differences (the Just Noticeable Difference (JND) of human perception for Reverberation Time) between condition states. If differences were found in the acoustical metrics, the deployment of the moveable curtains was considered as a potential source of extra absorption that could be employed.

To determine these effects, impulse responses were collected in the two most extreme Wall Test configurations: fully diffusive and fully absorptive. Several microphone positions were used for these measurements and it was found that the average difference of the Reverberation Time between the diffusive and absorptive Wall Test conditions was 0.03 s (0.46 s vs 0.49 s) for frequencies 250 Hz to 2000 Hz. This placed the spread of the two most extreme arrangements at approximately 5% for the mid-frequency reverberation, which was within JND tolerance. Therefore, it was determined that no room corrections were necessary during the Wall Test procedures.

This was fortunate, as an analysis of the acoustical curtains revealed that there was little difference between curtains when bunched versus when they were unfurled. At all frequencies between 125 Hz and 8000 Hz, there was a Reverberation Time difference of less than 0.02 s between the two curtain conditions, which was below the JND threshold in all octave bands. This was an unexpected result, as the additional surface area of the unfurled curtains was projected to provide more absorption within the space, but because the curtains were not removed from the room, even in the bunched condition, the absorption contributed was consistent between both configurations.

Wall Tests

3.3.1 Wall Tests Setup

The first tests that were conducted in the MOCAP Variable Acoustics Laboratory were the Wall Tests, which concentrated on a relatively small section of the reversible acoustical panels within the space. The purpose behind these tests was to investigate the effects caused by changing an isolated wall from a diffusive surface to an absorptive surface, specifically studying the early portion of the impulse response where first order reflections are prominent. To accomplish this, a wall section was changed gradually in a large number of steps from fully diffusive to fully absorptive, taking measurements at each configuration of the acoustical panels. The selected test wall was comprised of 32 acoustical panels, arranged four high and eight wide. As each panel was 2 ft. by 2 ft., this equated to a surface 8 ft. high by 16 ft. wide for a total area of 128 sq. ft. The test wall was positioned in the center of the North wall, which had the most acoustical panels, to minimize the influence of unwanted reflections from other surfaces.

Figure 3.3.1 shows the position of the selected test wall as well as the speaker and microphone locations. The speaker chosen for this test was an Electrovoice SX 100 directional loudspeaker powered by a Crown XS 700 power amplifier. The directional speaker type was chosen so that the primary sound radiation was directed at the test wall and not spread throughout the room. In the Wall Tests, the speaker was aimed at the center of the test wall and was positioned at a distance (~25 ft.) so that the sound radiation drop-off angles were located at the edges of the test wall.

There were a total of three receiver positions for the Wall Tests, as shown in Figure 3.3.1. It should be noted that two full cycles of the Wall Tests were necessary, both utilizing the same procedure. The purpose of the two cycles was to increase the number of receiver positions. Because it was also desired to measure the position of the Kemar with an Omni-directional microphone, the process needed to be completed twice. The first cycle included the Kemar Head & Torso in position one and the Earthworks microphone in position two. The second cycle had the Earthworks microphone placed in position one at the exact height where the Kemar was located and the Larson Davis microphone in position three. Throughout each cycle, all microphones remained stationary for all acoustical panel testing configurations to eliminate the possibility of changing measured acoustical conditions based on altering the position of the receivers.

Equipment	**X**	**Y**
Kemar/EW 2	25.2’	13.5’
Earthworks 1	29’	10.5’
Larson Davis	20’	10’
EV Speaker	20.8’	28’

- All measurements given from the lower left corner of the room.
- The Kemar was facing towards the center of the test wall.
- All receivers were placed at a listening height of 4’.
- An acoustical blanket was placed on the floor at the reflection point between the speaker and the Kemar.
- The receivers were positioned close to the test wall to isolate its effects, but far enough away to be in the farfield of the diffusers above 500 Hz.

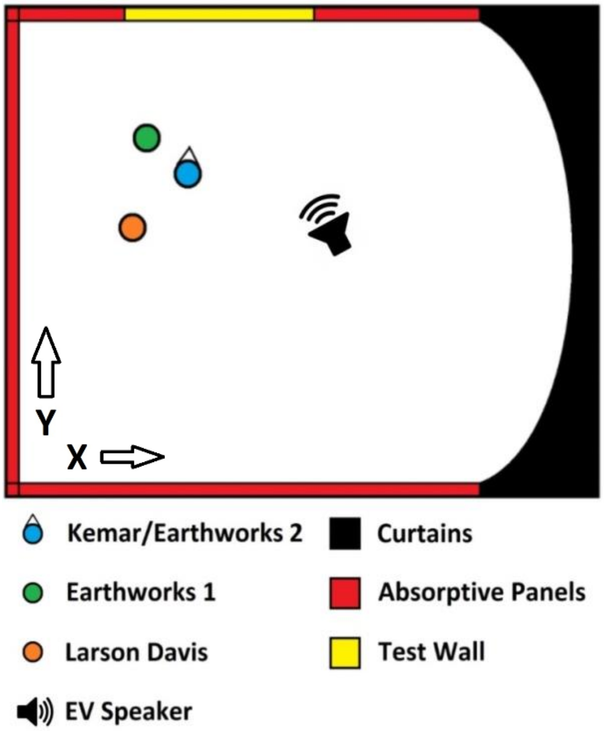


Figure 3.3.1: Wall Tests setup

3.3.2 Wall Tests – Diffusers & Absorbers

The Wall Tests began with all 32 reversible acoustical panels in the diffusive condition (showing the Schroeder diffuser) and all other panels in the room set to the absorptive condition. (Figure 3.3.2) An impulse response was measured individually for all receivers (One Earthworks microphone and the Kemar Head & Torso as shown in this example) with the wall in this configuration. Two acoustical panels were then reversed and turned from the diffusive side to the absorptive side, decreasing the number of diffusers to 30. Once again, impulse responses were collected from the receivers for this wall condition. The process of flipping the acoustical panels from diffusive to absorptive two at a time continued (i.e. 28, 26, 24, etc.) until eight panels remained diffusive. Figure 3.3.3 shows the test wall in two intermediate steps of sixteen and eight diffusers showing.

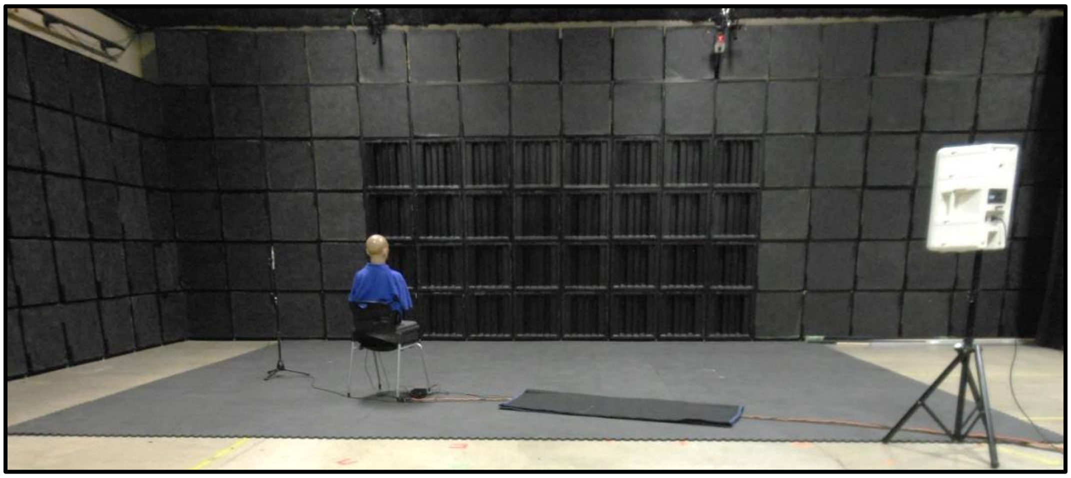


Figure 3.3.2: Wall Tests – Diffusers vs Absorbers – All reversible acoustical panels in the diffusive condition

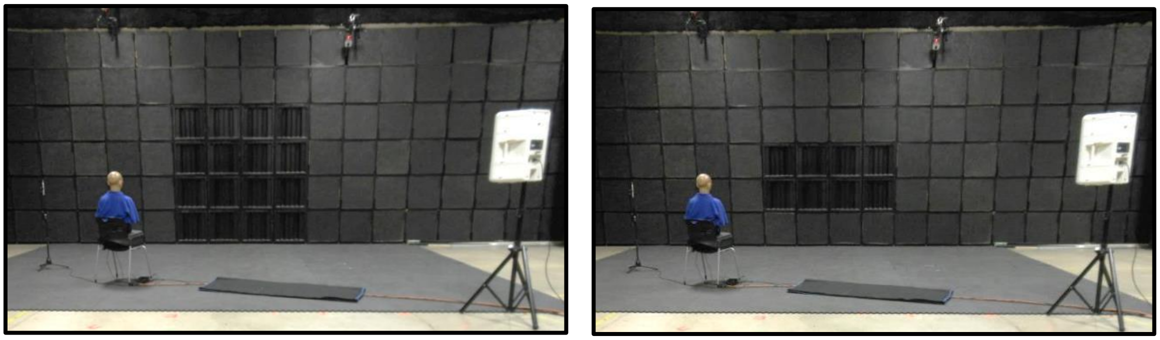


Figure 3.3.3: Wall Tests – (a) 16 Diffuser panels displayed and (b) 8 Diffuser panels displayed

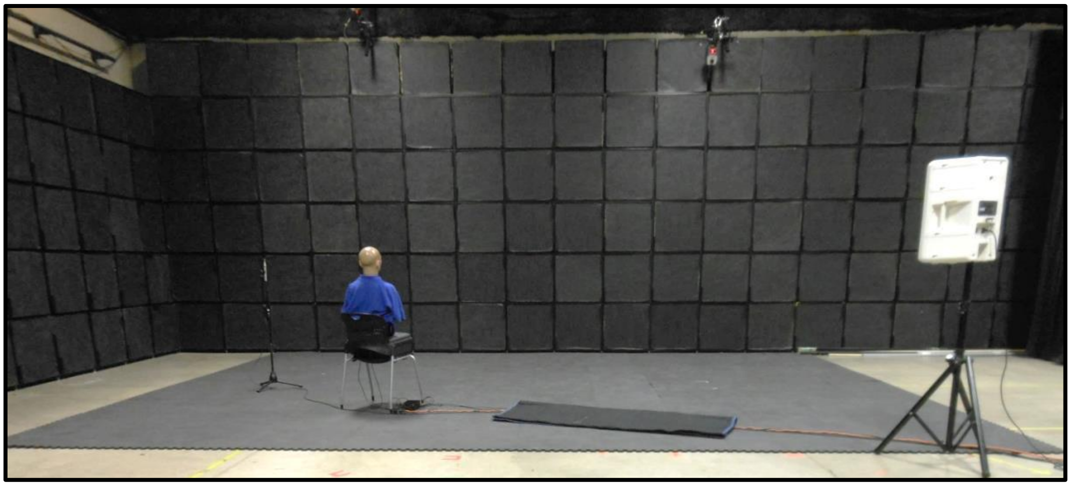
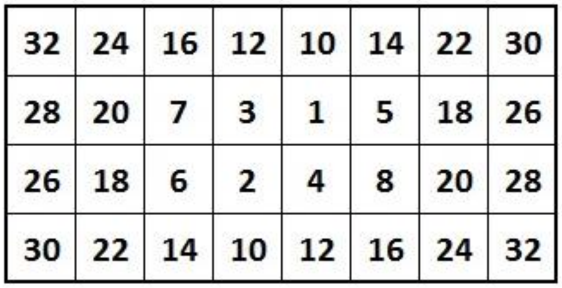


Figure 3.3.4: Wall Tests – Diffusers vs Absorbers – All reversible acoustical panels in the absorptive condition

Starting with eight diffusers remaining, one panel was turned at a time between wall states (i.e. 8, 7, 6, etc.) until the test wall was in the fully absorptive condition with zero diffusers showing. (Figure 3.3.4) In total, 21 wall conditions were measured, representing a gradual change from a fully diffusive to a fully absorptive test wall.

Figure 3.3.5 displays the order in which the reversible acoustical panels were changed from diffusive to absorptive. Beginning with 32 diffusers, two panels were flipped at a time. The process decreased the number of diffusers with each step while maintaining a roughly rectangular shape overall. At eight diffusers remaining, the acoustical panels were flipped one at a time in a symmetrical order to maintain consistency. This process was completed for both test cycles to collect the same diffusive wall conditions for all receiver positions.



32	24	16	12	10	14	22	30
28	20	7	3	1	5	18	26
26	18	6	2	4	8	20	28
30	22	14	10	12	16	24	32

Figure 3.3.5: Wall Tests - Reversible acoustical panel flipping order

3.3.3 Wall Tests – Diffusers & Reflectors

The above section described the conducted Wall Tests using the diffusive and absorptive acoustical panel configurations. These tests provided information comparing the two different surface types, beyond the fact that both decreased reflected sound strength. Now consider the difference between a diffusive surface and a hard reflective surface. This situation is much more common in typical buildings, such as when wall or ceiling diffusers are installed on surfaces with low absorption coefficients, such as gypsum, plaster, or concrete. In these situations, diffusers are used prevalently to eliminate unwanted reflection without removing sound energy from the space, such as at the rear wall of a concert hall or in a studio control room. The question becomes: How large of a diffusive surface is necessary to accomplish this task?

This was the reasoning behind conducting the Wall Tests comparing a diffusive surface to a reflective surface. To accomplish this, the reflector panels built by the author were installed on the test wall to obscure the reversible acoustical panels, creating a large specularly reflecting surface that would simulate a hard surface. (Figure 3.3.6) The acoustical panels behind the reflectors were set up in the diffusive condition for two reasons: to ease the process of reversing the panels between the diffusive and reflective conditions and to maintain the amount of test wall absorption behind the reflectors. This second point was important, for while the MDF panels reflect mostly mid and high frequency sound, low frequency sound would pass through them easily, as they were only 1 in. thick. It was therefore necessary to keep the acoustical panels behind the reflectors in the diffusive state so as to not increase the amount of absorption in the space.

The procedure for the Wall Reflection Tests was identical to the diffusion and absorption tests. The exact same speaker, microphones, and setup configurations were used in these tests as before, shown in Figure 3.3.1. The reversal methodology for changing the acoustical panels between wall conditions was maintained as well, although instead of starting in the fully diffusive condition (to be changed to fully absorptive), the test wall was setup in the fully reflective condition, shown in Figure 3.3.6. The diffusers were then revealed by removing reflector panels one at a time for the first eight (i.e. 1, 2, 3, etc.) and then two at a time for the remaining acoustical panels (i.e. 8, 10, 12, etc.), following same the pattern depicted in Figure 3.3.5. Figure 3.3.7 shows two intermediary steps with four and sixteen diffusers revealed. Again, impulse responses were taken from all receivers in the 21 wall states throughout the procedure of the Wall Reflection Tests.

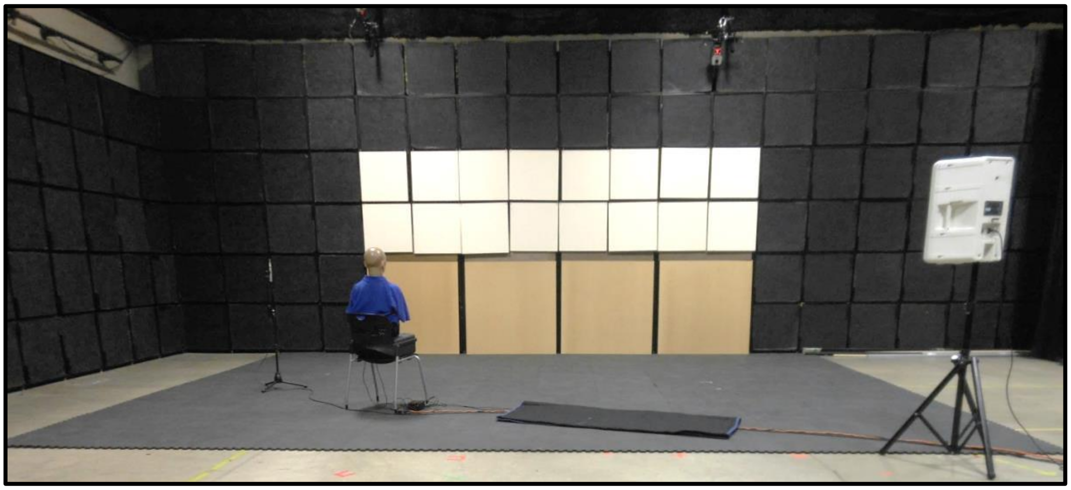


Figure 3.3.6: Wall Tests – Diffusers vs Reflectors – All reversible acoustical panels in the reflective condition

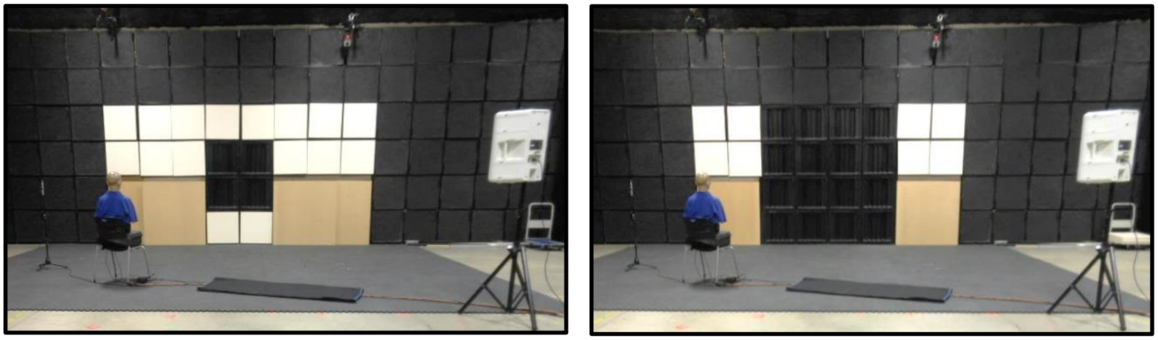


Figure 3.3.7: Wall Tests – (a) 4 Diffuser panels displayed and (b) 16 Diffuser panels displayed

Room Tests

3.4.1 Room Tests Setup

In addition to studying the effects of diffusion from an isolated wall section, it was also desired to investigate the effects caused by changing the diffusive conditions throughout an entire room. As the MOCAP Variable Acoustics Laboratory was constructed with reversible acoustical panels on three full walls, it was the perfect facility to research such a phenomenon. In the Room Tests, all 298 acoustical panels were utilized (as opposed to only 32 in the Wall Tests), changing from fully absorptive to fully diffusive. The primary question became: How could this transition between panel conditions be accomplished, because there were innumerable setups that could have been used with step sizes as small as one panel at a time.

Ultimately, it was decided that three different diffuser configurations would be used in converting the acoustical panels in the MOCAP space between fully absorptive and fully diffusive states. The three testing configurations were implemented to research whether the pattern in which the acoustical panels were flipped impacted the measured impulse responses. The three configurations were selected based on typical placements of installed diffuser panels in actual rooms. The first setup placed the diffusers at the midpoints of the walls, the second setup was a random configuration, and the third was a top-down order, starting with the top row of the acoustical panels and flipping them in downward steps until reaching the floor with all panels showing the diffusive side.

The step size between subsequent measurements was chosen to be 30 acoustical panels, which represented approximately 10% of the acoustically adjustable surface area. For each of the three diffuser configurations, measurements were taken at six different diffuser coverage percentages: 10% (30 diffusers showing), 20% (60 diffusers showing), 30% (90 diffusers showing), 40% (120 diffusers showing), 50% (150 diffusers showing), and 60% (180 diffusers showing). Finally, measurements were collected for the fully absorptive room condition and the fully diffusive room condition (Figure 3.4.1).

Figure 3.4.1: Room Tests – (a) Fully absorptive diffuser condition & (b) Fully diffusive diffuser condition

Two additional coverage percentages were measured for the top-down configuration: 70% (210 diffusers showing) and 80% (240 diffusers showing), taken during the conversion between the 60% coverage and the fully diffusive conditions. Given logistical reasons (MOCAP availability constraints, physical demands on the author, etc.), it was decided to limit the first two acoustical panel configurations to six diffuser coverage percentages. In the end, this decision was not a hindrance to the analysis of the data, as six analogous measurements were collected for the three setups, allowing comparisons of performance to be made.

The equipment utilized in the Room Tests was similar to that of the Wall Tests, with some modifications due to the setup requirements of testing the entire space. The receivers used in the Room Tests were the same: Earthworks microphone, Larson Davis sound level meter, and Kemar Head & Torso. The software, USB preamp, and associated connection hardware remained the same as well. However, the sources changed between the Room Tests and the Wall Tests. In the Room Tests, four QSC powered loudspeakers were set up in quadrature: the four speakers were aimed at the corners of the room, approximately 9 ft. away and 5 ft. in height. This method of impulse response collection is described in Appendix X2 of the ASTM C-423 testing standard for field collection of decay rates and room sound absorption. [4] Figure 3.4.2 displays the orientation of the four speakers and the microphones positioned in the center of the room.

Equipment	**X**	**Y**
Kemar	20.5’	22’
Earthworks	25.5’	23’
Larson Davis	15’	18’

- All measurements given from the top left corner of the room.
- The Kemar was facing towards the top of the room.
- All receivers were placed at a seated listening height of 4’.

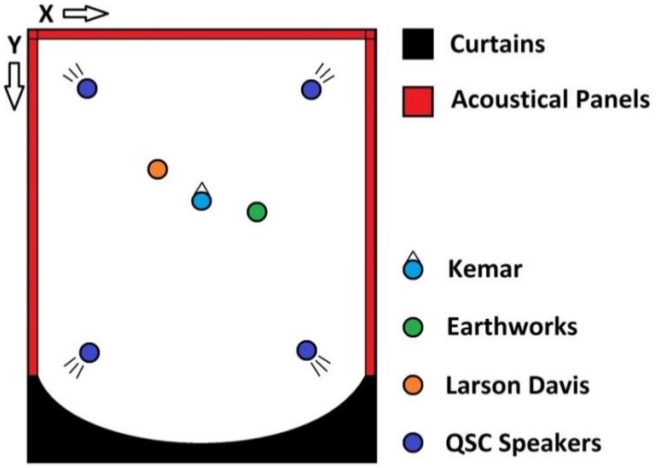


Figure 3.4.2: Room Tests setup

In the Room Tests, the three receivers (Earthworks, Larson Davis, and Kemar) were positioned in the center of the room to minimize the effects of direct sound, thereby measureing the most homogeneous acoustical conditions within the space. Also, there was only one cycle of tests for each of the three acoustical panel configurations, due to the time constraints reversing large number of panels between conditions posed, which meant all three receivers remained stationary for the duration of all Room Tests. Regarding the Kemar, it was faced towards the top of the room (as shown in Figure 3.4.2) which resulted in the acoustical panels being located on both the left and right side of the head as well as the front. This allowed the Kemar Head & Torso to experience the largest effects possible from the acoustical panels.

Once again, impulse responses were collected for the Room Tests (using the same setup parameters detailed above) for each receiver in all acoustical panel configurations.

To start, measurements were taken for the room in the fully absorptive condition, as shown in Figure 3.4.1. Next, the tests for the first panel configuration were completed, with the diffusers placed at the midpoints of the walls, expanding horizontally as diffusion coverage percentages grew. Figure 3.4.3 shows four iterations of this setup: 10% (30 diffusers), 20% (60 diffusers), 40% (120 diffusers), and 60% (180 diffusers). Data was also collected for the 30% and 50% coverage percentages, but pictures were omitted to conserve space. Because there were a total of 15 rows of acoustical panels between the three test walls, the selection of flipping 30 panels worked out quite well, as it resulted in two vertical rows on each wall being changed from absorptive to diffusive between each subsequent test configuration.

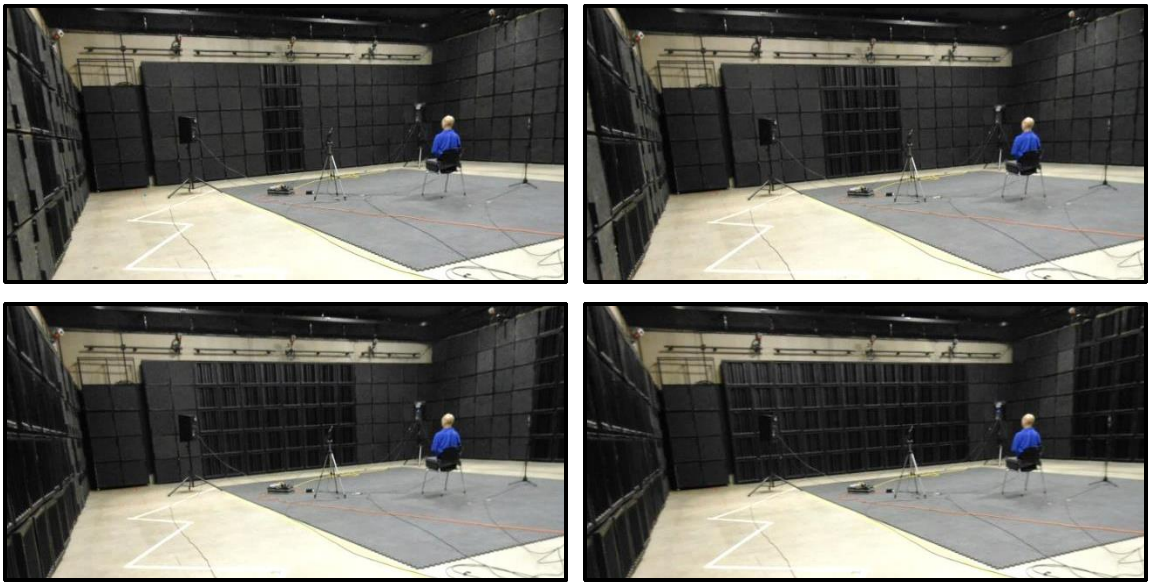


Figure 3.4.3: Room Tests – Midpoint of the Walls Orientation – (a) 10% Coverage (30 Diffusers), (b) 20% Coverage (60 Diffusers), (c) 40% Coverage (120 Diffusers), & (d) 60% Coverage (180 Diffusers)

Once the six coverage percentages were measured for the midpoint of the walls diffuser configuration, the Room Test measurements utilizing the random configuration were conducted. Again, the process began with a coverage percentage of 10% (30 diffusers) and concluded with a coverage percentage of 60% (180 diffusers), with each subsequent round of tests flipping 30 acoustical panels from the absorptive side to the diffusive side, this time in random order. (Figure 3.4.4) There was no specific pattern that was involved in reversing the panels, but the number of panels flipped on each wall was kept constant between each iteration and set relative to the total number of acoustical panels per wall: the left wall (as pictured) flipped eight panels, the center wall flipped ten panels, and the right wall flipped twelve panels (that wall contained the most diffusers).

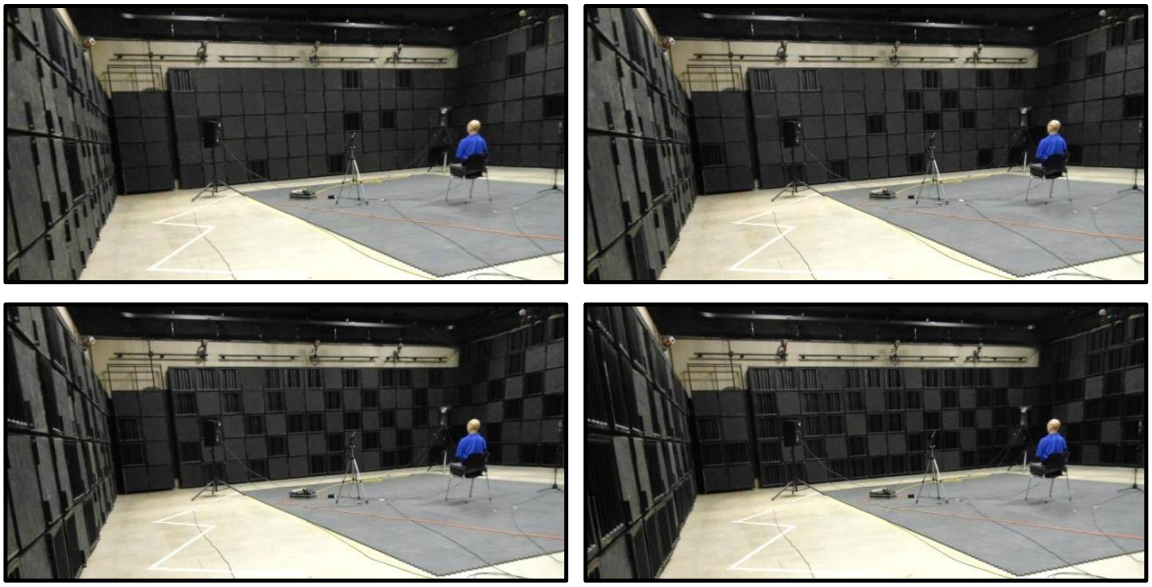


Figure 3.4.4: Room Tests – Random Orientation – (a) 10% Coverage (30 Diffusers), (b) 20% Coverage (60 Diffusers), (c) 40% Coverage (120 Diffusers), & (d) 60% Coverage (180 Diffusers)

To complete the Room Tests, a final round of measurements was conducted using the top-down acoustical panel configuration. In this setup, 30 panels were flipped between configurations, starting at the top row and working downward until all acoustical panels were showing the diffusive side. (Figure 3.4.5) The panels were evenly distributed on the three walls between conditions as the number of diffusers increased. Because this was the final testing cycle, additional coverage percentages of 70% (210 diffusers) and 80% (240 diffusers) were taken in route to the final configuration of the room, the fully diffusive condition with all acoustical panels showing the Schroeder diffusers.

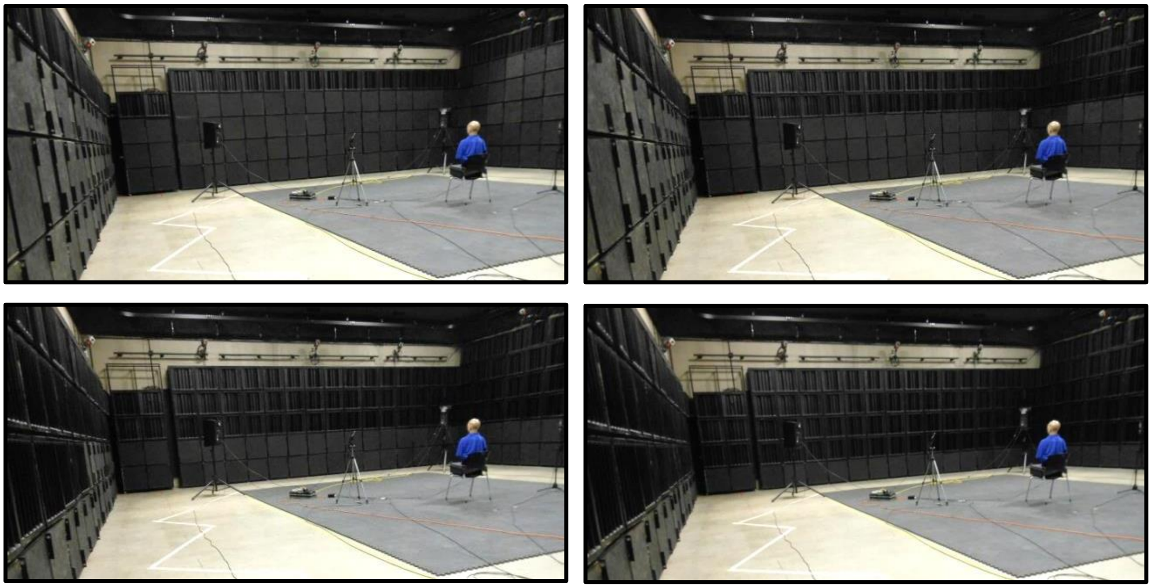


Figure 3.4.5: Room Tests – Top-Down Orientation – (a) 20% Coverage (60 Diffusers), (b) 40% Coverage (120 Diffusers), (c) 60% Coverage (180 Diffusers), & (d) 80% Coverage (240 Diffusers)

3.4.2 Room Tests Speaker Choice

There was a specific reason for using four QSC speakers setup in quadrature in the Room Tests as opposed to the preferred Larson Davis Dodecahedron speaker. The Larson Davis was an Omni-directional source, which would have provided a known sound radiation position, which the four corner facing QSC speakers precluded (as the sound was generated from four distinct locations). However, the Dodecahedron could not be used within the MOCAP due to immovable equipment in the space, specifically a fly-rig system installed on the ceiling in the center of the room. This large metal box resonated significantly when taking measurements using the Omni-directional source, caused by sound energy being directed upward. This corrupted all impulse response data between 200 – 500 ms while using the Dodecahedron in all source positions attempted. Because the decay of the MOCAP space ended at about 500 ms, this rendered the Larson Davis source useless, forcing the implementation of the quadrature speaker setup, which minimized the upward directed sound energy, eliminating impulse response corruption.

Physical Testing - Data Analysis

3.5.1 Collected Data

In total, there were 298 impulse responses collected during the physical testing procedure within the MOCAP, which included three primary testing configurations (Wall Absorption Tests, Wall Reflection Tests, and the Room Tests) and numerous microphone setups (Earthworks, Larson Davis, Kemar Head & Torso Left & Right ears). Looking specifically at the diffuser setups, there were 64 unique diffuser configurations tested: 21 in the Wall Absorption Tests, 21 in the Wall Reflection Tests, and 22 in the Room Tests. Grouping the data by test configuration and microphone location, there were 22 ‘testing groups’ for the entire dataset. This broke down into 5 groups for the Wall Absorption Tests (Earthworks 1 & 2, Larson Davis, and Kemar Left & Right) and 5 groups for the Wall Reflection Tests (the same microphones). There were a total of 12 testing groups for the Room Tests, comprised of three groups for each of the diffuser configuration arrangements (diffusers at the wall midpoints, random, & top-down order) for each of the microphones used. These testing groups were formed because of data disparities found between microphone setups, as the values from some testing groups were much larger or smaller than in other testing groups, meaning that comparisons between groups could not be calculated. This method of studying the data by test configuration and microphone setup was used throughout the analysis process, allowing this large dataset to be analyzed to find meaningful correlations between the collected values.

The first step in analyzing the immense quantity of impulse response data was to download all available information from the Easera testing software into Microsoft Excel.

A data collection spreadsheet was created that compiled all relevant data, broken down by testing configuration, microphone used, and diffuser conditions. Provided in the downloaded data were the Reverberation Times in 1/1 and 1/3 octave frequency bands for Early Decay Time (EDT), T10, T20, and T30 extrapolation times, Clarity in 1/3 octave bands for C7, C50, and C80, Definition in 1/3 octave bands, speech metrics such as Articulation Loss of Consonants (AL_{Cons}%) and Speech Transmission Index (STI), as well as spectral frequency plots. Also included in the download was numeric impulse response data, comprised of time (in seconds) and pressure (in Pascals) for all sampling points (determined by the sample rate of 48 kHz). Finally, the Energy Time Curve (ETC) graph (shown in Figure 3.5.1) was downloaded for each impulse response. These graphs display the energy decay of the collected impulse response which can be used to visually identify room reflections, acoustic defects, and other phenomena. The populated data collection spreadsheet only represented the first step in the analysis procedure, from which subsequent calculations stemmed from.

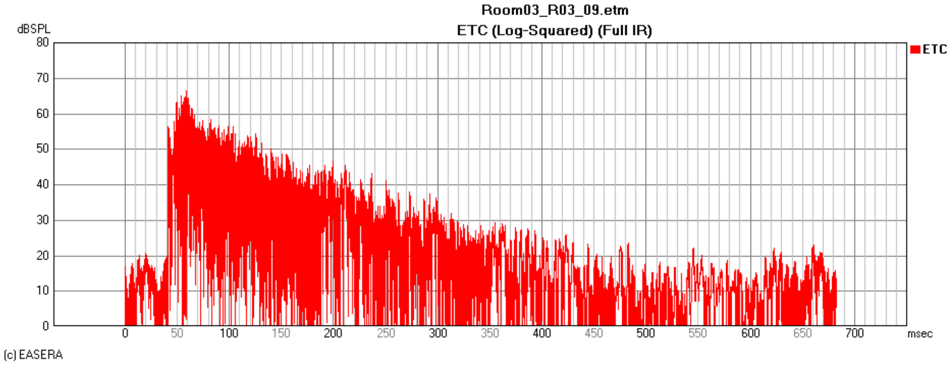


Figure 3.5.1: Energy Time Curve graph for an example impulse response

While it was possible to find useful information studying the individual acoustical values produced by the impulse responses, it was not until the data was compiled that substantive findings could be made. To accomplish this, the most important acoustical metrics (Reverberation Time, Clarity, Definition, as well as STI & AL_{Cons}% speech metrics) for each measurement were copied a second time into a separate analysis spreadsheet. For all measurements, the diffuser configuration was recorded as well, which included the number of diffusers or the diffuser coverage percentage in addition to the room configuration. It was then possible to look at large sections of the collected data in aggregate and analyze any potential correlations.

3.5.2 Basic Physical Testing Data Analysis

The first method used to look at the compiled acoustical metric data was to compute the range within of each testing group and the differences between individual measurements for the selected metrics. For example, the 500 Hz octave band for the T30 Reverberation Time was investigated for the Wall Absorption Tests using the Earthworks microphone testing group. In this example, the 500 Hz T30 Reverberation Time ranged between 0.32 s and 0.35 s, a span of 0.03 s. This difference was below the 5% JND threshold of Reverberation, so these differences would not be discernable by the average human. These range and difference comparisons were computed for all impulse responses to determine whether statistical changes in the selected acoustical metrics were present in the data generated under the different acoustical panel configurations.

For both Wall Test configurations, it was found that for greater than 90% of the tested metrics, the differences between the most extreme diffuser conditions tested (0 diffusers and 32 diffusers) were lower than the JND thresholds. These results indicated that there was very little change in the overall acoustical conditions within the MOCAP testing facility between the various diffuser configurations used during the Wall Tests. This was an expected (and desired) result because the test wall for this part of the study was only 128 sq. ft. in surface area, a very small percentage of the 7600 sq. ft. total surface area in the space. One of the intents of this research was to look at changes in diffusive room conditions without changing other acoustical conditions within the space; the results of the metric analysis confirmed the physical testing produced viable data. By keeping all ancillary acoustical metrics (Reverberation Time, Clarity, etc.) constant while changing the number of wall diffusers, the data collected by the impulse responses for the Wall Tests solely measured the differences in diffusive conditions. Therefore, this impulse response data was deemed acceptable to research how the change in diffusive conditions impacted subjective perception and objective analysis metrics.

The Room Test data was also analyzed using the basic methodologies of range and differences, though the results were less revealing. There were clear differences between the min and max values of the room configurations: the fully absorptive and fully diffusive room conditions. However, this variation was fully expected, as audible differences could be heard while the testing was taking place, with the fully diffusive condition seeming much more reverberant than the fully absorptive condition. In fact, there were some instances where the differences between subsequent measurements (such as 20% and 30% coverage percentages) were great enough to be discernable to the ear. Therefore the comparisons of the acoustical metrics in the Room Tests were only useful for numerically confirming the observations of the author.

3.5.3 Statistical Analysis of Physical Testing Data

In addition to the basic analysis, the compiled acoustical metric data statistically analyzed using linear regression models in SAS, Statistical Analytics Software. Each individual metric value (i.e. T20 reverberation time at 500 Hz) was correlated with the number of diffusers (for the Wall Tests) or the diffuser coverage percentage (for the Room Tests) for each test grouping to determine whether any linear trends were evident in the acoustical metric data that was not evident in the basic analysis.

For the Wall Tests, greater than 50% of the statistical tests generated significant results with p-values less than 0.05, indicating linear correlation between the test data and the diffusive wall conditions. However, the range of data still needed to exceed the JND threshold, which many of the collected metrics did not exceed (even though they were statistically correlated). For the Room Tests, there were consistent significant findings between the diffuser coverage percentages and the tested metrics. In particular, high frequency values of Reverberation Times, Clarity, and Definition were highly correlated to the diffusive room conditions. These findings confirmed both the basic statistical analysis findings as well as the perceptions of the author during testing. Due to these results, the impulse responses that were used to present auralizations to subjects in Room Test groupings were all grouped by diffuser coverage percentage, rather than microphone or diffuser configuration. For example, this meant that diffuser setup A at 20% coverage percentage was compared with diffuser setup B at 20% coverage percentage, as opposed to comparing diffuser setup A at 10%, 20%, 30%, and so on.

The data analysis of the generated acoustical metrics for the collected impulse responses provided significant information about the acoustic conditions within the MOCAP testing facility. It was invaluable in determining the consistency of the data from the Wall Tests and whether the analysis of diffusion would be free of influence from ancillary acoustical factors. This process also provided insight into the methodologies needed to present Room Test auralizations to subjects. Overall, this data analysis was a necessary step in the study, allowing the subjective perception testing and objective metric analyses to commence.

Chapter 4

Subjective Perception Testing

4.1.1 Perception Testing Goals

With the physical testing initial data analysis phases of the study completed, the next step was to use the collected data to answer specific questions regarding diffusion. The first part of this analysis, discussed here in Chapter 4, incorporated the use of human participants in subjective perception tests of diffusive room conditions; the second part of the analysis was the examination of several objective diffusion metrics, to be discussed later in Chapter 5. The subjective perception tests involved processing the collected impulse responses to create room auralizations (audio representations of the room) which would then be played for test volunteers in selected combinations. The information generated from each individual subject was then collected and compiled to form a complete test group allowing meaningful generalizations to be proposed. As described in Chapter 3, there were three main subdivisions of collected data: the Wall Absorption Tests, the Wall Reflection Tests, and the Room Tests. Each of these configurations represented three different sets of questions that could be posed and were thus presented to subjects separately, with each group independent of the others.

The Wall Absorption Tests addressed how well the difference between an isolated wall in diffusive and absorptive conditions could be discerned. For example, this could occur for an acoustical consultant when designing a room: choosing between a diffuser and an absorber in a potential installation. Specifically, these Wall Tests determined the diffuser area required to differentiate between the diffusive and absorptive acoustical panel conditions. This value was then used to calculate the percent between the diffusive area and the total test wall area (128 sq. ft.), which also defined the JND of the two wall states. In addition, comparisons between diffuser sizes were analyzed, such as four diffusive panels versus eight, to determine whether doubling or quadrupling diffuser area was distinguishable. This provided information on how well people could discriminate diffusers of differing coverage areas, which could influence the selection of diffuser dimensions when designing room acoustics.

The Wall Reflection Tests were aimed at answering how well the difference between an isolated diffusive and reflective wall could be discerned. This setup was more analogous to the installation of a diffuser onto an existing hard surface, such as in a concert hall or listening room. It is commonplace to prescribe diffusion to eliminate an unwanted reflection or to increase the homogeneity and isotropy of a space, but what is rarely known is how much diffusion is necessary. Generally, the approach is rather empirical, based on the experience of the acoustician or past performance of other similar venues. Given the cost of installing diffusers, though, the results of this could be very valuable when relating to the construction of new rooms. The same test methodology used for the Wall Absorption Tests was also implemented for the Wall Reflection Tests. Similar to before, the diffuser size necessary to be distinguished from a completely reflective surface was investigated, as well as comparisons of different diffuser coverage areas (doubling and quadrupling) on the reflective wall.

The Room Tests, in contrast to the Wall Tests, addressed the effects of diffusion on a much larger portion of the surface area within the MOCAP space. In this testing configuration, the primary question addressed whether the placement of the diffusers within the room perceptibly affected the acoustical conditions. Also, it was investigated whether the audibility of the different testing configurations changed with the diffuser coverage percentage area. To accomplish this, three different acoustical panel configurations were compared at each of the percentage coverage levels (10%, 20%, etc.). The results from the Room Tests could impact the implementation of diffusers in the design of rooms, as differences were found in the effectiveness of the tested room configurations. Together with the perception information from the Wall Tests, the data serve as a step forward in understanding how well humans can discern differences in the diffusive properties of a physical testing environment.

4.1.2 Room Auralizations

The first step in the subjective perception testing process was producing the audio auralizations. Binaural impulse responses collected from a Kemar Head & Torso were convolved with an anechoic source file to produce a single audio file, representing the anechoic source file being played within the tested room. Binaural audio files were created for all of the different room conditions using the same anechoic source files, allowing the comparison of the room response in each of the different room states.

Auralizations were also created using impulse responses taken from the Omni-directional receivers (Earthworks & Larson Davis) for a limited number of measurements and compared with those produced by the Kemar Head & Torso. It was readily apparent that the stereo representations produced by the two ears of the Kemar were clearly more realistic than either of the Omni-directional room responses. Most importantly, because the Kemar utilized lifelike molded ear pieces, spatial conditions within the MOCAP space were recorded accurately for human pinnae, which meant that the directionality of the incoming sound captured by the Kemar was preserved.

There were a total of five different anechoic source files that were used in the convolution process, although only two of them were ultimately presented to subjects. All of the source files were from the Odeon 6.5 Wave Signals collection, accessed from the Nebraska Acoustics Group Box folder online. The anechoic signals were selected to provide a wide variety of source material: a male voice, a female voice, a violin playing a passage from Boccherini, a trumpet playing a section of Somewhere Over the Rainbow, and a classical guitar playing a passage from Bach. These audio files were all very cleanly recorded (an important factor when performing convolution) and they all concentrated the frequency content in the mid and high ranges (500 Hz – 2000 Hz), the effective frequency range of the diffusers in the MOCAP space.

To create the room auralizations, Matlab was used to perform all of the necessary steps. First, the impulse response wave files (from the left and right ears of the Kemar) and the anechoic wave files were read into the program numerically using the audioread() command. This created a data matrix representation of the audio files, with the time on the X-axis and the pressure on the Y-axis. Next, the conv() convolution command was issued, using both the anechoic source and the impulse response matrices. The produced convolutions then required normalization to limit the values to between 0 and 1. This process did not change the relationship of the convolved data but was needed to eliminate distortion when converting the matrices back into audio files. Finally, the audiowrite() command was used to produce audio wave files of the convolved matrices.

The described process was conducted for all 298 impulse responses collected from the two Wall Tests and the Room Tests using all five of the anechoic source files. In total, 1490 convolved audio files were created for use in subjective perception testing. These audio files were then analyzed by the author to determine which were the most viable for the perception tests. It was decided that both a speech signal and a music signal would be presented to subjects to determine whether these signal types produced different perception results. In the end, the male voice was chosen as the speech signal (over the female voice) because the dictation was clearer and audio quality was better. For the music signal, the violin piece was chosen because it provided the largest distinction between the different audio files. The guitar and trumpet files were both viable presentation choices, but due to the audio content of these wave files, the task of distinguishing between the room conditions would have been much more difficult.

Once the Male Speech and Violin Music auralizations were selected, the audio files created using the left and right ears of the Kemar were combined into single stereo tracks using Adobe Audition audio editing software. These files were then cropped so that all of the presented tracks played the desired audio section with a consistent time length: 5.5 seconds for the male speech and 6.5 seconds for the violin. The levels of the audio files were also normalized between the different room conditions to eliminate the possibility of level being a contributing factor in the perception analysis. These volume differences between the created audio files ended up being quite small, but any change in level could have factored into subject testing, so it needed to be controlled. The final result of the auralization process was a collection of 128 stereo audio wave files, 64 using the male speech and 64 using the violin passage, which represented the 64 distinct wall and room configurations measured in the MOCAP Variable Acoustics Laboratory. These files were presented to subjects to address the perception of diffusive room conditions for both the Wall Tests and Room Tests.

4.1.3 IRB Application

To conduct the subjective perception tests, approval was required from the University of Nebraska Institutional Review Board (IRB) to determine whether the study was safe to conduct on human subjects. This process required submission of an application which stated the intended goals of the study, the potential risks involved to any participants, the information that was hoped to be gathered, the methodology that would be used, and any associated documentation from the study. The forms were submitted for the author, Jay Bliefnick, under the advisement of Dr. Lily Wang. The information provided to the IRB was essentially a condensed version of the goals and procedures outlined in this document. Also included were copies of the pamphlets that advertised the study to potential volunteers, the subject email contact template, the participant questionnaire (asking age, gender, and musical background), as well as the informed consent form that subjects were required to sign, which spelled out the process of their involvement with the study. Once all information was provided to the IRB and the review process was completed, the subjective testing commenced.

4.1.4 Subject Selection

The subjects recruited for the study were any individuals with ‘normal’ hearing, identified by having hearing thresholds less than 25 dB HL between 125 Hz and 8000 Hz. No delineation was made for age or gender, although a roughly even split between genders was desired. Subjects were not required to have any experience in music, although this information was asked for each participant to correlate with subjective perception results. The subject pool could have been limited to musicians, but a cross section of the entire population was desired, not just the subset of musicians. This might have impacted overall results but also allowed for the comparison between musicians and non-musicians, an interesting analysis in itself. Table 4.1.1 displays the demographic information for all subjects in the study. The gender split was 15 male and 10 female, and the age range was from 19 to 54. Musical experience was spread over the four potential groupings (0 – 3 years, 3 – 5 years, 5 – 10 years, & 10 + years) with the majority of subjects in either the first or last group. The split between musicians (5 – 10 years & 10 + years groups) and non-musicians was 10 musicians to 15 non-musicians.

Table 4.1.1: Subject demographic information: Gender, age, & musical experience

Subject Demographics

Gender	M	M	F	M	M	F	F	M	M	F	M	F	M	M	F	F	M	M	M	M	F	F	M	M	F
Age	25	26	23	20	29	22	41	28	24	23	27	25	33	26	27	54	23	28	23	22	19	22	23	19	20

Musical Experience	1	1	4	2	1	1	1	4	1	4	1	4	4	1	3	1	4	1	3	4	4	1	2	2	2

* 1: 0 - 3 Yrs, 2: 3 - 5 Yrs, 3: 5 - 10 Yrs, 4: >10 Yrs

A total of 25 participants were tested in the study, providing a sufficient subject pool to achieve adequate statistical power in the analysis. Each subject was compensated with a $30 Amazon gift card for the completion of the approximately 2.5 hour testing period. The compensation was provided from Dr. Wang's discretionary research funds.

Subjective Perception Testing – Setup & Conducted Tests

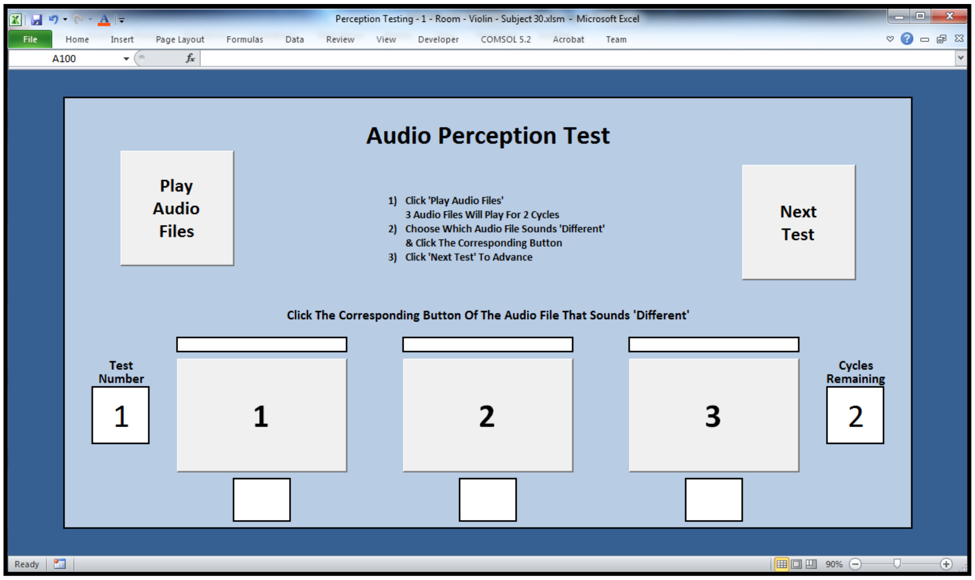
4.2.1 Programs Implemented

Once the room auralizations were created and permission was granted by the University of Nebraska IRB to conduct the subjective perception testing, the next task of the study was to create the testing protocol. There were numerous ways that this process could be completed, but in the end Microsoft Excel was selected to present subjects the various combinations of audio files from the selection of different diffuser configurations. This process was accomplished with the use of the Visual Basic for Applications (VBA) functionality built into Excel, which allowed the creation macros: user written programs accessible within the worksheet interface. Microsoft Excel was chosen for two reasons, the first being the familiarity the author had with the program, the second being the compatibility it provided with the post processing analysis of the subjective testing data. All answers given by the participants were directly copied into a master worksheet to be assimilated and studied. This produced a very efficient procedure, as the same program was used for the testing of subjects, collection of data, and eventual analysis of the compiled information. In addition, the ability of Excel to produce visually attractive graphs, figures, and tables made it a productive choice to utilize for the testing interface.

4.2.2 Subjective Perception Testing Interface

Figure 4.2.1 displays the graphical user interface that was presented to subjects in the perception trials. The layout was quite simple in design to minimize any confusion of participants. The users were presented with five buttons: Play Audio Files, Next Test, and three buttons representing the three audio files that were being compared. The subjects were instructed to press the Play Audio Files button when ready, beginning the sequence of three audio files from different diffusive conditions being played for full two cycles: a total of 6 audio files were played for each particular trial. They were instructed to choose the audio file which sounded ‘different’ by clicking on the associated button, 1, 2, or 3. The bars above the three buttons would light up yellow while the sounds were playing to inform subjects which audio files were associated with which selection; once they clicked on one of the three buttons, the box below the depressed button would highlight red. At that point, the participant could hit the Next Test button to move on to the next trial, or click one of the other audio file buttons if they wanted to change their selection. Once the Next Test button was pressed, the answer chosen by the subject was recorded and the program would move on to the next trial with a new set of audio files.

To make sure subjects listened to the entire sequence of audio files, the program was designed to prohibit the clicking of the three selection buttons or the Next Test button until all six audio files were played in full. This provided a standardized listening experience for all subjects and ensured that participants were not simply clicking wildly to get through the testing process faster. Also, participants were not given the option to listen to the audio files a second time (which they were informed of before the testing began) so they were instructed to concentrate fully on the presented sounds, because the audio cycles were not repeatable. Error correction measures were also built into the program to ensure that the audio files could not be played twice or that the Next Test button could not be selected until an audio file choice had been made.



1) Click 'Play Audio Files'
   3 Audio Files Will Play For 2 Cycles
2) Choose Which Audio File Sounds 'Different'
   & Click The Corresponding Button
3) Click 'Next Test' To Advance

Click The Corresponding Button Of The Audio File That Sounds 'Different'

Figure 4.2.1: Subjective Perception Test - Microsoft Excel graphical user interface

The data generated by the Excel graphical user interface worksheet were tables which listed all of the trials completed by the subject for the given test, the order in which the trials were presented, the audio files used for each of the three selections, the choice made by the participant, the correct answer for each trial, and whether the user's selected answer was correct. This collection of data made it very easy to determine how well each subject performed on the tests and allowed the data to be quickly transferrable to a master data spreadsheet, which compiled the results for all testing subjects into a single file.

4.2.3 Presented Subjective Perception Tests – Wall Tests

Using the programmed Excel testing interface worksheet, the created room auralizations were presented to subjects to answer the numerous questions on perceptions of diffusion. The subjective perception tests presented to participants were divided into six different groups, associated with the three primary physical testing setups and the selection of speech or music source material. In total, there were the Wall Absorption Tests with speech and music, the Wall Reflection Tests with speech and music, and the Room Tests with speech and music. The six test groupings were presented independently of each other with between 30 and 40 audio trials for each dataset, which equated to approximately 20 minutes of testing time for each test grouping. This choice of separating the different configurations ensured the continuity of audio files being presented, as each sound within a test grouping was taken from the same microphone position with the same speaker orientation. This meant that the only change within a given test grouping would be the orientation of the acoustical panels in the room.

The trials of the presented Wall Tests were divided into two separate categories: the first focusing on the JND between the varying diffusive conditions and the wall anchor conditions (fully absorptive or fully reflective). This category began by comparing the most disparate test wall configurations, being 32 diffusers (all acoustical panels of the test wall showing diffusers) and zero diffusers (anchor value). The anchor condition remained the same for all trials, but as comparisons were answered correctly, the number of diffusers used in comparison diminished. The number of presented diffusers began with 32, and then decreased to 24, then 16, 8, 7, 6, 5, 4, 3, and finally 2. (Unfortunately, the impulse responses with one diffuser showing were corrupted and could not be used in the subjective perception tests) If the subject was able to correctly identify the difference between two diffusers and the anchor value, the test would conclude.

A three alternative forced choice (3AFC) methodology was implemented here, meaning that three audio files were presented within each trial, two being identical and one being a different audio file. The goal for the subjects was to identify the sound that was different from the other two. With one correct answer amongst three choices, there was a 33% possibility for subjects to guess the correct answer, which served as the baseline of the psychometric function that compared subject performance against the independent variable: the number of diffusers. Furthermore, a two-up-one-down format of presented conditions was utilized, so for subjects to move forward to the subsequent (fewer diffusers) wall comparisons, they needed to answer two identical trials in a row correctly. If an incorrect answer was given, the previous (more diffusers) comparison would be presented again. In total, the minimum number of trials subjects could have heard was five, if the first five trials were all answered wrong. The maximum number of trials that could be heard was 28, if the test was fully completed with four total reversals.

For example, as stated above the first trial presented for all test groupings was 32 vs 0 diffusers. This comparison set would need to be answered correctly twice before a participant would be presented with the next set of 24 vs 0 diffusers. If that combination was answered correctly twice, the subject would move to 16 vs 0 diffusers, and so on. If any trial was answered incorrectly, say the 16 vs 0 diffusers condition, the previous comparison would be presented: 24 vs 0 diffusers in this instance. Each time a wrong answer was given after a correct answer or vice versa (a correct answer was given after a wrong answer) a reversal value was recorded. Figure 4.2.2 displays an example of this procedure for a single subject with reversal points noted. Each subsequent 'level' of presented trials required two correct answers to move down to the next (shown in the first five trials), but when an incorrect answer was given, as it was for trial six, the level moved back up. The next correct answer (trial seven) marked the second reversal, with the remaining three reversals being found at 9, 10, and 13 trials respectively. The number of diffusers was recorded on each reversal and then all five values were averaged to find the Just Noticeable Difference for the subject. This JND represented the point at which a 67% correct answer probability would occur for this participant and testing scenario. [22]

In this instance, the calculated JND was 19 diffusers or 59% (19 out of 32 diffusers). This meant that this subject would require diffusers to cover 59% of the total test wall surface area to accurately determine the difference between the diffusive and anchor wall conditions. This process was completed for all test subjects and then these JND values were averaged over the entire participant pool to compute the Just Noticeable Difference for each of the Wall Test groups: absorptive/reflective and speech/music. This resulted in a total of four unique JND values computed for the four tested configurations.

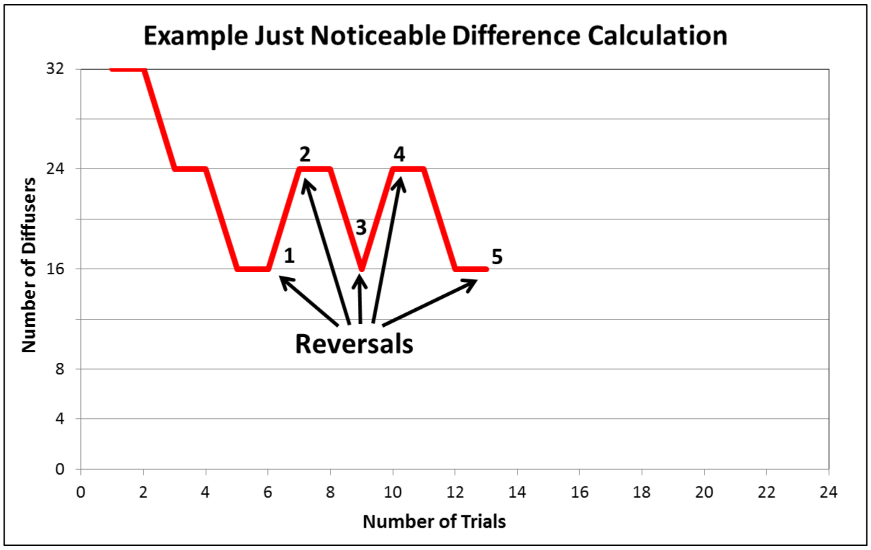


Figure 4.2.2: Example subject response for 3AFC two-up-one-down methodology

The second category of trials presented for the Wall Tests was the comparison between different levels of diffusion. Again utilizing the 3AFC methodology described above (but not the two-up-one-down procedure), pairs of audio files were played for subjects which represented the test wall under different diffusive conditions. (The anchor value was not used in this procedure) There were six combinations of audio files presented to subjects: 2 vs 4 diffusers, 2 vs 8 diffusers, 4 vs 8 diffusers, 4 vs 16 diffusers, 8 vs 16 diffusers, and 8 vs 32 diffusers. Note that the greater diffuser value for each trial set was either a doubling or quadrupling of the smaller value. These comparisons were set up to determine whether increasing the size of a diffusive surface by two or four times could be discerned. Each of the six comparisons listed above were presented to subjects twice: once with the smaller diffuser value as the duplicated audio file, once with the larger diffuser value as the duplicated audio file. This resulted in a total of 12 trials from this category of Wall Test trials, which were presented in pseudo-random fashion, using a Latin Square Design to vary the sequences between subjects. The order was selected by the author, choosing an arrangement which would prohibit the same trial set (2 vs 4 diffusers and 4 vs 2 diffusers for example) to be presented back to back.

The two categories of presented Wall Test trials were presented together within each of the four test groupings. The trials were randomized between the JND category and the comparison category so that each trial was independent of the next, preventing subjects from cueing on a specific aspect of the audio files. In particular, the anchor value from the JND trials could have been susceptible to this phenomenon if the trials were not randomized, as it would have played multiple times during every trial, allowing subjects to pick out small nuances that could identify it. The Microsoft Excel spreadsheet handled this randomization process as the tests were conducted and thus would differ from subject to subject, ensuring that no specific sequence was created.

4.2.4 Presented Subjective Perception Tests – Room Tests

By comparison, the trials presented for the Room Tests were much simpler than the Wall Tests, as only one category of testing was implemented. The Room Test trials were all comparisons between different Room Test conditions, so a similar methodology was implemented to that which was described above for the Wall Test comparisons. In this instance, the three Room Test configurations (midpoints of the walls, random, and top-down order) were compared at five different diffuser coverage percentages: 10%, 20%, 30%, 50%, and 60%. Several of the impulse responses for the 40% coverage were corrupted and thus could not be used in the subjective perception tests. The comparisons presented to subjects represented the six possible combinations of the three diffuser configurations: (1) midpoints of the walls vs random, (2) midpoints of the walls vs top-down, (3) random vs midpoints of the walls, (4) random vs top-down, (5) top-down vs midpoints of the walls, and (6) top-down vs random. In each of these combinations, the first configuration was the duplicated value and the second was the singular value. In total there were 30 trials for each of the two Room Test groupings: speech and music. As before, these trials were pseudo-randomized using a Latin Square Design, so no identical combinations were presented sequentially.

The order of the six acoustical groupings was also pseudo-randomized between subjects using a Latin Square Design, meaning that the order in which the acoustical test groupings were presented was altered for each subject. The first and fourth groups were always a Room Test, with the second, third, fifth, and sixth groups being Wall Tests. This allowed the sequence of speech and music files to alternate so that subjects would not have to listen to two groups of speech or two groups of music in a row.

4.2.5 Subjective Perception Testing Procedure

The subjective perception testing was conducted at the University of Nebraska Acoustic Listening Laboratory, located in the Peter Kiewit Institute in Omaha, Nebraska. The room is isolated and windowless with approximately 150 sq. ft. of floor area. With minimal background noise and few distracting elements, it allows subjects to concentrate on the given tasks, namely listening to auditory stimuli. The space also has multiple absorptive elements, including two corner bass traps, wall absorption panels, and acoustical ceiling tiles to control room reverberation. The room is appointed with a centrally located chair, a computer monitor, and several different speaker setups. (Figure 4.2.3) No speakers were in use during this study, however, as all listening was performed using headphones. The headphones used were Audio Technica model M40-fs which have a closed-back design with full surround ear cups and comfortable padding for extended listening sessions. With a flat frequency response between 80 Hz and 20 kHz, they were designed for studio production use, but served quite well in this auditory listening task. They faithfully reproduced the room auralizations, allowing subjects to concentrate on presented audio material free of distractions caused by the quality of headphones used.

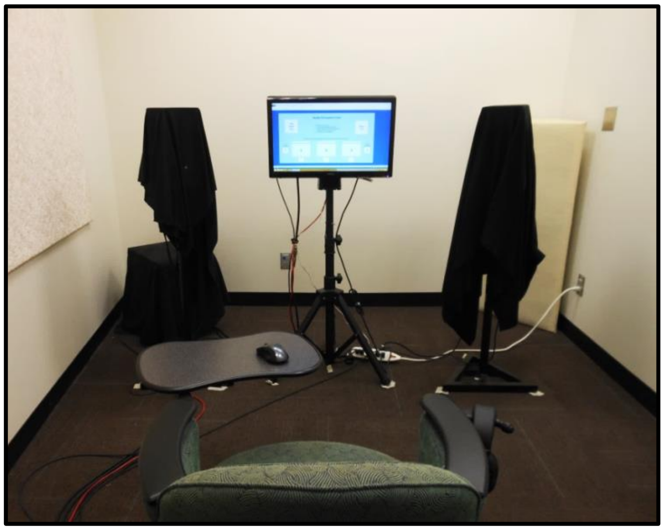


Figure 4.2.3: University of Nebraska Acoustics Listening Laboratory

The headphones were connected via a headphone extension cable to an M-Audio USB audio interface which was connected to the laboratory computer. The computer had dual monitor capabilities, so the test screen could be viewed in both the testing office and the testing chamber itself. The computer also utilized a wireless mouse setup, so subjects could easily select buttons on the test monitor without being distracted by cables.

Before beginning the subjective perception tests, the headphones and USB interface were calibrated to ensure the listening volume was at a safe and comfortable volume below 70 dBA. This was completed using the Larson Davis headphone calibration equipment, which allowed the coupling of the Larson Davis 831 sound level meter and microphone capsule to a surface which encompassed the entire surface area of the headphone ear piece. This unit was comprised of a large flat plate with a hole in the center for the capsule to protrude from and a side connection for the body of the sound level meter to connect. The headphone ear pieces were placed on the plate one side at a time, with a weighted bag set on top to simulate the pressure that would be experienced while wearing the headphones. The source files (the speech and music auralizations) were then played and monitored through the readout of the sound level meter. The USB interface was adjusted until a consistent value of 70 dBA was recorded for both sides.

The subjective perception testing procedure began with subjects reading and signing the Informed Consent document, described in the IRB section above, which detailed the steps involved in the testing. They then filled out the subject questionnaire asking their age, gender, and musical experience. Next, the subjects took a hearing screening to ensure that they had hearing thresholds less than 25 dB HL. This was completed using the UNL hearing threshold test equipment in the controlled environment of the laboratory testing chamber where background noise was very low. In this procedure, subjects heard pure tones at frequencies between 125 Hz and 8000 Hz starting at 0 dB HL. The level was raised until they could hear the tones, at which point they would press the supplied trigger button. This was completed on both right and left ears to ensure participants had ‘normal’ hearing in both ears before testing would proceed.

Once the hearing screening was passed, subjects moved on to an ‘initial test’ group, which was a set of six auditory trials using the testing interface described above. The purpose of this grouping was to allow subjects familiarize themselves with the subjective testing methodology, the interface being used, and the types of auditory stimuli that would be employed. The results from these tests were recorded but were not included in the final data assessment. The hearing screening and the ‘initial test’ group, along with the signing of paperwork, was completed in the first 30 minute session of testing. Most subjects would then come back on a second day to begin the second session, but some chose to continue on to the primary testing phase in the same day.

After subjects were familiarized with the process of the perception testing, the primary acoustic test groups (those which were included in the final data assessment) were presented. Each of these test groupings was approximately 20 minutes long, and comprised of between 20 and 40 individual trials. Generally, the primary sessions were administered in sets of three test groupings, which resulted in approximately one hour of listening per session. This length of time seemed to be a good duration for the subjective perception testing, as sitting and concentrating for any longer than one hour was tiresome for most subjects. Between each test grouping, the author would enter the room to save the data from the completed test and open the file for the next dataset, at which point the subjects could take a few minutes to break if needed.

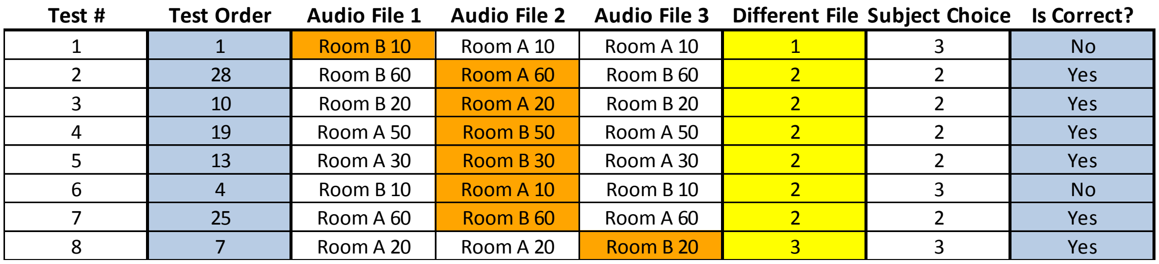
Including the initial 30 minute session and the two one hour primary sessions, the total testing time for each subject was approximately two and a half hours, which was usually finished on three different days. As previously stated, some subjects chose to complete more than one session in a day due to time constraints or scheduling issues, but this was not the norm for the subject pool. After completing all sessions, the participants were paid for their time with a $30 Amazon gift card and asked to sign a release form stating they received payment. At that point, answers provided by each subject were assimilated into the master spreadsheet of subjective perception testing data where they were analyzed with the entire dataset.

Perception Testing - Data

4.3.1 Raw Subject Data Collected

Once each subject completed the perception testing procedure, the data generated from the interface spreadsheets was extracted and compiled into a master spreadsheet. Each of the six testing files (for each primary testing configuration) recorded the audio tracks presented for each trial, the subject answer, the correct answer, and if the subject answered correctly. An example of data produced by the interface spreadsheet is shown in Table 4.3.1. Note that the 'Test #' column indicates the presented order of the specific trials. The 'Test Order' column, on the other hand, displays the number of the trial ordered pseudo-randomly based on a Latin Square design. These numbers were coded to specific trials (i.e. Test 1 referred to Room A compared with Room B at 10% diffusive coverage) which aided in the randomization and data collection processes.

Table 4.3.1: Example data produced in subjective perception testing for one subject & one testing configuration



Test #	Test Order	Audio File 1	Audio File 2	Audio File 3	Different File	Subject Choice	Is Correct?
1	1	Room B 10	Room A 10	Room A 10	1	3	No
2	28	Room B 60	Room A 60	Room B 60	2	2	Yes
3	10	Room B 20	Room A 20	Room B 20	2	2	Yes
4	19	Room A 50	Room B 50	Room A 50	2	2	Yes
5	13	Room A 30	Room B 30	Room A 30	2	2	Yes
6	4	Room B 10	Room A 10	Room B 10	2	3	No
7	25	Room A 60	Room B 60	Room A 60	2	2	Yes
8	7	Room A 20	Room A 20	Room B 20	3	3	Yes

The end result of these spreadsheets was a collection of specific testing trials and subject answers. To allow the data to be more easily analyzed, a Visual Basic macro was written to compile the most important information from the table above, namely the presented trials and the subject responses listed in sequential order. Once this sorting was completed, the column filled with 'Yes' and 'No' was copied into the master spreadsheet, compiling the answers from all subjects and testing configurations. Table 4.3.2 displays an example of the assembled data that was generated for each of the primary testing configurations. This specific section was from the Room Tests using Male Speech tests and shows the data for the first six trials (out of 30 total trials). These answers were subsequently analyzed further, the manner of which is described in the next section.

Table 4.3.2: Example data produced in subjective perception testing for all subjects & one testing configuration

Room Speech			**Subject ID**																								
Test	**Duplicated Audio File**	**Different Audio File**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
1	Room A - 10	Room B - 10	No	Yes	No	No	No	No	No	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes	Yes	No
2	Room B - 10	Room A - 10	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
3	Room A - 10	Room C - 10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No	Yes	Yes
4	Room C - 10	Room A - 10	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
5	Room B - 10	Room C - 10	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
6	Room C - 10	Room B - 10	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

The type of data shown in the above tables was generated for the Wall Test comparison tests and all of the Room Tests. The Wall Test Just Noticeable Difference testing produced slightly disparate data, as the parameters of the trial presentations were different. For the JND data, the audio tracks presented for each of the trials, the answer of the subject, the correct answer, and whether the subject answered correctly were recorded. The primary difference with the Wall Test JND trials was the inclusion of the reversal value count in the data spreadsheet. This additional column indicated when a reversal in the testing procedure would occur.

The final datasets for the JND trials were also different, as instead of recording ‘Yes’ and ‘No’ answers, the progression of diffusers for each presented trial was listed in sequential order. Therefore, the number of diffusers used in each presented trial was transferred into the master spreadsheet. For example, a subject 1 below (Table 4.3.3) was presented with a trial order of 32, 32, 24, 24, 32, and so on, indicating the first two trials (comparing 32 to 0 diffusers) were answered correctly and the fourth trial (comparing 24 to 0 diffusers) was answered incorrectly because the following trial was a ‘level’ higher.

Table 4.3.3: Wall Absorption Just Noticeable Difference tests data using Male Speech source material – Numbers indicate the sequence of presented tests for all subjects

Wall Abs Speech **Subject ID**

JND Test			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 0	Diffusers - 32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
2	Diffusers - 0	Diffusers - 24	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
3	Diffusers - 0	Diffusers - 16	24	24	24	32	24	24	24	24	24	24	24	24	24	24	24	24	24	32	24	24	32	32	24	24	32
4	Diffusers - 0	Diffusers - 8	24	24	24	24	24	24	24	24	32	24	24	24	24	24	24	24	32	32	24	24	32	32	24	24	24
5	Diffusers - 0	Diffusers - 7	32	16	32	24	16	16	16	16	32	16	16	16	16	16	16	16	32	32	16	16	32	32	16	32	32
6	Diffusers - 0	Diffusers - 6	32	16	32	16	24	16	16	16	24	16	16	24	16	16	16	16	32	32	16	16	24	32	16	32	32
7	Diffusers - 0	Diffusers - 5	24	8	24	16	32	24	24	8	32	8	8	24	8	8	24	24	32		8	8	24	32	24	24	24
8	Diffusers - 0	Diffusers - 4	24	8	24	8	32	24	24	8	32	8	8	16	8	8	24	24	32		8	8	16		32	24	32
9	Diffusers - 0	Diffusers - 2	16	7	16	8	24	32	16	7		7	7	24	7	7	16	16	32		7	7	24		32	16	
10	Diffusers - 0		16	7	16	7	24	32	24	7		7	7	24	7	7	16	16			7	7	32		24	24	
11	Diffusers - 0		8	6	8	7	16		24	6		6	6	16	6	6	8	24			6	6	32		24	24	
12	Diffusers - 0		8	6	8	8	24		16	6		6	6	16	6	6	8	24			6	7			32	16	
13	Diffusers - 0		16	5	7	8	24		16	5		5	5	8	5	5	7				5	7			32	16	
14	Diffusers - 0		24	5	7	7	16			5		5	6	8	5	5	7				5	6			24		
15	Diffusers - 0		24	4	6	7				4		4	6	7	4	6	6				6	6			24		
16	Diffusers - 0		16	4	6	6				4		4	5	7	4	6	6				7	5			16		
17	Diffusers - 0		16	2	5	6				2		2	5	6	2	5	5				7	5			16		
18	Diffusers - 0			2	5	5				2		2	4	6	2	6	5				6	4					
19	Diffusers - 0			0	4	5				0		0	4	5	0	6	4				6	4					
20	Diffusers - 0				4	4							2	5		5	4				5	2					
21	Diffusers - 0				2	4							2	4			2				6	2					
22	Diffusers - 0				2	5							0	4			2				7	0					
23	Diffusers - 0				0									2			0				7						
24	Diffusers - 0													2							6						
25	Diffusers - 0													0							6						
26	Diffusers - 0																				5						
Best Completed			**8**	**2**	**2**	**4**	**24**	**16**	**16**	**2**	**32**	**2**	**2**	**2**	**2**	**5**	**2**	**16**	**32**	**32**	**6**	**2**	**24**	**32**	**16**	**16**	**32**
																							Average: 13.2				

A wide variance in performance was evident between subjects for the Just Noticeable Difference Tests in Table 4.3.3. In general, the more trials subjects completed the 'better' they did on the test, meaning that they answered more trials correctly and thus proceeded further in the testing procedure. If a subject reached the end of the test by answering the final trial correctly, the last listed value is denoted as 0, indicating that they exceeded the limitations of the testing configuration. These subjects would be given a JND diffuser value of 2 (the smallest diffuser comparison) for all 'unused' reversals. For example, subjects 2, 8, 10, and 13 completed the entirety of the Wall Absorption Tests using Male Speech above without making one incorrect answer, so they received the best JND diffuser value of 2. On the other hand, subjects 9, 18, 22, and 25 did quite poorly in this test, as they answered many trials incorrectly and were unable to advance further through the testing procedure. The best completed trial for each subject was also computed of which an overall average was calculated for the entire participant pool. JND calculations followed from this set of data values, which is described in the next section.

The datasets for all testing configurations, source materials, and subjects is listed in Appendix A. Included in this section is the demographic information (gender, age, and musical experience) for each subject, the answers given for all presented subjective trials, and the computed statistics based on these answers.

4.3.2 Wall Tests – Generated Subject Data

With all subjective perception testing raw data compiled into the master spreadsheet, analysis could begin on each of the primary testing configurations. The Wall Tests (diffusive and absorptive as well as diffusive and reflective conditions) produced two groups of statistics, one for the JND tests and one for the diffuser comparison tests. Data from these two groups were separated when being input into the master spreadsheet, as the specific topics that each group addressed were not related to one another, even though the trials were presented within the same testing procedure.

The Wall Test JND values were calculated using the raw subject data as shown in Table 4.3.3. The five reversal values were tabulated for each subject and then the average was calculated. This computation is shown in Table 4.3.7 for one testing setup. Similar tables can be found for each of the four Wall Test configurations in the following sections. The average value of the five reversals equaled the Just Noticeable Difference for that testing subject and specific testing configuration. By averaging all 25 subject JND values, an overall Just Noticeable Difference value was found for each of the four Wall Test configurations. The values used to calculate the JND was the number of diffusers necessary to discern the diffusive wall condition from the anchor configuration. To put this into a percentage, common for JND values, the average number of diffusers was divided by the total number of diffusers in the test wall, 32. The equivalent surface areas for the JND values were also calculated by multiplying the number of diffusers by the surface area of each diffuser (4 sq. ft.). Therefore, each Wall Test configuration produced three JND values: the number of diffusers required to discriminate between the diffusive and absorptive/reflective wall conditions, the JND percentage area of the total test wall, and the equivalent surface area.

The JND values from each Wall Test configuration were also subdivided into several demographic groups. Male and female groups were calculated as well as musician and non-musician groups. The musician group was made up of subjects who responded to the ‘musical experience’ demographic question as having greater than 5 years of music experience. Not surprisingly, this grouping was comprised of both males and females. The three JND values were computed for the male, female, musician, and non-musician test groupings and then compared statistically using ANOVA analysis procedures.

In addition to the JND values calculated for each Wall Test configuration, the average completion percentage was found for each of the presented trials. These values were calculated for each subject by determining each individual’s performance for all trial pairings. For example, subject 1 answered 100% of the trials comparing 32 diffusers with 0 diffuser (top left cell), 83% (5/6 trials correct) of the trials comparing 24 versus 0 diffusers, and so on. If a specific trial value was not reached by the subject, a nominal value of 33% was input, indicating random chance. The overall values for each diffuser comparison were found by averaging the completion percentages of all subjects. Figure

4.4.1 displays a graphical depiction of the average completion percentages for one testing configuration, showing decreasing subject performance as the test wall size decreased.

Table 4.3.4: Example JND % correct values for each diffuser comparison (Averages in highlighted column)

Diffuser #	% Correct	Individual Percent Correct																								
32	**84.1**	100	100	100	67	100	50	100	100	33	100	100	100	100	100	100	100	63	33	100	100	57	33	100	100	67
24	**78.3**	83	100	75	100	86	75	100	100	33	100	100	100	100	100	100	83	33	33	100	100	33	33	71	83	33
16	**65.7**	40	100	100	100	33	50	60	100	33	100	100	50	100	100	75	50	33	33	100	100	33	33	50	33	33
8	**66.0**	50	100	100	100	33	33	33	100	33	100	100	100	100	100	100	33	33	33	100	100	33	33	33	33	33
7	**64.3**	33	100	100	75	33	33	33	100	33	100	100	100	100	100	100	33	33	33	100	100	33	33	33	33	33
6	**63.0**	33	100	100	100	33	33	33	100	33	100	100	100	100	100	100	33	33	33	75	67	33	33	33	33	33
5	**58.7**	33	100	100	100	33	33	33	100	33	100	67	100	100	33	100	33	33	33	33	100	33	33	33	33	33
4	**58.0**	33	100	100	50	33	33	33	100	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	33	33
2	**57.3**	33	100	100	33	33	33	33	100	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	33	33

Also computed for the Wall Tests was the comparison of diffuser sizes, assessing the discernibility between doubling and quadrupling the size of a diffusive surface. In this portion of the testing, doubling diffuser comparisons (2 vs 4, 4 vs 8, & 8 vs 16) were contrasted against quadrupling diffuser comparisons (2 vs 8, 4 vs 16, 8 vs 32). Each trial combination was presented twice, which were used to compute an average for each comparison. Table 4.3.5 displays the calculation of the diffuser size comparison values for one test configuration. It shows the specific trial, the number of subjects, the number correct, the percent correct, and the combined percent correct for each comparison. The overall values for the doubled and quadrupled testing configurations were also calculated.

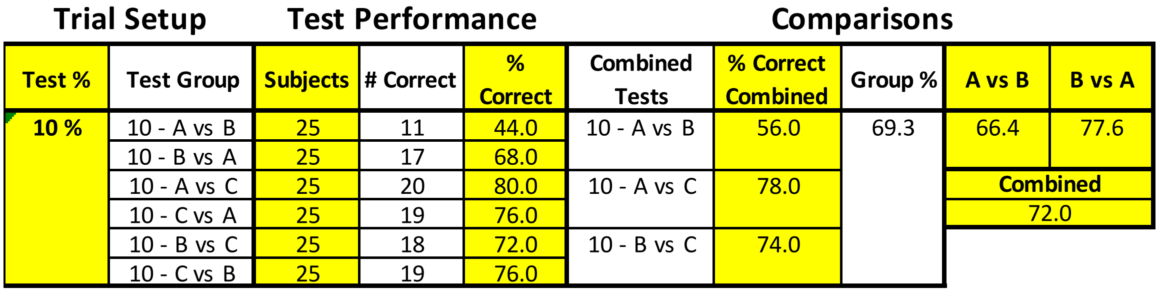
Table 4.3.5: Wall Absorption comparison tests compiled data using Male Speech source material

Test Performance					Comparisons			
Test	**Test Group**	**Subjects**	**# Correct**	**% Correct**	**Combined Tests**	**% Correct Combined**	**Double**	**Quadruple**
1	2 vs 4	25	10	40.0	2 vs 4	50.0	50.0	72.7
2	4 vs 2	25	15	60.0				
3	2 vs 8	25	15	60.0	2 vs 8	58.0		
4	8 vs 2	25	14	56.0				
5	4 vs 8	25	8	32.0	4 vs 8	50.0		
6	8 vs 4	25	17	68.0				
7	4 vs 16	25	20	80.0	4 vs 16	78.0		
8	16 vs 4	25	19	76.0				
9	8 vs 16	25	14	56.0	8 vs 16	50.0		
10	16 vs 8	25	11	44.0				
11	8 vs 32	25	20	80.0	8 vs 32	82.0		
12	32 vs 8	25	21	84.0				

4.3.3 Room Tests – Generated Subject Data

The Room Tests produced only one grouping of statistics which compared the subjective perception of the three diffuser setup configurations at five different diffuser coverage percentage levels. All trials presented in the Room Tests were comparisons between room states, specifically designed to compare pairs of diffuser configurations at set coverage percentages (i.e. Diffuser Setup A at 10 % coverage vs Diffuser Setup B at 10% coverage). As with the Wall Tests, each trial comparison was presented twice, the averages of which were combined to determine the overall subject performance for that pairing of diffuser configurations. Table 4.3.6 displays a portion of the Room Test data that was generated for the Male Speech source material. Shown are the results for the 10% diffuser coverage percentage trials only.

Table 4.3.6: Room Tests compiled data using Male Speech source material (10% Diffuser coverage only)



Trial Setup		Test Performance			Comparisons				
Test %	Test Group	Subjects	# Correct	% Correct	Combined Tests	% Correct Combined	Group %	A vs B	B vs A
10 %	10 - A vs B	25	11	44.0	10 - A vs B	56.0	69.3	66.4	77.6
	10 - B vs A	25	17	68.0					
	10 - A vs C	25	20	80.0	10 - A vs C	78.0		Combined	
	10 - C vs A	25	19	76.0				72.0	
	10 - B vs C	25	18	72.0	10 - B vs C	74.0			
	10 - C vs B	25	19	76.0					

Once the trial pairings were averaged across all subjects, these figures could be combined in different ways for analysis. First, the trials were averaged for each diffuser coverage level (i.e. 10% A vs B, 10% A vs C, & 10% B vs C) to determine how well subjects performed at each quantity of diffusive coverage (Denoted 'Group %' in Table 4.3.6). The data was also grouped by diffuser configuration across coverage percentages. That is, all trials comparing diffuser configuration A to diffuser configuration B for all coverage percentages, 10% – 60 %. These values were found for all setup combinations, A vs B, A vs C, and B vs C and both Male Speech and Violin Music source material.

4.3.4 Wall Tests – Diffusion & Absorption Speech

The most important data for each of the four Wall Test configurations has been included in the following sections, with the remainder of the information provided in Appendix A. Included in this chapter are the reversal values for each subject along with all computed averages, the three overall JND values (number of diffusers, percent area, & equivalent area), and the three JND values for each demographic grouping. Also included is a graphical representation of the subject performance on each JND test. Finally, the double and quadruple diffuser size comparison values are listed for each trial pairing and the overall averages for both groupings. Additional exploration of the Wall Test data can be found in the following section entitled Perception Testing – Analysis.

The first Wall Test configuration to be analyzed was the Wall Absorption using Male Speech group. Subjects performed quite well on this testing configuration in general, with 9 of 25 subjects fully completing the test by correctly answering all trial comparison levels. In fact, three subjects even completed all trials without answering a single comparison incorrectly. Looking at the JND values between the four Wall Test configurations, the Wall Absorption using Male Speech tests were the most discernible for subjects, achieving the lowest JND value. Table 4.3.7 displays the reversal values for all subjects and the JND values for all test groupings.

The Just Noticeable Difference for the Wall Absorption using Male Speech tests was found to be 51% which equated to 16.4 diffusers or 65.6 sq. ft. of diffusive surface area. This meant that it would require 51% of the total test wall surface area covered in diffusers for the average subject to be able to discriminate it from the absorptive wall condition under these testing parameters. This value was larger than expected, as it was not anticipated to need diffuser coverage on more than half of the wall surface for the average subject to differentiate between the diffusive and absorptive surfaces, especially considering that this was the easiest testing configuration.

Table 4.3.7: Wall Absorption JND tests data using Male Speech source material – 5 reversal values, JND for each subject, & JND values for all demographic groups

	Subject ID																								
Reversal	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
1st Reversal	24	2	24	32	16	16	16	2	24	2	5	16	2	5	16	16	24	32	5	6	32	32	16	24	32
2nd Reversal	32	2	32	7	32	24	24	2	32	2	6	24	2	6	24	24	32	32	7	7	32	32	32	32	24
3rd Reversal	8	2	2	8	16	24	16	2	24	2	2	16	2	5	2	16	32	32	5	2	16	32	24	16	32
4th Reversal	24	2	2	4	24	32	24	2	32	2	2	24	2	6	2	24	32	32	7	2	32	32	32	24	24
5th Reversal	16	2	2	5	16	32	16	2	32	2	2	2	2	5	2	24	32	32	5	2	32	32	16	16	32
Avg/JND	**21**	**2**	**12**	**11**	**21**	**26**	**19**	**2**	**29**	**2**	**3**	**16**	**2**	**5**	**9**	**21**	**30**	**32**	**6**	**4**	**29**	**32**	**24**	**22**	**29**

	Avg	%	Area
JND Value	**16.4**	**0.51**	**65.6**

	Avg	%	Area
Male JND Value	**14.3**	**0.45**	**57.3**
Female JND Value	**19.5**	**0.61**	**78.1**
Musician JND Value	**11.3**	**0.35**	**45.1**
Non-Musician JND Value	**19.8**	**0.62**	**79.3**

The JND values were also calculated for each demographic grouping, and in the Wall Absorption speech configuration, men performed better than women and musicians performed better than non-musicians. The 16% difference between men and women was found to be not significant ((F(1,24) = 1.38, p = 0.253) under these parameters, nor was the musician and non-musician groupings ((F(1,24) = 4.14, p = 0.054) even though a 27% difference was found. Also, of the four demographic groups, musicians performed the best and non-musicians performed the worst, with male and female groups in the middle. These results were expected, given results of musicians in prior subjective perception testing, but these predictable outcomes were not the case for all Wall Test configurations, as will be seen in the coming sections.

It was also possible to look at the performance of subjects by graphing their JND progression through the presented trials. Figure 4.3.1 shows the answers for all subjects in sequential order for the Wall Absorption JND tests using Male Speech. Having data from all 25 subjects makes the graph a bit messy, but the individual lines for each subject are less important than the overall graph trend. On the X-Axis, the trial number of each presented test is listed. On the Y-Axis, the number of diffusers used in comparison with the anchor value (0 diffusers) is shown for each presented trial. The graphing begins in the upper left corner, with 32 diffusers being compared to 0 diffusers as the first trial. If subjects answered the presented trials correctly, they moved to the next test level (down and to the right), but were forced to go back up a level if trials were answered incorrectly. The process continued until a limit of five reversals was met, signaling the end of the test. Subjects who performed well ended the JND tests in the lower right part of Figure 4.3.1. As can be seen, many subjects performed well on this test configuration, having reached the bottom of the graph (the end of the tests). Other subjects did not do quite as well, answering trials incorrectly, and were unable to proceed far into the testing procedure.

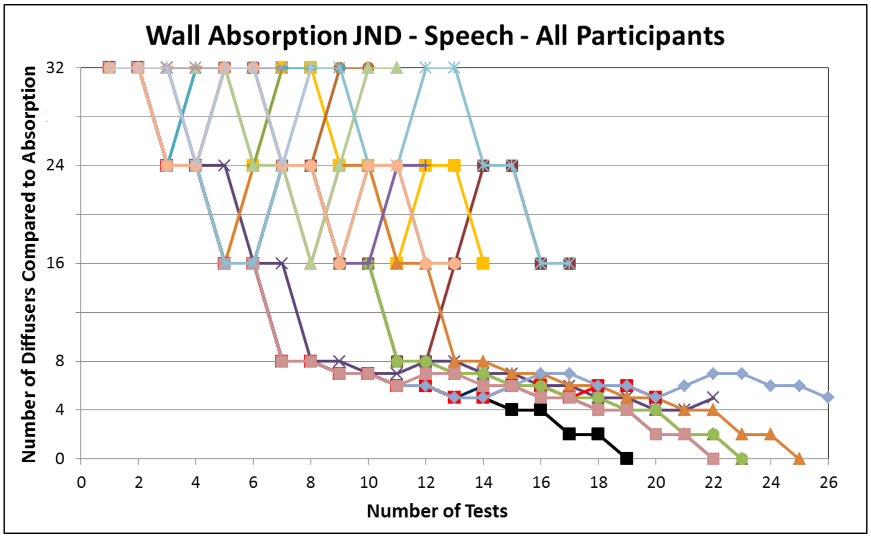


Figure 4.3.1: Wall Absorption using Male Speech JND tests subject performance

The Wall Absorption using Male Speech tests also produced data comparing doubling and quadrupling diffuser sizes. Table 4.3.8 displays the computed subject performances for the different presented size combinations as well as the combined averages for the double and quadruple size comparisons. In all cases, the quadruple diffuser sizes were more apparent than the doubled sizes, with differences increasing with each relative size pairing (the difference between the 2 vs 4 and 2 vs 8 pairings was 8% whereas between 8 vs 16 and 8 vs 32 the difference was 32%). This meant that while the quadrupled diffuser sizes were easier to discern in all conditions, as the relative size of the test walls increased it became even more distinguishable. Overall subjects answered 50% of double diffuser size comparisons compared to 72.7% of quadruple comparison trials, indicating far better performance ((F(1,11) = 9.60, p = 0.011) in discrimination between the two diffuser sizes under these testing conditions.

Table 4.3.8: Wall Absorption comparison tests compiled data using Male Speech source material

Combined Tests	% Correct Combined
2 vs 4	50.0
2 vs 8	58.0
4 vs 8	50.0
4 vs 16	78.0
8 vs 16	50.0
8 vs 32	82.0

Double	Quadruple
50.0	72.7

4.3.5 Wall Tests – Diffusion & Absorption Music

The next Wall Test configuration to be analyzed was the Wall Absorption using Violin Music group. Overall subjects again performed okay on this testing configuration, though not as well as the group utilizing Male Speech. Using Violin Music as the source material, 7 of 25 subjects fully completed the test by correctly answering all trial comparison levels, with five subjects completing all trials without answering a single comparison incorrectly. Looking at the Just Noticeable Difference values between the four Wall Test configurations, the Wall Absorption using Violin Music tests were the second most discernable for subjects. Table 4.3.9 displays the reversal values for all subjects and the JND values for all test groupings.

Table 4.3.9: Wall Absorption JND tests data using Violin Music source material

Reversal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Subject ID																								
1st Reversal	16	24	16	32	32	24	24	24	32	2	2	2	2	32	2	24	32	24	24	32	32	32	32	6	32
2nd Reversal	32	32	24	24	32	32	32	32	32	2	2	2	2	24	2	32	32	32	32	2	32	32	32	7	32
3rd Reversal	24	7	16	32	32	32	32	24	32	2	2	2	2	32	2	24	32	32	24	2	32	24	24	2	32
4th Reversal	32	32	32	32	32	32	24	32	32	2	2	2	2	32	2	32	32	24	32	2	32	32	32	2	32
5th Reversal	6	32	32	32	32	32	32	32	8	2	2	2	2	24	2	24	32	32	24	2	24	32	32	2	8
Avg/JND	**22**	**25**	**24**	**30**	**32**	**30**	**29**	**29**	**27**	**2**	**2**	**2**	**2**	**29**	**2**	**27**	**32**	**29**	**27**	**8**	**30**	**30**	**30**	**4**	**27**

	Avg	**%**	**Area**
JND Value	**21.3**	**0.67**	**85.3**

	Avg	**%**	**Area**
Male JND Value	**21.9**	**0.69**	**87.7**
Female JND Value	**20.4**	**0.64**	**81.8**
Musician JND Value	**15.8**	**0.50**	**63.4**
Non-Musician JND Value	**25.0**	**0.78**	**99.9**

The Just Noticeable Difference for the Wall Absorption using Violin Music tests was found to be 67% which equated to 21.3 diffusers or 85.3 sq. ft. of diffusive surface area. So, 67% of the total test wall surface area would need to be covered in diffusers for the average subject to be able to tell the difference between the wall conditions under these testing parameters. Again this value was larger than expected, as it took more than two thirds of the test wall covered in diffusive surfaces for the average subject to differentiate between a diffusive and absorptive conditions using music source material.

The JND values were also calculated for each demographic grouping, and in the Wall Absorption using Violin Music testing configuration women performed better than men and musicians performed better than non-musicians. The 5% difference between women and men was not significant ((F(1,24) = 0.09, p = 0.776) under these testing parameters. The gap between musicians and non-musicians was quite large (28%) though could only be considered marginally significant ((F(1,24) = 4.02, p = 0.057). And as before in the Male Speech grouping, musicians performed the best and non-musicians performed the worst of the four demographic groupings, with male and female groups ending up in the middle.

The performance of subjects for the Wall Absorption JND tests using Violin Music is shown graphically in Figure 4.3.2. Again, all subject data begins in the upper left corner of the graph and moves right as each subject answered the presented trials. Subjects who performed well on the tests, answering the presented trials correctly, moved down and to the right to subsequent testing levels until the limit of five reversals was met. Fewer subjects ended the Wall Absorption JND tests using Violin Music at the lower right than in the previous example, but enough to conclude that the test could be completed by participants with discerning ears.

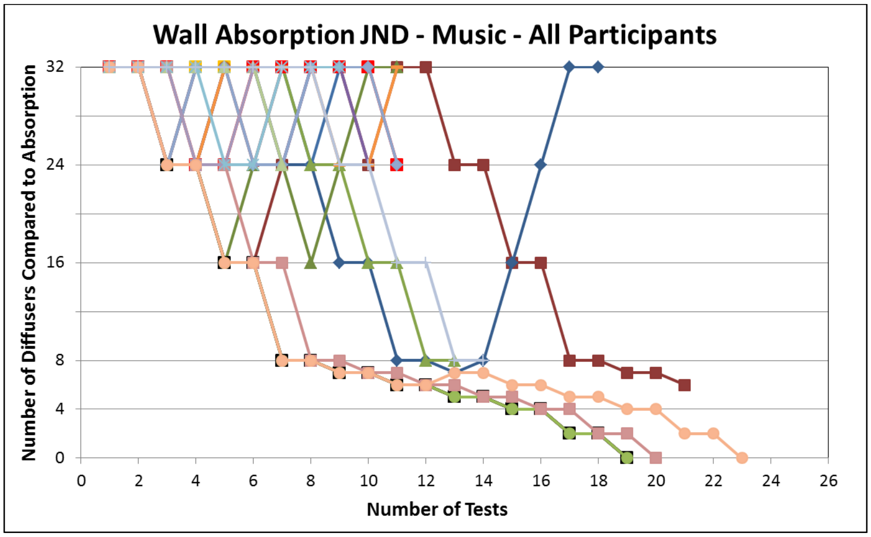


Figure 4.3.2: Wall Absorption using Violin Music JND tests subject performance

The Wall Absorption tests using Violin Music also produced data comparing doubling and quadrupling diffuser sizes. Table 4.3.10 displays the computed subject performances for the different presented diffuser size combinations as well as the combined averages for the double and quadruple size comparisons. For this testing configuration, the quadrupled diffuser sizes were not more apparent than the doubled sizes in all trial combinations. For the tests comparing 2 vs 4 diffusers and 2 vs 8 diffusers, the doubled value was much higher than the quadrupled value (52% and 38% respectively). This was an unexpected result and went against the logic that a quadrupled diffuser size should be more discernable than a doubled diffuser size. Overall subjects answered 42.7% of the doubled size comparisons as opposed to answering 45.3% of quadrupled comparisons, indicating no statistical difference between the two diffuser size comparisons under these testing conditions ((F(1,12) = 0.29, p = 0.605).

Table 4.3.10: Wall Absorption comparison tests compiled data using Violin Music source material

Combined Tests	% Correct Combined
2 vs 4	52.0
2 vs 8	38.0
4 vs 8	38.0
4 vs 16	42.0
8 vs 16	38.0
8 vs 32	56.0

Double	Quadruple
42.7	45.3

4.3.6 Wall Tests – Diffusion & Reflection Speech

With the Wall Absorption tests examined, the Wall Reflection using Male Speech was the next group from the Wall Tests to analyze. Subjects did not perform well on this testing configuration in general, and much worse than the absorptive configuration counterpart. In this testing setup, only 4 of 25 subjects fully completed the test, correctly answering all trial comparison levels, with two subjects completing all trials without answering a single comparison incorrectly. Comparing Just Noticeable Difference values between the four Wall Test configurations, the Wall Reflection using Male Speech tests were the second hardest for subjects to complete. Table 4.3.11 displays the reversal values for all subjects and the JND values for all test groupings.

Table 4.3.11: Wall Reflection JND tests data using Male Speech source material

	Subject ID																								
Reversal	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
1st Reversal	32	32	32	16	32	32	32	8	24	24	32	24	2	32	24	24	32	32	32	2	24	32	32	32	24
2nd Reversal	32	24	5	24	32	32	24	16	32	32	24	32	2	32	32	32	32	32	32	2	32	16	32	24	32
3rd Reversal	32	32	7	8	32	32	32	7	24	32	32	24	2	32	8	16	32	32	24	2	32	32	32	32	32
4th Reversal	32	24	5	32	32	32	24	8	32	24	24	32	2	32	16	24	32	32	32	2	32	8	32	32	32
5th Reversal	32	32	6	32	24	32	32	5	16	32	32	2	2	32	2	24	32	24	32	2	32	16	32	32	32
Avg/JND	**32**	**29**	**11**	**22**	**30**	**32**	**29**	**9**	**26**	**29**	**29**	**23**	**2**	**32**	**16**	**24**	**32**	**30**	**30**	**2**	**30**	**21**	**32**	**30**	**30**

	Avg	%	Area
JND Value	**25.5**	**0.80**	**101.9**

	Avg	%	Area
Male JND Value	**24.5**	**0.77**	**98.1**
Female JND Value	**24.5**	**0.77**	**98.2**
Musician JND Value	**18.5**	**0.58**	**73.8**
Non-Musician JND Value	**28.6**	**0.89**	**114.3**

The JND for the Wall Reflection using Male Speech tests was found to be 80% which equated to 25.5 diffusers or 101.9 sq. ft. of diffusive surface area. Therefore, 80% diffuser coverage was needed on the test wall surface area for the average subject to be able to differentiate between the wall conditions under these testing parameters. The JND values were also calculated for each demographic group, and in the Wall Reflection using Male Speech test configuration men and women performed nearly identically and musicians performed much better than non-musicians. The difference between men and women was not considered statistically significant ((F(1,24) = 0.00, p = 0.996). The gap between musicians and non-musicians was the largest of all testing configurations (31% between groups) and found to be significant ((F(1,24) = 9.60, p = 0.005). As before, musicians performed the best and non-musicians performed the worst of the four demographic groupings, with male and female groups landing in the middle.

The performance of subjects in the Wall Reflection JND tests using Male Speech is displayed graphically in Figure 4.3.3. As this testing configuration was harder than the previous groups in general, many more subjects ended the Wall Reflection JND tests using Male Speech at the top left part of the graph, as opposed to the lower right corner (only three participants) indicating poorer overall subject performance.

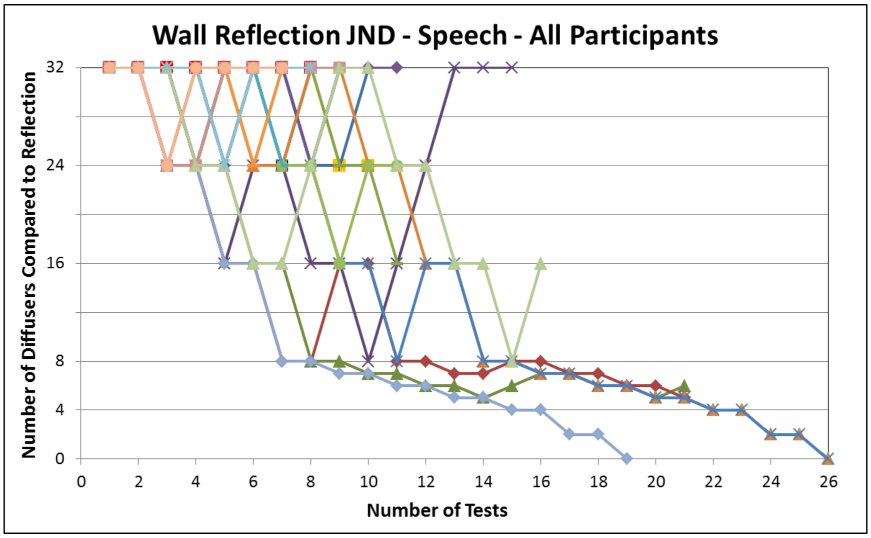


Figure 4.3.3: Wall Reflection using Male Speech JND tests subject performance

The Wall Reflection tests using Male Speech also produced data comparing doubling and quadrupling diffuser sizes. Table 4.3.12 shows the calculated subject performances for the different presented size combinations as well as the combined averages for the doubled and quadrupled size comparisons. For this testing configuration, the quadrupled diffuser sizes were not more apparent than the doubled sizes in all trial combinations. Again for the 2 vs 4 diffusers and 2 vs 8 diffusers comparison, the doubled value was much higher than the quadrupled value (70% and 50%, respectively), which was unexpected. Overall subjects answered 54% of the presented trials for the doubled diffuser comparisons as opposed to answering 60.7% of quadrupled size comparison trials, indicating no statistically significant differences between the two groupings ((F(1,12) = 0.77, p = 0.401).

Table 4.3.12: Wall Reflection comparison tests compiled data using Male Speech source material

Combined Tests	% Correct Combined
2 vs 4	70.0
2 vs 8	50.0
4 vs 8	52.0
4 vs 16	64.0
8 vs 16	40.0
8 vs 32	68.0

Double	Quadruple
54.0	60.7

4.3.7 Wall Tests – Diffusion & Reflection Music

The Wall Reflection using Violin Music configuration was the final Wall Test group analyzed. Overall subjects did not perform well on this testing configuration, similar to the Wall Reflection tests using Male Speech. In this testing setup, only 2 of 25 subjects fully completed the test by correctly answering all trial comparison levels, with zero subjects completing all trials without answering a single comparison incorrectly. Comparing JND values between the four Wall Tests configurations, the Wall Reflection using Violin Music tests were the least discernible for subjects. Table 4.3.13 displays the reversal values for all subjects and the JND values for all test groupings.

Table 4.3.13: Wall Reflection JND Tests data using Violin Music source material

	Subject ID																								
Reversal	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
1st Reversal	32	6	32	32	32	32	32	24	8	32	32	16	6	24	32	32	32	24	32	24	32	32	24	32	32
2nd Reversal	32	16	32	32	32	32	32	32	32	32	2	24	7	32	8	32	32	32	32	32	32	32	32	16	32
3rd Reversal	32	7	32	32	24	32	32	24	32	24	5	24	3	8	16	24	24	24	24	24	32	32	24	32	32
4th Reversal	32	8	32	24	32	32	24	32	32	32	5	32	5	24	8	32	32	32	32	32	32	32	32	8	24
5th Reversal	32	7	32	32	32	32	32	16	32	24	6	16	2	24	16	2	32	32	8	8	32	32	8	16	32
Avg/JND	**32**	**9**	**32**	**30**	**30**	**32**	**30**	**26**	**27**	**29**	**10**	**22**	**5**	**22**	**16**	**24**	**30**	**29**	**26**	**24**	**32**	**32**	**24**	**21**	**30**

	Avg	%	Area
JND Value	**25.9**	**0.81**	**103.5**

	Avg	%	Area
Male JND Value	**23.0**	**0.72**	**92.0**
Female JND Value	**28.0**	**0.88**	**112.2**
Musician JND Value	**24.1**	**0.75**	**96.6**
Non-Musician JND Value	**25.6**	**0.80**	**102.4**

The Just Noticeable Difference for the Wall Reflection using Violin Music tests was found to be 81% which equated to 25.9 diffusers or 103.5 sq. ft. of diffusive surface area. Therefore, 81% diffuser coverage was necessary on the test wall for the average subject to be able to discriminate between the wall conditions under these parameters. The JND values were also calculated for each demographic grouping, and in the Wall Reflection using Violin Music testing configuration men performed better than women and musicians performed slightly better than non-musicians. The difference between men and women was not significant ((F(1,24) = 2.70, p = 0.114), nor was the difference between musicians and non-musicians ((F(1,24) = 0.21, p = 0.652). In these testing conditions, men performed the best and women performed the worst of the four demographic groups, with musician and non-musician groups in the middle, a departure from previous results.

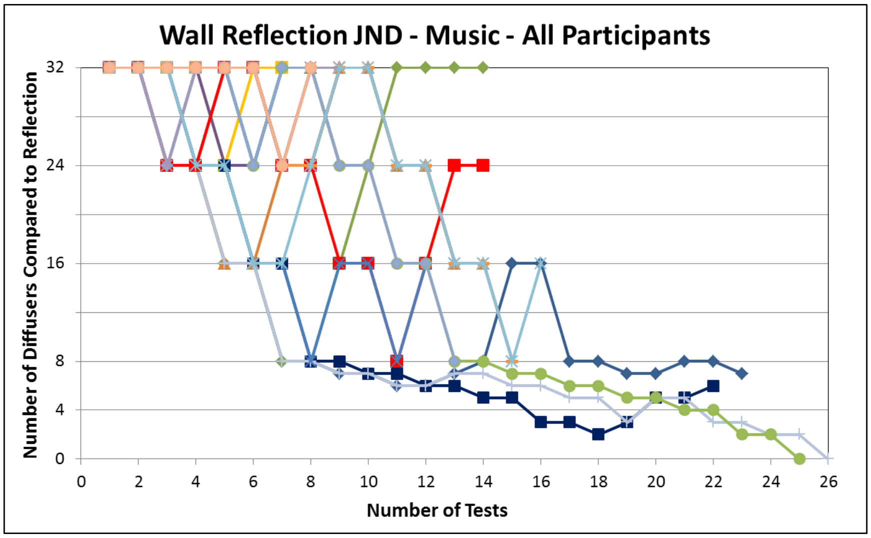


Figure 4.3.4: Wall Reflection using Violin Music JND Tests subject performance

The performance of subjects in the Wall Reflection JND tests using Violin Music is displayed graphically in Figure 4.3.4. As this was the hardest testing configuration, many more subjects ended the Wall Reflection JND tests using Violin Music at the top left of the graph, as opposed to the lower right corner indicating poorer performance.

The Wall Reflection tests using Violin Music also produced data comparing doubling and quadrupling diffuser sizes. Table 4.3.14 shows the calculated subject performances for the different presented size combinations as well as the combined averages for the doubled and quadrupled comparisons. For this testing configuration, the quadrupled diffuser sizes were not more apparent than the doubled sizes in all trial combinations. For the 2 vs 4 diffusers and 2 vs 8 diffusers comparison, the doubled value was the same as the quadrupled value (38% each). Overall subjects answered 45.3% of the presented trials for the doubled size comparisons as opposed to answering 54% of quadrupled diffuser comparisons, although this difference was not statistically significant under these testing conditions ((F(1,12) = 0.99, p = 0.344).

Table 4.3.14: Wall Reflection comparison tests compiled data using Violin Music source material

Combined Tests	% Correct Combined
2 vs 4	38.0
2 vs 8	38.0
4 vs 8	48.0
4 vs 16	50.0
8 vs 16	50.0
8 vs 32	74.0

Double	Quadruple
45.3	54.0

4.3.8 Room Tests – Speech

The most important data for the Room Tests using both the Male Speech and Violin Music source material has been included in the following sections, with the remainder of the information provided in Appendix A. Included in these sections are the completion values for each trial comparison at all presented diffuser coverage percentages, the combined group averages, and the comparisons between the three Room Test configurations (midpoints of the walls, random, and top-down order). Also included is a graphical representation of the subject performance for each diffuser coverage percentage and configuration comparison. Additional investigation can be found in the following section entitled Perception Testing – Analysis.

The first Room Test configuration to be analyzed was the Male Speech group. Overall subject performance varied considerably across the different diffuser coverage percentages and room configuration comparisons. Table 4.3.15 displays the completion percentages, combined group percentages, and room configuration comparisons for all test groupings. The data spanned from a minimum completion percentage of 40% to a maximum of 94%, which showed how much difference there was between the different presented trial groupings. In general, there was a significant ((F(1,29) = 4.66, p = 0.040) upward trend in the data as the diffusion coverage percentage increased, meaning that it was easier for subjects to differentiate trial comparisons at higher levels of diffusion. The progression of the data was not fully linear, however, as both the 20% and 60% diffuser coverage percentage groups were below the estimated linear trend line. Figure 4.3.5 shows a graphical representation of subject performance in the Room Test using Male Speech for all diffuser coverage percentages and room configuration comparisons.

Table 4.3.15: Room Tests compiled data using Male Speech source material

Room Tests Speech Compiled Data

Test %	Combined Tests	% Correct Combined	Group %
10 %	10 - A vs B	56.0	69.3
	10 - A vs C	78.0	
	10 - B vs C	74.0	
20 %	20 - A vs B	66.0	60.0
	20 - A vs C	40.0	
	20 - B vs C	74.0	
30 %	30 - A vs B	84.0	78.7
	30 - A vs C	68.0	
	30 - B vs C	84.0	
50 %	50 - A vs B	72.0	84.0
	50 - A vs C	94.0	
	50 - B vs C	86.0	
60 %	60 - A vs B	82.0	76.7
	60 - A vs C	90.0	
	60 - B vs C	58.0	

Configuration Comparisons

A vs B	B vs A	Combined
66.4	77.6	72.0

A vs C	C vs A	Combined
74.4	73.6	74.0

B vs C	C vs B	Combined
73.6	76.8	75.2

The comparison between room configurations was also analyzed for the Room Test using Male Speech. To compute these values, the group comparisons were averaged across all diffuser coverage percentages (i.e. A vs B diffuser configuration comparison averaged across 10%, 20%, 30%, 50%, & 60% coverage levels). These calculations showed that there was almost no difference ((F(1,29) = 0.08 p = 0.773) between the three configuration comparisons: midpoints of the walls versus random, midpoints of the walls versus top-down order, and random versus top-down order (or A vs B, A vs C, & B vs C). The three configuration comparison completion percentages were 72%, 74%, and 75.2%, indicating that on average the three room diffuser configurations were equally discernable from one another. As all three average completion percentages were above 70%, it was also clear that for the most part, subjects could tell the difference between all room diffuser configurations quite well when using the Male Speech source material

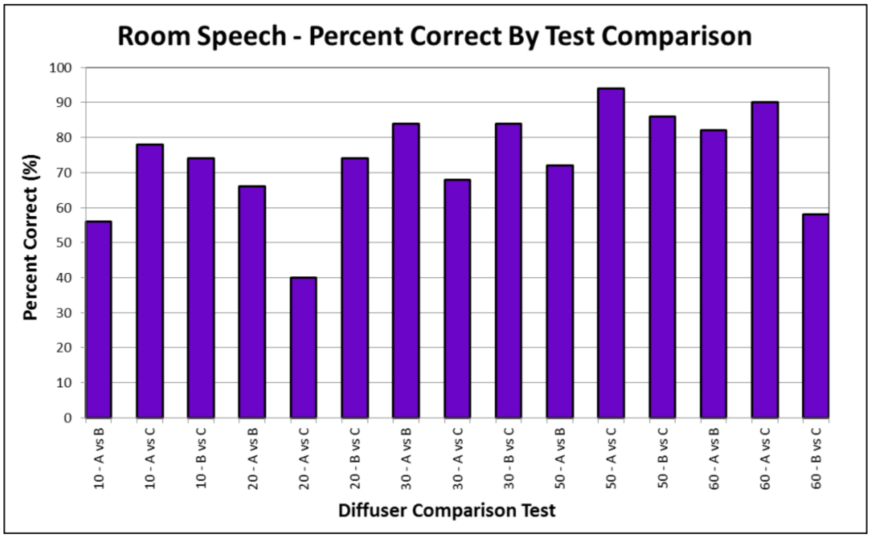


Figure 4.3.5: Room Tests data using Male Speech source material for all diffuser coverage percentages & configuration comparisons

4.3.9 Room Tests – Music

The Violin Music source material was the other configuration analyzed in the Room Tests. Again, overall subject performance varied across the different diffuser coverage percentages and room configuration comparisons, although not as broadly as in the Male Speech group. Table 4.3.16 displays the completion percentages, combined group percentages, and room configuration comparisons for all test groupings. The data spanned from a minimum completion percentage of 42% to a maximum of 80%, which still showed a descent gap between the different presented trial comparisons. In general, no significant trend was found ((F(1,29) = 0.02, p = 0.878) as diffusion coverage percentages increased, meaning that the difficulty for subjects to differentiate between trial comparisons remained consistent for all levels of diffusion. Figure 4.3.6 shows a graphical representation of subject performance in the Room Test using Violin Music for all diffuser coverage percentages and room configuration comparisons.

Table 4.3.16: Room Tests compiled data using Violin Music source material

Room Tests Music Compiled Data

Test %	Combined Tests	% Correct Combined	Group %
10 %	10 - A vs B	54.0	52.7
	10 - A vs C	58.0	
	10 - B vs C	46.0	
20 %	20 - A vs B	62.0	57.3
	20 - A vs C	60.0	
	20 - B vs C	50.0	
30 %	30 - A vs B	80.0	68.0
	30 - A vs C	60.0	
	30 - B vs C	64.0	
50 %	50 - A vs B	68.0	62.7
	50 - A vs C	70.0	
	50 - B vs C	50.0	
60 %	60 - A vs B	60.0	52.7
	60 - A vs C	56.0	
	60 - B vs C	42.0	

Configuration Comparisons

A vs B	B vs A	Combined
56.0	73.6	64.8

A vs C	C vs A	Combined
64.0	57.6	60.8

B vs C	C vs B	Combined
49.6	51.2	50.4

The comparison between room configurations was also analyzed for the Room Test using Violin Music source material. To compute these values, the group comparisons were averaged across all diffuser coverage percentages. These calculations showed that there were minor differences between the three configuration comparisons, 64.8%, 60.8%, and 50.4%, indicating that on average some differences could be discerned by subjects between the three configuration comparisons. The difference between the first two comparisons was not considered statistically significant ((F(1,29) = 0.60, p = 0.442), whereas the third comparison was significant ((F(1,29) = 6.50, p = 0.017). Also, the first two comparisons included room configuration A (comparisons A vs B & A vs C) and those were the two highest of three configuration comparisons, so it was concluded that the midpoint of the walls diffuser configuration was the most discernable of the three. In addition, because the third configuration comparison (B vs C) produced a completion percentage of 50.4%, indicating that in the Violin Music condition no difference could be heard by subjects between these two diffuser configurations.

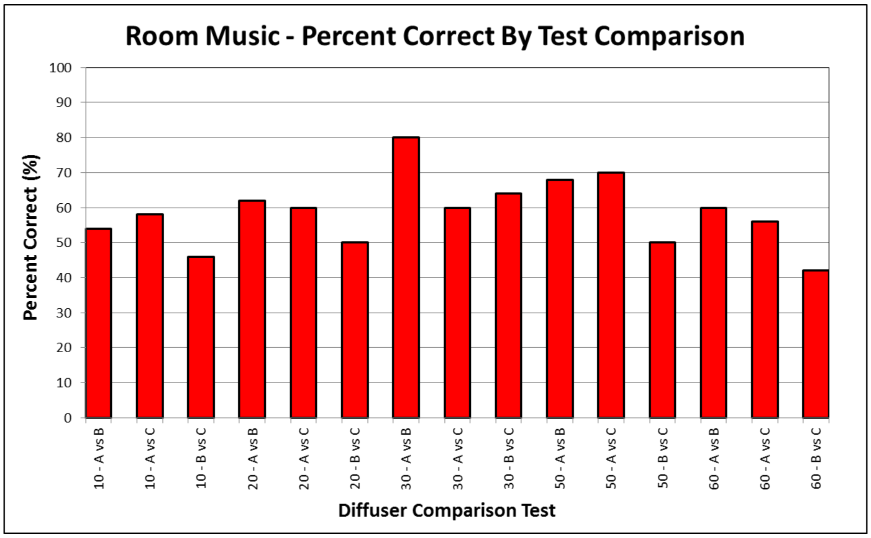


Figure 4.3.6: Room Tests data using Violin Music source material for all diffuser coverage percentages & configuration comparisons

Perception Testing - Analysis

4.4.1 Wall Tests – Diffusion & Absorption JNDs

The Wall Absorption testing conditions produced two sets of JND values: one for Male Speech and one for Violin Music. Figure 4.4.1 shows completion percentages for the Male Speech dataset at all presented number of diffusers and the JND value of 51%. Random selection in the 3AFC testing design implemented was 33% and is denoted in the graph below. As expected, subject performance decreased as the number of diffusers increased, with only one value (16 diffusers) out of linear alignment. The completion percentages across all presented number of diffusers was greater than 55% indicating this testing configuration could be completed by half of the subject pool. However, a JND value of 51% indicated that for the average subject, more than half the test wall area required diffusion to be discernible from the absorptive comparison configuration.

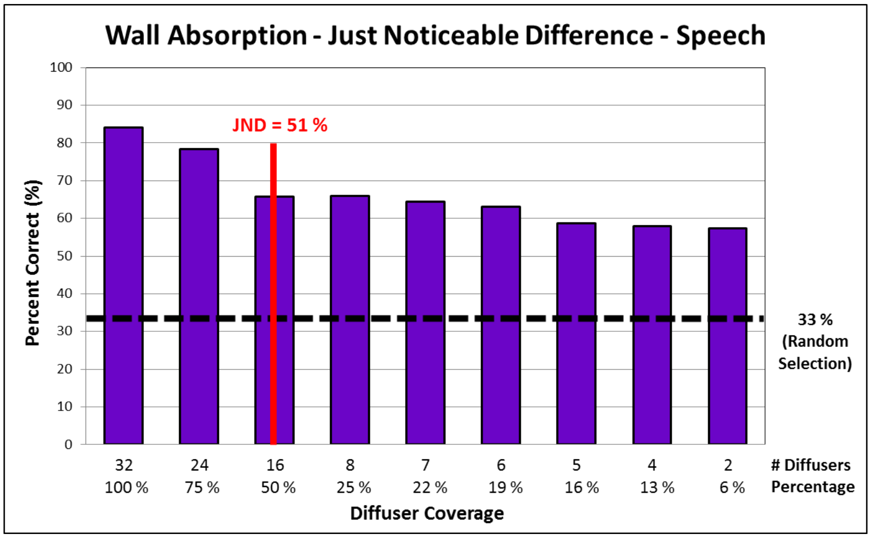


Figure 4.4.1: Wall Absorption using Male Speech JND tests percent correct for all diffusion coverage levels

Figure 4.4.2 displays completion percentages of subjects for the Violin Music source, the JND value of 67%, and the random selection threshold of 33%. Again, subject performance decreased as the number of diffusers increased, with only one value (six diffusers) out of expected alignment. The completion percentages across presented trials was greater than 50%, indicating that the Wall Absorption using Violin Music test configuration could once again be completed by half of the subject pool. With a JND value of 67%, however, the average subject required diffusion on more than half the test wall surface area to be distinguishable from the absorptive comparison configuration.

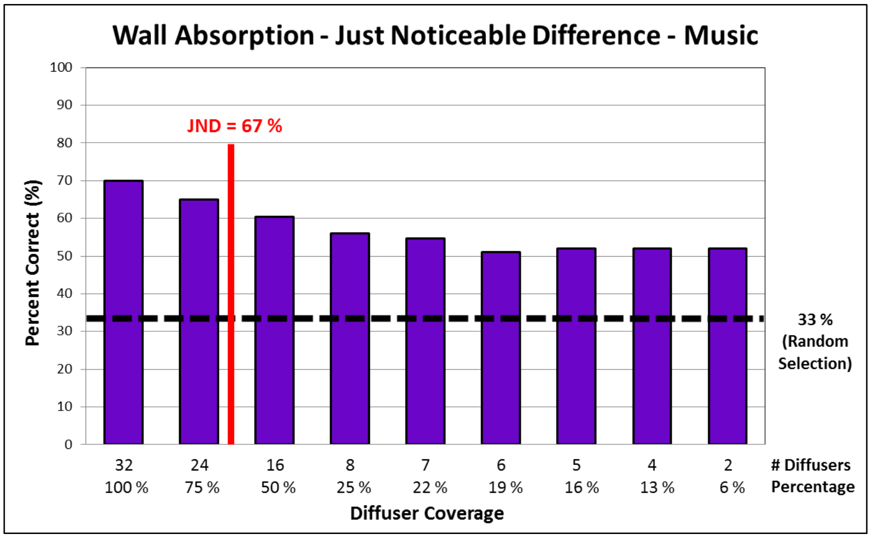


Figure 4.4.2: Wall Absorption using Violin Music JND tests percent correct for all diffusion coverage levels

Another way of analyzing the Just Noticeable Difference values was to look at the JND equivalent areas, which determined the amount of diffusive surface area required to be discernible from the absorptive comparison condition. For the Male Speech source, the JND percentage of 51% equated to a distinguishable area of 65.6 ft^2. For the Violin Music source, the JND percentage of 67% equaled a differentiable area of 85.3 ft^2. A graphical representation of the Wall Absorption JND equivalent areas is shown in Figure 4.4.3. The left figure is for the Male Speech source and displays the 51% diffusive test wall coverage necessary for subjects to discern wall conditions. The right figure is for the Violin Music source and demonstrates how much more diffusive coverage was required for subjects to be able to differentiate wall conditions in the music tests.

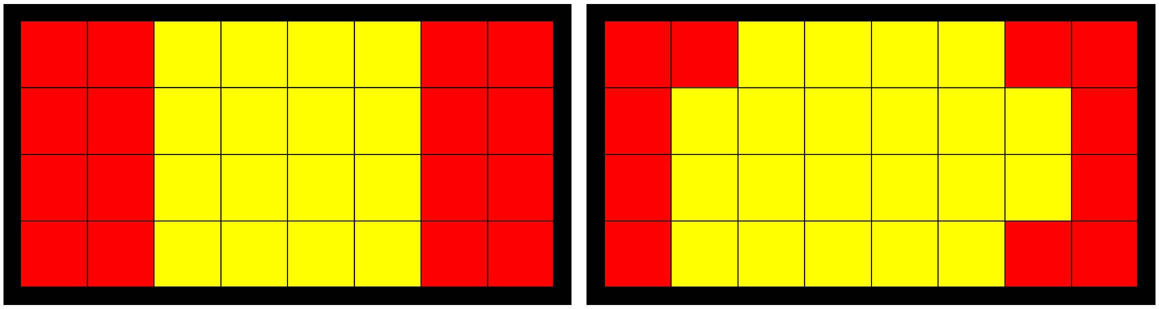


Figure 4.4.3: JND equivalent areas for the Wall Absorption tests – (Left) Male Speech, (Right) Violin Music

Overall, both the Male Speech and the Violin Music source materials exhibited similar properties when analyzing the subjective perception of the Wall Absorption testing conditions. The Male Speech source was more discernible on average than the Violin Music source, having a JND value of 51% versus 67%. However, in both conditions more than half of the subject pool was able to 'finish' the tests, meaning they could differentiate between the smallest diffusive configuration and the absorptive anchor condition. This indicated that for the adept listener, the diffusers utilized in this testing configuration were fully distinguishable from the absorptive comparison condition for all presented trials. Because the JND of the Violin Music source was so much higher, this signified that the music source material was more difficult than the speech source, especially for subjects who did not perform well on the Wall Absorption Tests overall.

4.4.2 Wall Tests – Diffusion & Absorption Size Comparisons

In addition to the JND values, the Wall Absorption Tests generated comparison data between doubled and quadrupled diffuser sizes. Figure 4.4.4 displays the comparison values using the Male Speech source. The blue columns indicate the doubling diffuser conditions (2 vs 4, 4 vs 8, & 8 vs 16) which stayed consistent between groups, with the red columns indicating the quadrupling diffuser conditions (2 vs 8, 4 vs 16, & 8 vs 32) which increased as the diffuser size grew. The graph shows that for Male Speech, the relative size of the diffusive area impacted subject performance for quadrupled pairings.

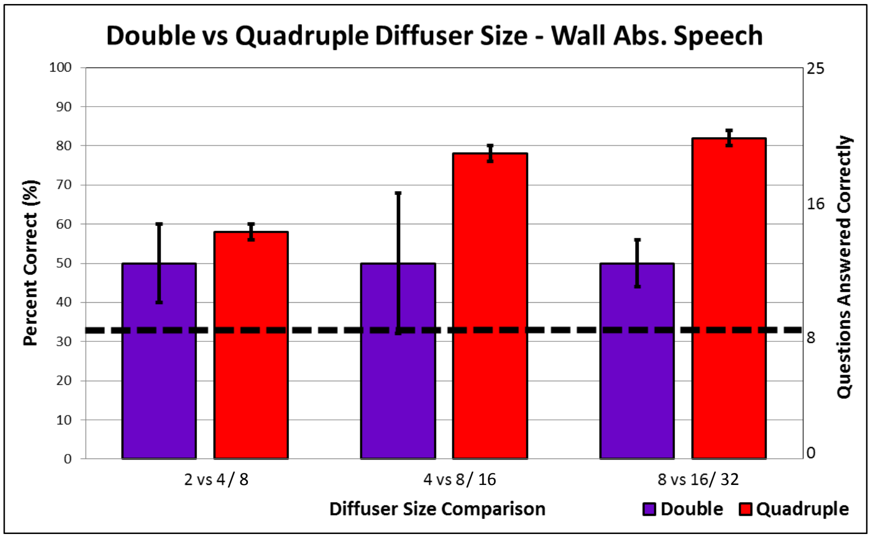


Figure 4.4.4: Wall Absorption comparison tests for three comparison levels using Male Speech source material (Error bars denote Standard Error of the Mean for each comparison group)

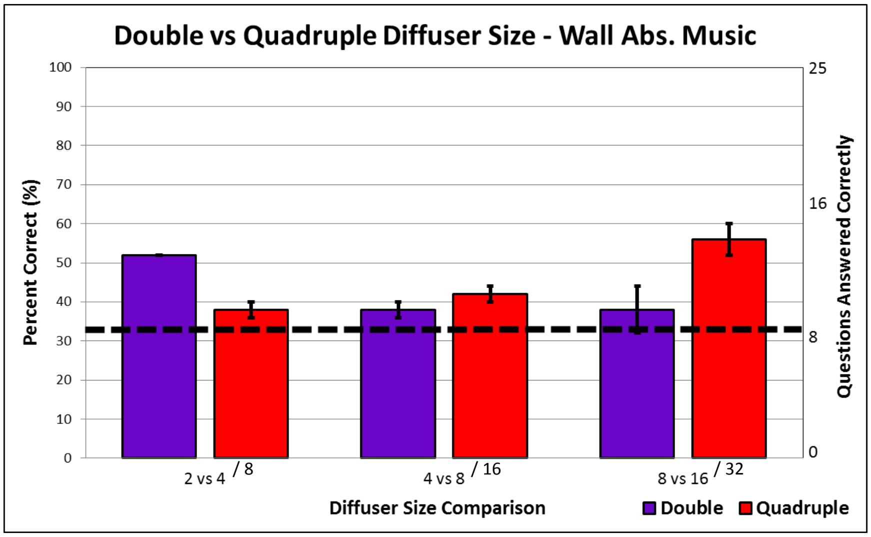


Figure 4.4.5: Wall Absorption comparison tests for three comparison levels using Violin Music source material (Error bars denote Standard Error of the Mean for each comparison group)

The Wall Absorption tests comparison values using the Violin Music source material were not as consistent as was speech, shown in Figure 4.4.5. The blue columns for the doubling diffuser conditions show a decrease in performance as relative diffuser size grew. The red columns of the quadrupling conditions trended in reverse, increasing as the diffuser size grew. In addition, all comparison values were relatively low in completion percentage, especially for the middle four quantities which barely exceeded the random chance answering percentage, so a trend was not discernable for the Wall

Absorption diffuser size comparison tests using Violin Music. However, Figure 4.4.6 displays how much more distinguishable the Male Speech was than Violin Music ((F(1,23) = 10.13, p = 0.004) between doubled and quadrupled diffuser configurations.

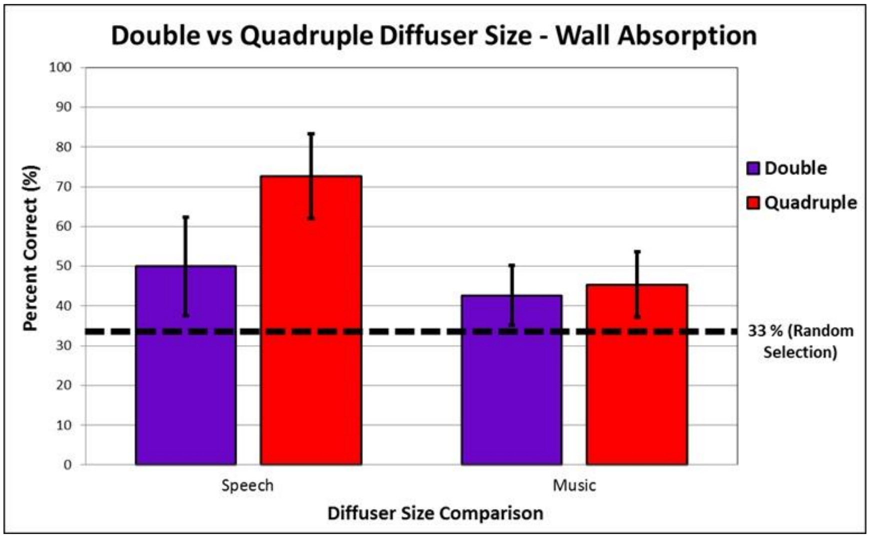


Figure 4.4.6: Wall Absorption comparison tests data grouped by Male Speech & Violin Music source materials (Error bars denote Standard Error of the Mean for each diffuser size grouping)

4.4.3 Wall Tests – Diffusion & Reflection JNDs

The Wall Reflection testing conditions also produced two sets of Just Noticeable Difference values: one for each of the Male Speech and Violin Music source materials. Figure 4.4.7 shows completion percentages for the Male Speech dataset at all presented number of diffusers as well as the JND value of 80%. As in the previous test configurations, subject performance decreased as the number of diffusers increased, with only two values (6 & 7 diffusers) marginally out of linear alignment. The completion percentages across all presented number of diffusers were greater than 40%, indicating that this testing configuration was much more difficult on average, given the random selection percentage of 33%. A JND value of 80% confirms this assessment, indicating that for the average subject, more than eighty percent of the test wall area required diffusive coverage to be discernible from the absorptive comparison configuration.

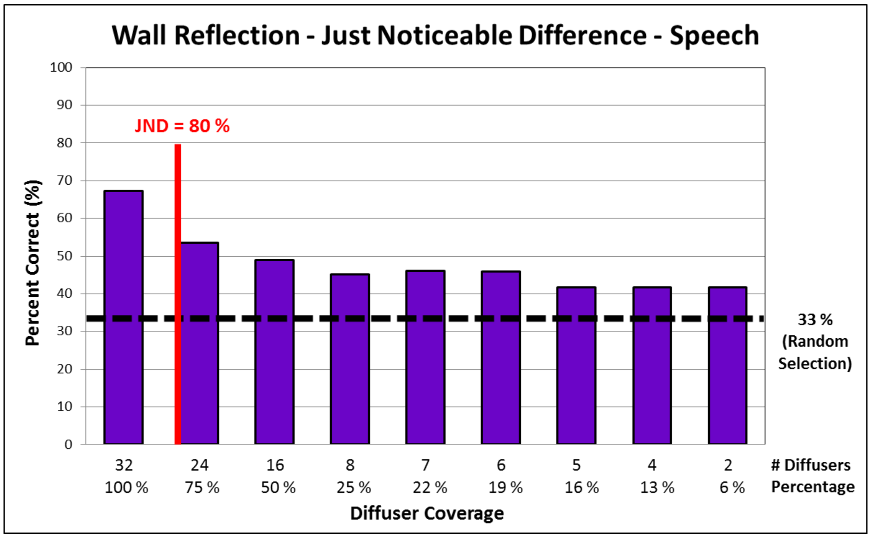


Figure 4.4.7: Wall Reflection using Male Speech JND tests percent correct for all diffusion coverage levels

Figure 4.4.8 displays completion percentages of subjects for the Violin Music source and the JND value of 81%. Again, subject performance decreased as the number of diffusers increased, with only one value (16 diffusers) out of linear alignment. The completion percentages across all presented number of diffusers was only greater than 35%, indicating that the completion percentages for the Wall Reflection using Violin Music testing configuration were nearly down to random chance. This testing condition was clearly difficult, and the JND value of 81% was in agreement with this assessment.

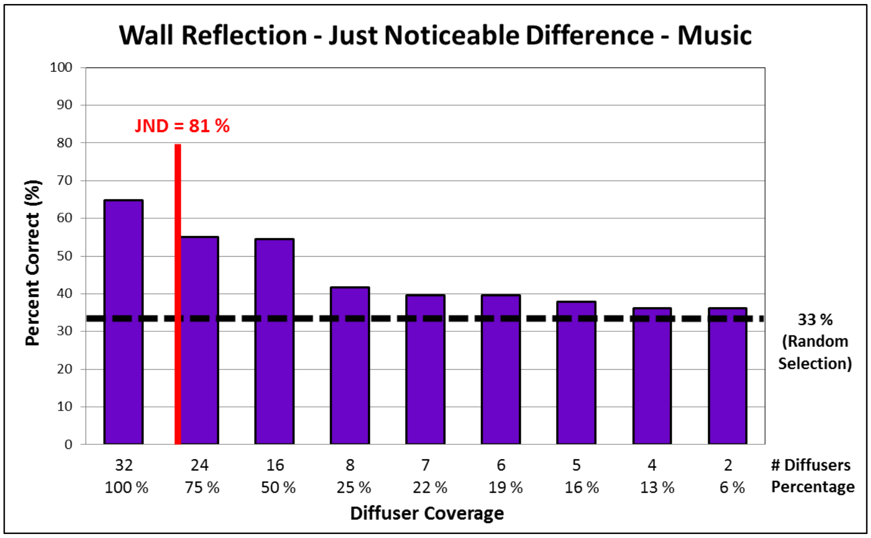


Figure 4.4.8: Wall Reflection using Violin Music JND tests percent correct for all diffusion coverage levels

Looking at the JND equivalent areas, the Male Speech source the JND percentage of 80% equated to a distinguishable area of 101.9 ft^2. For the Violin Music source the JND percentage of 81% equaled a differentiable area of 103.5 ft^2. A graphical display of the Wall Absorption JND equivalent areas is shown in Figure 4.4.9. The left figure is for the Male Speech source and the right for the Violin Music source material: both required over 80% diffusive coverage necessary for subjects to discern wall conditions. So, in the Wall Reflection tests more diffusive coverage was not required for subjects to be able to differentiate wall conditions between the Male Speech and Violin Music source materials. However, the Wall Reflection tests were very difficult for subjects in general, with JND values of 80% and 81% for the speech and music sources, respectively. So under reflective testing conditions, which are the most common found in real building environments, a diffusive coverage percentage of greater than 80% would be required to be discernible for the average subject compared with the reflective comparison condition.

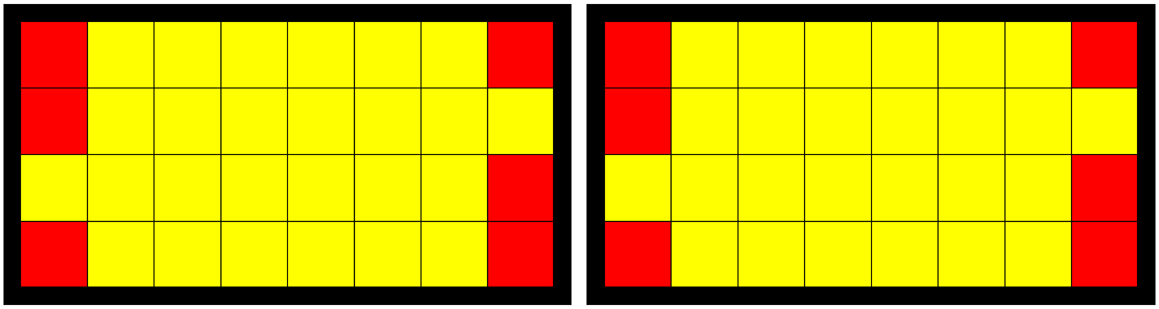


Figure 4.4.9: JND equivalent areas for the Wall Reflection tests – (Left) Male Speech, (Right) Violin Music

4.4.4 Wall Tests – Diffusion & Reflection Size Comparisons

The Wall Reflection Tests also generated comparison data between doubled and quadrupled diffuser sizes. Figure 4.4.10 displays the Wall Reflection Tests comparison values using the Male Speech source material. Again, the blue columns indicate the doubling diffuser conditions which showed a downward trend between the three groups. The red columns indicate the quadrupling diffuser conditions which increased as the diffuser size grew, the same as in the two previous testing configurations. This meant that for the Male Speech source, the relative size of the diffusive area impacted subject performance for both the doubled and quadrupled pairings, though in opposite directions.

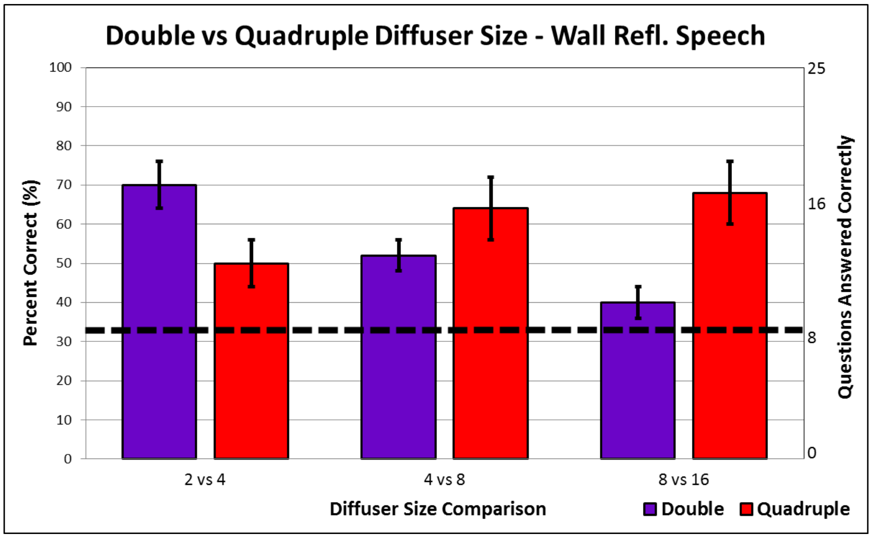


Figure 4.4.10: Wall Reflection comparison tests for three comparison levels using Male Speech source material (Error bars denote Standard Error of the Mean for each comparison group)

The Wall Reflection tests comparison values using the Violin Music source again showed varying results, as displayed in Figure 4.4.11. The blue columns for the doubling diffuser conditions and the red columns of the quadrupling diffuser conditions both showed an increase in performance as relative diffuser size grew. In addition, all comparison values across double and quadruple sizes were less than 50% (except for 8 vs 32), indicating low subject performance for most testing conditions. An overall upward trend was discernable for the Wall Reflection diffuser size comparison tests using Violin Music for both doubling and quadrupling groups. However, the doubled and quadrupled size groupings were not distinguishable from each other for all of the testing groups other than the last (the 8 vs 16 & 8 vs 32 comparison group). Figure 4.4.12 does display how the doubled and quadrupled diffuser configurations were differentiable from one another for both the Male Speech and Violin Music ((F(1,23) = 1.77, p = 0.197).

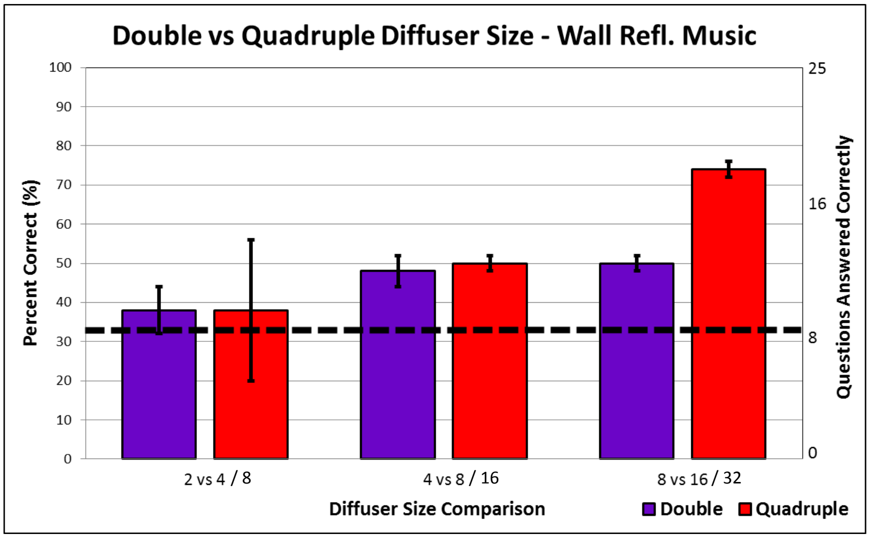


Figure 4.4.11: Wall Reflection comparison tests for three comparison levels using Violin Music source material (Error bars denote Standard Error of the Mean for each comparison group)

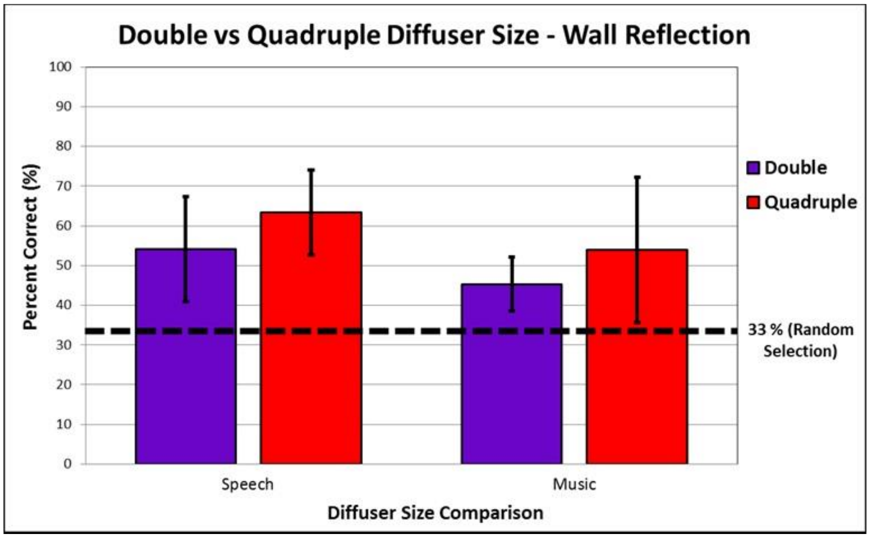


Figure 4.4.12: Wall Reflection comparison tests data grouped by Male Speech & Violin Music source materials (Error bars denote Standard Error of the Mean for each diffuser size grouping)

4.4.5 Just Noticeable Difference Test Grouping Analysis

The compiled data from the Wall Test JND values were analyzed not only for the entire dataset, but also by gender and musical experience. Comparing performances of males (15 subjects) and females (10 subjects), the data was varied and somewhat inconclusive. In two of the Wall Test configurations (Wall Absorption using Male Speech and Wall Reflection using Violin Music), men performed ~16% better than women. In the Wall Absorption using Violin Music condition, women outperformed men by 5% and in the Wall Reflection using Male Speech tests the genders performed equally. Overall, men performed 9% better than women when averaging across the four Wall Test configurations, indicating a non-significant difference ((F(1,99) = 1.03, p = 0.313) in performance in diffuser differentiation, at least for this subject pool.

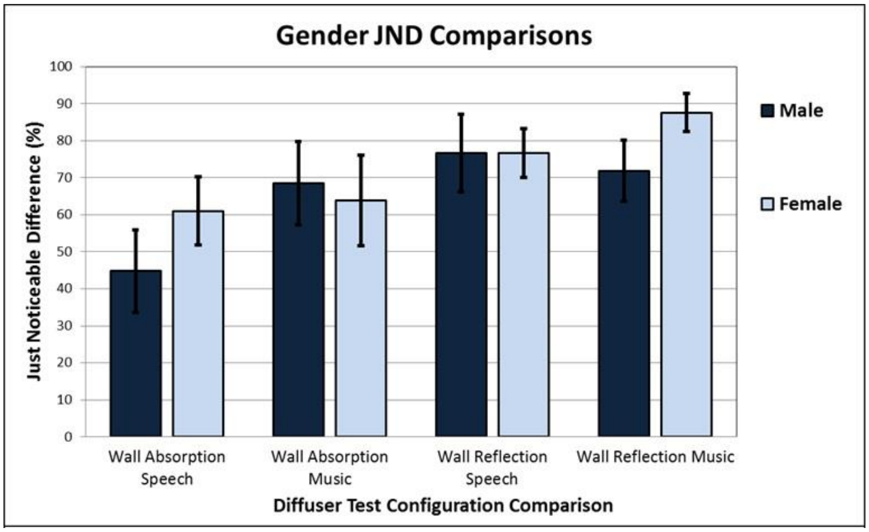


Figure 4.4.13: Wall JND values for all wall setup/source configurations for the male & female testing groups (Error bars denote Standard Error of the Mean for each test grouping)

Looking at the subjective perception performance of musicians (10 subjects) versus non-musicians (15 subjects) on the JND tests, the results were very consistent, with the musician group performing better in every testing configuration. In three of the Wall Tests musicians performed 26 – 31% better than non-musicians, and in the fourth condition (Wall Reflection using Violin Music), the difference was down to 5%. Overall, musicians performed 23% better than non-musicians when averaging across the four Wall Test configurations, indicating a significant difference in performance in diffuser differentiation ((F(1,99) = 13.06, p = 0.001). This finding was consistent with prior work which has indicated that musicians made for better subjects in subjective perception testing. While the results found in this study were impacted by the inclusion of subjects of all musical backgrounds, it was (and still is) the opinion of the author that the correct decision was made in regards to the selection of the subjects. The values generated for all facets of the perception testing were for 'average' listeners, who are not all musicians: some are and some are not, as in this study. So, while limiting this research to subjects with significant musical experience would have produced 'better' JND values, these testing conditions would not have fully represented the average individual.

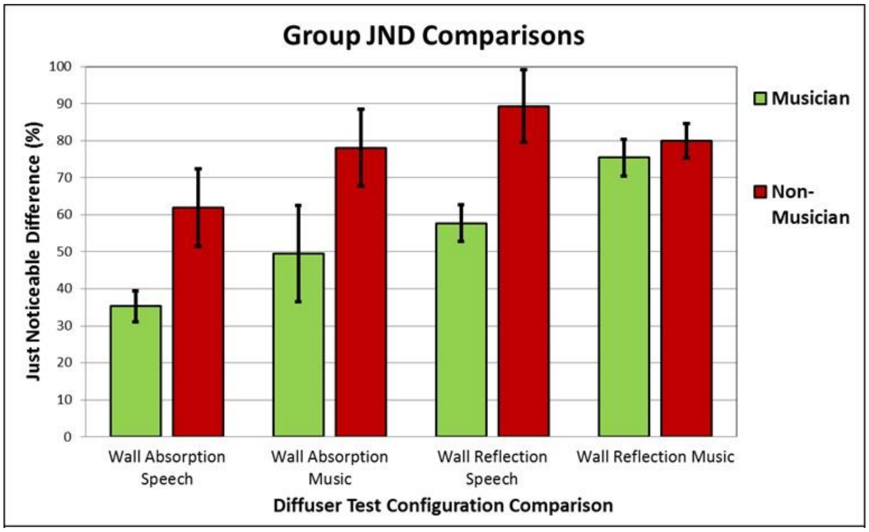


Figure 4.4.14: Wall JND values for all setup/source configurations for musician & non-musician testing groups (Error bars denote Standard Error of the Mean for each test grouping)

4.4.6 Room Tests – Diffuser Configuration Comparisons

The Room Tests produced completion percentage datasets for both Male Speech and Violin Music source material at an array of room testing configurations. These room parameters included diffuser coverage percentage which ranged from 10% to 60%, as well as the three diffuser setup configurations: midpoints of the walls, random, and top-down order (Groups A, B, & C). Once averaged across all test subjects, the completion percentages for each presented trial combination were grouped in one of two ways: by diffuser coverage percentage or diffuser setup configuration. Figure 4.4.15 displays the completion percentage data for all subjects and diffuser setup configurations grouped across diffuser coverage percentages. Each of the five coverage levels (10%, 20%, 30%, 50%, & 60%) are represented with both Male Speech (in blue) and Violin Music (in red) source material. Also denoted by the error bars on each column are standard deviations from the mean for each diffuser configuration that went into averaging the displayed values. Clearly, there was a wide variance for most of the testing configurations.

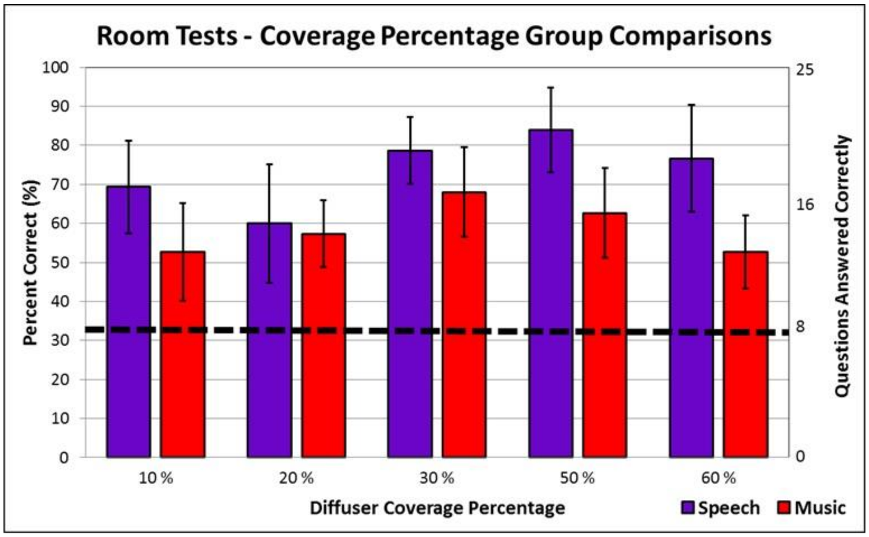


Figure 4.4.15: Room Tests data – Tests divided by diffuser coverage percentage level (Error bars denote Standard Error of the Mean for each coverage percentage)

The above figure shows several interesting facts about the Room Tests, starting with the comparison of the two source materials. The Male Speech source was easier for subjects to discern than the Violin Music source in all diffuser coverage percentage levels, many times by a margin of more than 20%. Also, there appeared to be either a slight rise in subject performance as diffuser coverage increased, or a parabolic rise and fall in performance with increasing diffuser coverage. For the first four conditions (10% – 50%) the data seems linear for both sources, but the 60% diffuser coverage trended downward, indicating that a peak level of subject acuity might have been reached at between 30% and 50% diffuser coverage percentage. It was also unknown whether or not the completion percentage spans of 15% (outside of one outlier) for both the speech and music sources were truly differentiable from one another, as these ranges might shrink or grow if more subjects were added to the testing pool.

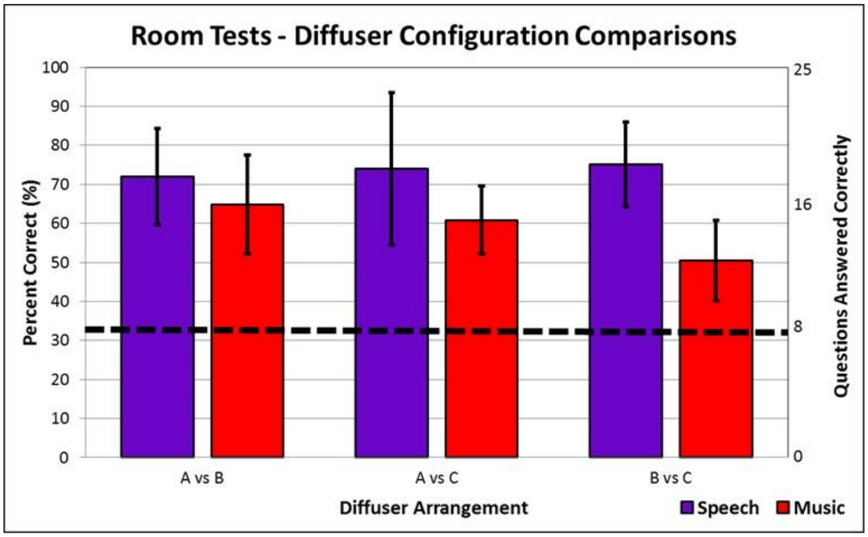


Figure 4.4.16: Room Tests data – Tests divided by diffuser configuration comparison (Error bars denote Standard Error of the Mean for each diffuser configuration grouping)

It was also possible to look at the Room Test data by diffuser configurations, namely contrasting the three main trial comparisons (A vs B, A vs C, & B vs C) for Male Speech and Violin Music source material. Figure 4.4.16 displays the completion percentages for all subjects and diffuser coverage percentages grouped across diffuser setup configuration. The Male Speech values (in blue) show almost no difference between comparison conditions. This indicated that when using the Male Speech source, the room configurations were equally distinguishable from one another. Comparatively, for the Violin Music source (in red) the three trial comparison values were different, with the A vs B and A vs C testing setups more discernible than the B vs C trials. This indicated that room diffuser configuration A was the most discernable by subjects when presented with the Violin Music source material. Also, as was the case when the data was grouped by diffuser coverage percentage, the Male Speech source was more differentiable than the Violin Music source for all diffuser trial comparisons.

4.4.7 Perception Testing – Conclusions

The subjective perception testing phase of this study produced a significant amount of data and statistics addressing a wide range of diffusion perception questions. Two of the primary testing configurations were the Wall Absorption Tests and the Wall Reflection Tests which both utilized Male Speech and Violin Music source material. Each of the testing configurations produced Just Noticeable Difference values for both speech and music sources, for a total of four distinct JND values. Figure 4.4.17 displays the JND percentages for all four testing conditions and points out how different subject performance was between configurations. The Wall Absorption tests were on average more discernible than the Wall Reflection tests for both source materials, considerably so for the Male Speech signal. When looking at the performance of subjects across sources, Male Speech was easier for subjects to distinguish than Violin Music for the Wall Absorption tests but not the Wall Reflection tests. In the Wall Reflection configuration, the speech and music sources were equally difficult to discern.

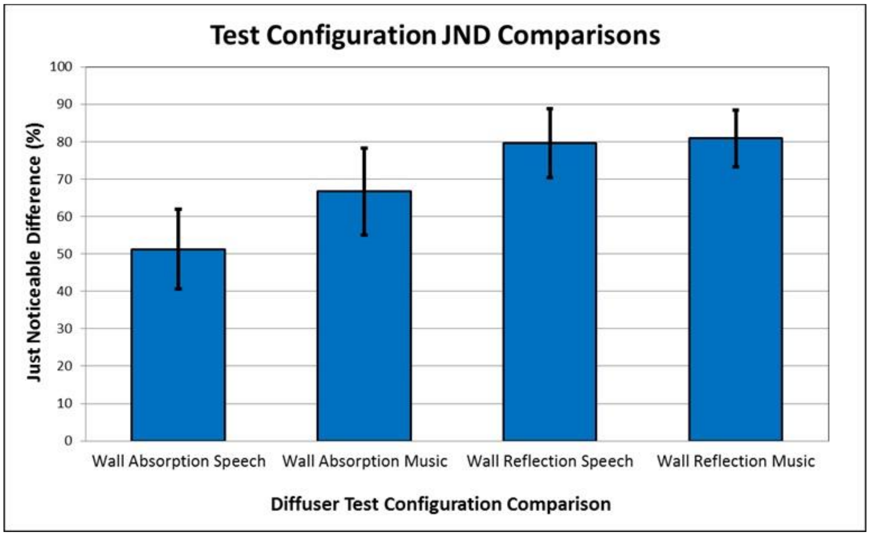


Figure 4.4.17: Wall Just Noticeable Difference values for all wall setup & source configurations (Error bars denote Standard Error of the Mean for each test grouping)

Overall, a significant amount of diffusive surface area was necessary for subjects to be able to discern the diffusive wall conditions from the absorptive or reflective conditions, regardless of the source material used. Even in the ‘easiest’ testing condition (the Wall Absorption tests using Male Speech) coverage of more than 50% was necessary for the average subject to be able to discriminate the difference. That equated to a surface area of 65.6 sq. ft. which would be a significant portion of any interior wall. Obviously, these area values increased even higher in the other testing configurations. For some subjects, however, the wall conditions presented in the Wall Test JND trials were distinguishable throughout the entire procedure, especially in the Wall Absorption tests. These subjects had better acuity in this subjective perception testing and indicated that some individuals could discern fine differences in diffusive room conditions.

By grouping the JND values by demographics, it was able to parse the subject perception performance data even further. In general, men performed better than women by 9% overall, achieving lower JND values for three of the presented testing configurations. This indicated that at least under these testing conditions, men actually were better listeners than women! (Although this result was not statistically significant) When the JND data was grouped by musical experience, there was a clear difference between subjects who were musicians and those who were not. Musicians outperformed non-musicians in all testing configurations and by an overall average of 23%.

The Wall Tests also produced data comparing the doubling and quadrupling of diffuser sizes, although the results from this analysis were varied across the four testing configurations. Figure 4.4.4 displays the data from the Wall Absorption tests using Male Speech, which was the way the Wall Test diffuser size comparison tests were anticipated to go, with the quadrupled trials more discernible than the doubled trials and trending in one direction or the other (either upward or downward) between groupings. Unfortunately, the subsequent testing configurations were much more varied, as some datasets trended upward, some remained constant, and others trended downward. Also, many of the trial completion percentages were near the random chance threshold of 33%, indicating that in those instances subjects were essentially guessing on each presentation. The Wall Test diffuser size comparisons therefore produced inconclusive data contrasting the differences between doubled and quadrupled diffuser size comparisons.

The final testing configuration was the Room Test, which implemented both Male Speech and Violin Music source materials. In this configuration, the Male Speech source was more discernible than the Violin Music source in all testing conditions. There was also a slight upward trend to subject completion percentages as the diffuser coverage percentages rose, though this result could have been the result of low statistical power. Looking at the diffuser configurations, when using the Male Speech source subjects showed no difference in discrimination capabilities, but when the Violin Music source was implemented, the midpoints of the wall configuration was more discernable than the other two.

Chapter 5

Objective Diffusion Metrics

5.1.1 Objective Metric Analysis Purpose

In addition to the subjective perception testing described in the previous chapter, the collected physical testing data was also analyzed numerically. The goal in this phase of the study was to quantify the diffusive conditions within the MOCAP space using passive metrics of sound field isotropy and monaural impulse responses. Numerically assessing the diffusive room conditions would be useful because knowing these diffusive properties within a room could potentially provide insights into the acoustic quality of the space or allow one to measure the effectiveness of installed acoustical treatments. The implementation of monaural inputs was also integral to the study, as these type of measurement microphones are standard in the field of acoustics. Performing this 'new' analysis would not require any additional testing procedures in the field: it would only require minor post-processing of the collected impulse responses. This contrasts with methodologies which implement multi-channel microphones (such as a 4-channel B-format microphone or a 30-channel Eigenmike), which provide more detailed measurements, but would not be ubiquitously applicable to a majority of the acoustics field, due to equipment availability. Therefore, it was determined before physical testing commenced that monaural impulse responses and monaural diffusion quantification methods would be implemented during the course of this study.

Because the 298 room impulse responses were collected in 64 unique and known diffuser configurations during the physical testing process, it allowed the comparison of acoustic conditions within the room under a variety of diffusive states. To perform this comparison, three previously proposed diffusion quantification metrics were selected to analyze each of the impulse responses. Values were generated using all three of the metrics for all impulse responses using data analysis procedures developed by the author, based on the methodologies described in the available literature. Ultimately, these values were compiled and statistical correlations were run, testing these selected metrics against the number of diffusers for each measured configuration. Through this analysis process, the diffusion quantification method best at assessing diffusive room conditions was determined, the most effective room diffuser configuration was studied, and the limit of diminishing returns for the number of diffusers installed was investigated.

5.1.2 General Analysis Procedure

To assess the diffusive conditions within the MOCAP space, three diffusion quantification metrics were used to analyze the impulse response data: Transition Time Utilizing Slope Ratio, proposed by Jeong, et al. in 2012 [22], Degree of Time Series Fluctuation, proposed by Hanyu in 2014 [19], and Number of Peaks, proposed by Jeon, et al. in 2015 [21]. Other diffusion quantification methodologies were also investigated, such as Mixing Time (Polack 2008) [17] and Kurtosis (Jeong 2016) [23], but the three listed best fulfilled the parameters of the study. All three metrics utilized monaural impulse responses to analyze the diffusive qualities of rooms, they could all be executed numerically using spreadsheet software, and they all produced single-number values which could be compared between room states, namely different diffuser configurations.

To perform the analysis of diffusive properties within the MOCAP Variable Acoustics Laboratory, a template spreadsheet was created in Microsoft Excel which would input impulse response data from individual measurements and compute values for each of the three metrics using sub-programs written with Visual Basic macros. The collected impulse responses were text files comprised of two columns, time (in seconds) and pressure (in Pascals), with values collected for every time interval, based on the sampling rate of 48 kHz. These values digitally represented the acoustic impulses that were generated and recorded which could subsequently be analyzed to determine any number of acoustical room properties, such as Reverberation Time, Clarity, Definition, speech intelligibility, and even diffusive conditions within the space.

In addition to the numeric impulse response data, the calculation spreadsheet also required the input of several testing conditions, such as room dimensions, sampling rate, speed of sound (determined by atmospheric conditions), and Reverberation Time across frequency, as measured by the acoustical testing software. Each of these additional testing properties were used in the methodologies of the selected metrics and listed on the acoustical data spreadsheet, so when setting up the calculation spreadsheet for each impulse response, both the numeric data and this additional information was transferred in before running the analysis macro to determine the values of the three metrics. The template spreadsheet was created so that all settings and conditions (such as room dimensions or metric setup values) were the same between measurements, so that the process could quickly be completed identically for all of the impulse responses.

Once the proper data from an impulse response was input into the calculation spreadsheet and the macros were run for each measurement, the values generated for the three metrics (using multiple threshold values, to be described below) were compiled and transferred into a master spreadsheet, where further analysis could be conducted. The final dataset was divided into three main configurations, based on the three different physical testing setups: the Wall Absorption Tests, the Wall Reflection Tests, and the Room Tests. Similar to the earlier analysis of the standard acoustical metrics, each of these configurations was further subdivided into testing groups by the microphone used to perform the test: Earthworks, Larson Davis, or Left/Right Kemar. The data from each microphone needed to be grouped in this manner because the metric values between testing groups were disparate enough that it made combining the data of the across testing configurations simply not possible.

The values from each of these testing configurations and microphone setups were then graphed and statistical regression tests were completed on all of the different setup conditions to determine whether any linear trends could be found between the diffusion metrics and the number of diffusers. The values generated from this analysis were then used to assess the efficacy of the three proposed metrics in their ability to measure the diffusive room conditions in the MOCAP testing space. In addition, the most effective room diffuser configuration and the limit of diminishing returns for diffusers were also investigated in this process.

Objective Metrics - Transition Time

5.2.1 Metric Description

The first diffusion quantification metric investigated was Transition Time, proposed by Cheol-Ho Jeong, Finn Jacobsen, and Jonas Brunskog in 2012. [22] The principal behind Transition Time was to analyze a room impulse response measurement and determine the time, in milliseconds after the direct sound, at which 'diffuse conditions' within the room would be reached. According to Jeong, "Transition Time is the time at which the width of a specularly reflected pulse becomes broader, therefore comparable to the average spacing between specular reflections, by analogy with the Schroeder frequency." [22] Taking this a step further, the Transition Time can be taken as the point in time at which there are no strong energy peaks, or reflections, remaining in the impulse response. For example, a room with only flat concrete surfaces (say a building under construction) would have very little absorption and therefore a long reverberation time with strong late reflections, generating a very large Transition Time. On the other hand, that same room appointed with a diffusive ceiling surface and filled with furniture and people (which also help to scatter sound) would have a Transition Time lower in value.

"(Transition Time) can be used for quantifying the diffusion in a room with different configurations of diffusers and absorbers," [22] with more diffuse conditions resulting in a lower Transition Time. Also proposed by Jeong et al. in the literature was the Transition-to-Reverberation Time Ratio, which was determined by dividing the Transition Time by the mid-frequency Reverberation Time, as calculated by the acoustical measurement software. This metric determined the relative position of the Transition Time as compared with the overall Reverberation Time in the room. For example, a very diffuse room might have a low Transition-to-Reverberation Time Ratio of 0.2, indicating that the Transition Time would be found after the initial 20% of the total impulse response time. However, a very specular room might have a value of 0.5 or higher, indicating that the Transition Time would not occur until the latter half of the impulse response. These metrics provide useful ways of analyzing the data, so statistical correlations were completed for both the Transition Time and Transition-to-Reverberation Time Ratio. . Interestingly, these values were very consistent with one another throughout all of the different room and microphone setups. Because of this uniformity, graphs and further analysis using this methodology were limited to the Transition Time metric alone. Full data for both of these metrics for all impulse responses can be found in Appendix B.

5.2.2 Transition Time Calculation Procedure

The calculation of Transition Time began with the numeric impulse responses, which were comprised time and pressure data points representing the measurement recorded. Each measurement contained 32774 data points, which represented an impulse response time span of 683 milliseconds, at a sampling rate of 48 kHz. Once the time and pressure data was transferred into the calculation spreadsheet, the squared pressure values were calculated for all data points in the measurement. These squared pressure values were then normalized to limit the range of data to between 0 and 1 by using the equation:

$$(Normalized\ Value)_i = \frac{(Squared\ Pressure)_i - (Squared\ Pressure)_{Min}}{(Squared\ Pressure)_{Max} - (Squared\ Pressure)_{Min}} \qquad (2)$$

Each value denoted with a subscript *i* indicates an individual squared pressure data point.

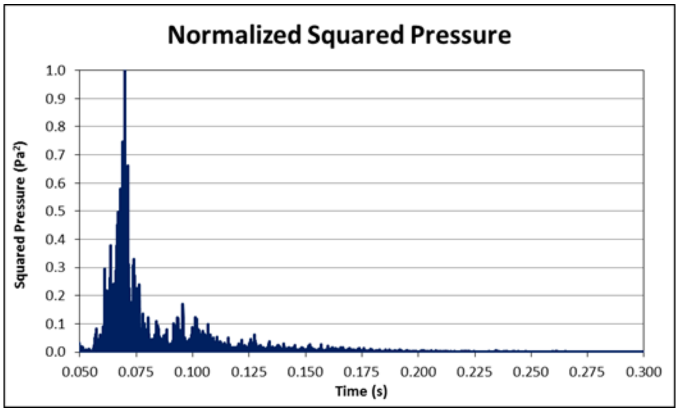


Figure 5.2.1: Normalized Squared Pressure graph for an example impulse response

The next step in determining the Transition Time was to calculate the reverse integrated Schroeder decay curve ($E_s(t)$). This was computed using the equation:

$$E_s(t) = \int_t^{\infty} p^2(\tau)d\tau \qquad (3)$$

The p^2 term in the equation refers to the normalized squared pressure values; the decay curve was calculated at all data points in the impulse response by starting at the last sequential value (t_1 = 32774) and working backwards all the way to the first data point (t_{Final} = 1). During this process, the reverse Schroeder decay curve values were subsequently converted into decibels by dividing each value by the squared reference pressure (20 µPa), taking the log (base 10), and finally multiplying by 10.

One note must be made on how the initial integration value (the value the summation variable was set at before calculation) was selected. Because the impulse responses collected were of finite length without an infinite decay, the end of the measurement time created an unwanted steep falloff in the pressure values (dropping from 50 µPa to 0 µPa, for instance). This caused issues in the calculation of the Schroeder decay curve, because the values of consecutive data points in the curve were being compared and then used to measure the Transition Time. By setting the initial integration value at 0, the calculation was performed as if the decay in the room dropped to 0 immediately after the measurement period and thus rate the final values of the impulse response much too strongly, rendering this methodology invalid. A second (failed) initial integration value was investigated using the final pressure value of each impulse response as the starting point. The problem with this method was due to the phase (meaning the position within the wave cycle) of the recorded impulse response at the end of the measurement, because depending on whether the wave was at a peak or a trough at that time determined the initial integration value. This setup caused significant variability between the collected impulse responses, and thus could not be used for the diffusion analysis process.

The methodology chosen for selecting the initial Schroeder integration value was to calculate an average pressure of the background noise level in the impulse response. This value was determined by first selecting a time clearly beyond the decay of the room response but before the end of the measured time period. A value of 500 ms was chosen as the start of the averaging time period for all measurements in this study. This methodology resulted in an initial integration value unique for each measurement which would lie between the min and max values of the background noise level of that impulse response. This simulated a smooth decay of one second beyond the end of the measured time period. Utilizing the RMS values of the background noise was also investigated, but the values produced were less consistent than when using standard averaging techniques.

With the reverse integrated Schroder decay curve computed and converted into decibels, the instantaneous slope values (*S(t)*) were calculated for the impulse response. To find these, the differences between sequential points on the decay curve were divided by the time difference (which equated to the time rate of 1/48000 s), as per the equation:

$$S(t) = \frac{L(t+\Delta t)-L(t)}{\Delta t} \tag{4}$$

L in the equation is the level, in decibels, of the Schroeder decay curve with t being the specific time of the sample and Δt the time rate. Because the values of the decay curve always descended, the values of the instantaneous slopes were always greater than zero. The Slope Ratio (R_{Slope}) could then be computed by dividing each instantaneous slope value, $S(t)$, by the average instantaneous slope value, $\bar{S}$, as per the equation:

$$R_{Slope} = \frac{S(t)}{\bar{S}} \tag{5}$$

It should be noted, that the Slope Ratio can be a very useful way of looking at the room impulse response data, as it displays the relative strength of energy peaks (i.e. reflections) in the impulse response absent from the energy time curve. This means that a strong late reflection would stand out in a Slope Ratio graph (as highlighted in Figure 5.2.2 (b)), as opposed to only looking at the squared pressure where the low relative levels of the later part of the impulse response would obscure these reflections (Figure 5.2.1).

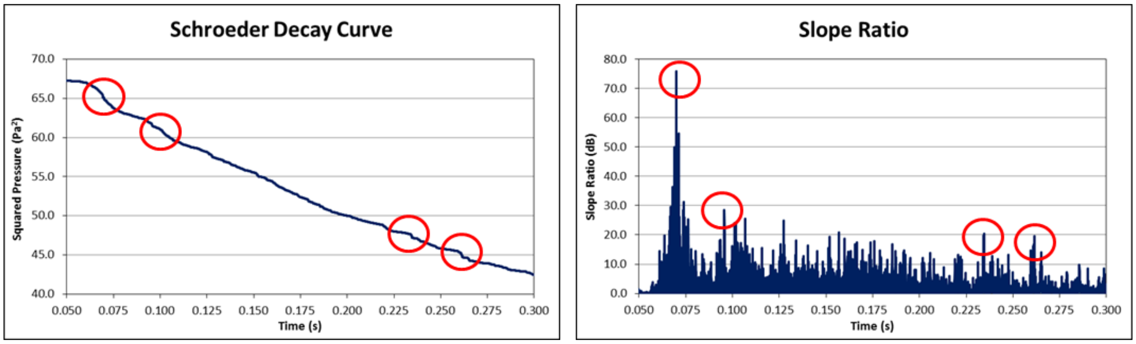


Figure 5.2.2: (a) Schroeder Decay Curve and (b) Slope Ratio for an example impulse response - Red circles show points of high instantaneous slope

The Transition Time was finally determined by finding the last reflection that exceeded a given Slope Ratio threshold. The threshold used in this study was 11 dB, as recommended by Jeong in the literature. This meant that a peak in the impulse response would require a Slope Ratio of 11 dB or higher to contribute toward the calculation of the

Transition Time. The last reflection to exceed this threshold would be deemed as the point at which diffuse room conditions had been met, and thus would represent the Transition Time for that measurement. Other threshold values were investigated, namely 9 dB (also researched by Jeong), but it was found that the recommended value of 11 dB produced the most consistent results. The full dataset for both 11 dB and 9 dB thresholds can be found in Appendix B.

The Transition Time and Transition-to-Reverberation Time Ratio metrics both provided an interesting way of analyzing diffusive room conditions using monaural impulse response data. The former defined a specific time after which room conditions could be considered ‘diffuse’, whereas the latter indicated a relative time ratio of diffuse room conditions compared with the Reverberation Time of the space. It should be noted that the computation of these metrics were influenced by more room properties beyond the number of diffusers present. This was due to the fact that these metrics indirectly measured the diffusive conditions within room by calculating a time of diffuse transition. Consequently, absorption on the walls, the size of the room, and the room configuration all influence the calculation of Transition Times, which is obviously not desired when specifically studying diffusion. Therefore, the use of Transition Times when analyzing diffuse room conditions must be handled carefully as numerous acoustical properties, not just diffusion, can come into play when implementing this metric.

Objective Metrics - Degree of Time Series Fluctuations

5.3.1 Metric Description

The second diffusion quantification metric investigated in this study was the Degree of Time Series Fluctuations, proposed by Toshiki Hanyu in 2014. [19] The principal behind this metric was to find a way to quantify the fluctuation of an impulse response using a single number metric. Knowing the time fluctuation characteristics of the room could therefore shed light about its diffusive conditions as well, for an impulse response with significant time variation would be expected from a diffuse room and not from a specularly reflecting room. For the Degree of Time Series Fluctuation metric, lower values correlated to more diffusive room conditions. Another feature of this analysis methodology was the Decay Cancelled Impulse Response, which had the capabilities of measuring the strength of impulse response reflections, similar to the Slope Ratio described in the previous section.

5.3.2 Degree of Time Series Fluctuations Calculation Procedure

The calculation of the Degree of Time Series Fluctuations closely resembled the procedure laid out for the Transition Time above. With time and pressure data transferred in from the impulse response text file, the squared pressure (p^2) was calculated for each data point. Next, the reverse integrated Schroeder decay curve ($E_s(t)$) was computed from the squared pressure values using the same equation above:

$$E_s(t) = \int_t^{\infty} p^2\,(\tau)d\tau \qquad (6)$$

Then, the squared Decay Cancelled Impulse Response ($g^2(t)$) was calculated by dividing the squared pressure values by the Schroeder decay curve using the equation:

$$g^2(t) = \frac{p^2(t)}{E_S(t)} \tag{7}$$

This function can be used to assess the relative strength of reflections within an impulse response, as Slope Ratio could for the Transition Time metric. The comparisons of these two quantities can be found later in the chapter. The decay rate (*A*) was then calculated as the approximate mean of the squared Decay Cancelled Impulse Response:

$$A \cong \overline{g^2(t)} \tag{8}$$

The Reverberation Times (*RT*) within the space could then subsequently be estimated using the decay rate values calculated for a decay range of 60 dB (i.e. a T_{60} reverberation time estimation) and a bit of algebraic manipulation to come to the equation:

$$RT \cong \frac{13.82}{A} \tag{9}$$

The next step in determining the Degree of Time Series Fluctuations was to compute the normalized squared Decay Cancelled Impulse Response ($h^2(t)$) using the equation:

$$h^2(t) = \frac{g(t)}{\sqrt{\overline{g^2(t)}}} \tag{10}$$

This process changed the mean value of the normalized Decay Cancelled Impulse Response from the decay rate (as it was before normalization) to a value of 1 for all measurements. This allowed the comparison of impulse responses taken from different rooms or microphones, at least in theory. In practice, the data from this study produced significantly varied results between room/microphone test groupings even though the mean normalized Decay Cancelled Impulse Response values were all 1, which precluded the comparison between the various setup configurations.

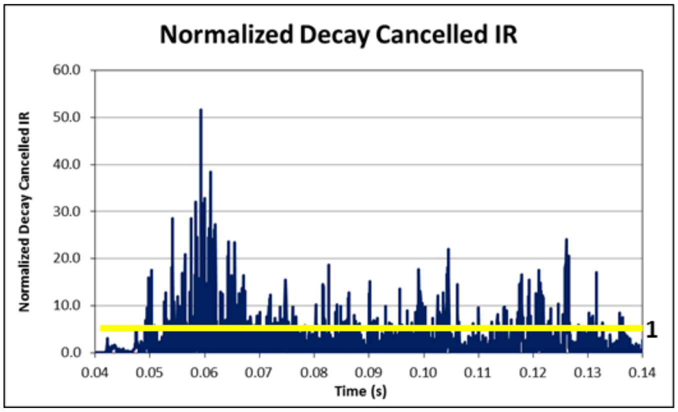


Figure 5.3.1: Normalized Decay Cancelled Impulse Response for an example measurement

The final step in calculating the Degree of Time Series Fluctuations involved taking the normalized Decay Cancelled Impulse Response and integrating over a specified range, namely the time range of the decay between the direct sound and the background noise level. For this dataset, the integration time range was between 0.04 s and 0.30 s for all measurements, chosen as the average decay time range for all collected impulse responses. The result of these integrations were single number values representing the area underneath the normalized Decay Cancelled Impulse Response for the selected time range, denoted R_{Total} and calculated using the equation:

$$R_{Total} = \int_{t_1}^{t_2} h^2(t)dt \qquad (11)$$

The threshold between the top 1% and the lower 99% of the integrated R_{Total} was then calculated. This threshold was also named the Degree of Time Series Fluctuations (k) value, as shown in Figure 5.3.2. The selected percentage value of 1% implemented was proposed by the author of this methodology, as Hanyu described "the Degree of Time Series Fluctuation indicates how large the reflected sound energy is where probability of occurrence is 1%." [19]

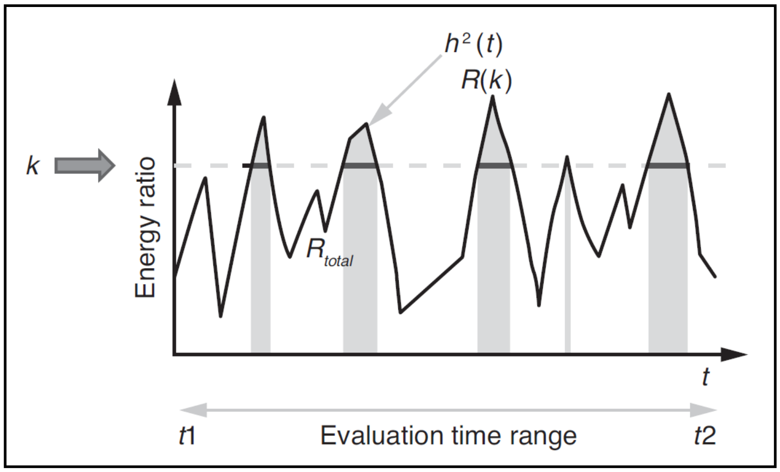


Figure 5.3.2: Degree of Time Series Fluctuations calculation (Source: Hanyu 2014)

The Degree of Time Series Fluctuations metric theoretically produces smaller values in diffuse room conditions, due to acoustic energy being spread more evenly throughout the room, creating a greater number of peaks (which are lower in level) in the impulse response, generating a lower threshold value (k). Specular conditions in an identical room would produce a higher Degree of Time Series Fluctuations, because the acoustic energy would be concentrated within a smaller number of peak reflections, which would ultimately raise the value of k.

The Degree of Time Series Fluctuations is a useful metric that can be used to compare diffusive room conditions using measurements collected from monaural impulse responses. However, the values produced are proprietary in design due to the numerous calculation steps involved, meaning these values do not correlate to any specific scientific quantity (such as time, pressure, frequency, etc.). Therefore, the application of this metric is not fully intuitive. (A k value of 56 does not denote a meaningful quantity, whereas a Reverberation Time of 0.5 s does) This does not negate its potential usefulness, however, as this metric still has the capabilities to assess diffusive room conditions.

Objective Metrics - Number of Peaks

5.4.1 Metric Description

The final diffusion quantification metric investigated in this study was the Number of Peaks, proposed by Jin Yong Jeon, Hyung Suk Jang, and Yong Hee Kim in 2013. [21] The principal behind this methodology was to count the number of instances in an impulse response where a peak pressure point could be found within a given level threshold. This metric provided the most direct measurement of diffusive conditions within the testing room, as it concentrated on the fine early structure of the collected impulse responses, as opposed to more general features of the data like the reverberation time or decay rate. This resulted in the metric being less influenced by superfluous room factors, such as wall absorption and source/receiver configurations, and better at directly rating the diffusive conditions of the MOCAP testing facility.

To perform the analysis, the number of pressure peaks above a given threshold in an impulse response were counted. If diffusers were added to the room, generally the fine structure of the impulse responses became more fluctuating, indicating more reflections, resulting in a higher Number of Peaks. If diffusers were removed from the room, the opposite effect would occur and the Number of Peaks was likely to decrease. There seemed to be a direct correlation between the values produced by the Number of Peaks metric and the number of diffusers present in the collected impulse responses, which helped the performance and accuracy of the metric in assessing the diffusive room conditions. In fact, the link between the Number of Peaks metric and the number of diffusers in the impulse response data was so strong that all statistical correlations proved significant, as will be shown in the results section below.

5.4.2 Original Number of Peaks Calculation Procedure

There were two methods that were investigated in the calculation of the Number of Peaks metric. The first method was based upon the exact equations provided in the literature written by the authors, the second being a simpler numeric approach. In this study, the methodology to calculate the Number of Peaks in the literature was researched, but due to a lack of specific information regarding the variables utilized in the formulas, this method could not be employed. A numeric methodology for determining the Number of Peaks metric was developed by the author, which accomplished the desired task of the described metric utilizing a more straightforward approach. This second method was used to analyze the impulse response data collected from the MOCAP space.

The original methodology as described by Jeon uses the principal of wavelets to analyze collected impulse response data in small time windowed sections. One of the advantages of wavelet analysis is the ability to perform a local analysis of the data, due to its time and level scalability. Specifically, the continuous wavelet transform (CWT) is implemented, which has the capabilities to analyze impulse responses, including the similarities between diffusive room conditions. “The CWT signal of a wavelet family generated by a mother wavelet is defined below, where *x(t)* is the input signal such as an impulse response, *g(t)* is a continuous function in both the time and frequency domains called the mother wavelet, *a* is the frequency scale factor, and *b* is the shift factor indicating the time domain position.” [21]

$$CWT(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} x(t) * g\left(\frac{t-b}{a}\right) dt \tag{12}$$

The Morlet wavelet, which is a modified Gaussian function, was chosen as the mother wavelet due to its sensitivity to frequency signal characteristics. Other wavelet shapes were possible for this analysis, though they were not investigated in the literature. The Morlet wavelet is defined as:

$$g(t) = e^{\frac{-t^2}{2}} * cos(5t) \tag{13}$$

The Morlet wavelet is used to compare different time sections against identical time sections of the original signal for the entire duration of a measurement. The CWT generates values which showed the similarity between the wavelet and the signal, with higher numbers indicating a greater similarity. The process of comparison is continued, with "the wavelet scaled (stretched) and the above process repeated, for all scales. In room impulse response analysis, one reflection is defined as a wavelet with one or more peaks." [21] Finally, these wavelets are used to count the number of peaks in the data and compute the Number of Peaks metric. (Figure 5.4.1)

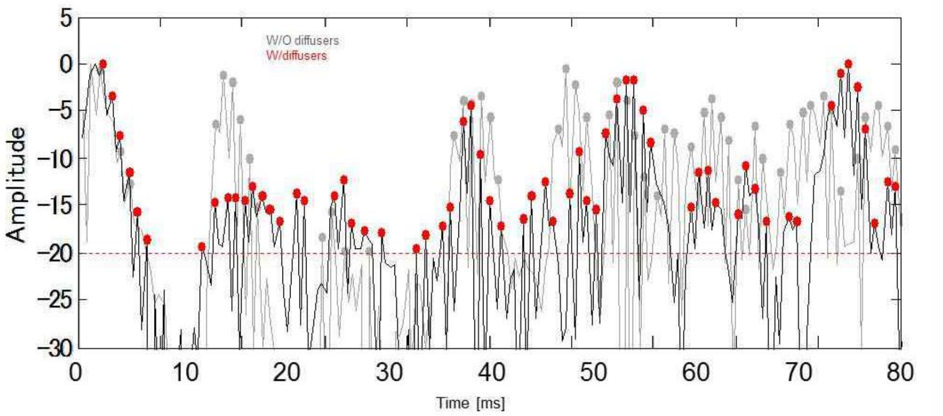


Figure 5.4.1: Example calculation of the Number of Peaks metric - Red dots indicate peaks (Source: Jeon 2013)

Using these descriptions and equations, it should have been possible to calculate the Number of Peaks metric as Jeon was able to in the literature. Unfortunately, there was a lack of information regarding the specific details in how to implement the procedure. First of all, the frequency scale factor and the shift factor (variables *a* and *b* in the equations above) were not sufficiently discussed in the literature with no values being provided. Considering the wavelet analysis was to be conducted 'for all scales', this was an important variable to omit information about. Another concern regarding the methodology involved the actual counting of the peaks. According to Jeon, "the number of local maxima can be estimated when considering the diffuseness differences in the temporal reflection density in an impulse response. If we transfer this concept to the time domain, the "reflections" are counted as long as they have enough time between them. However, they can overlap and build some arbitrary peak structure depending on the sampling frequency." [21] This was all of the information provided on *how* to compute the Number of Peaks, which was lacking in detail to say the least. Due to these numerous concerns, it was decided to either look for an alternate way of computing this metric or not use it in the analysis at all.

5.4.3 Implemented Number of Peaks Calculation Procedure

Fortunately, an alternate method to calculating the Number of Peaks metric was formulated by the author. This methodology took a simplified approach by counting the number of samples in the impulse response that represented 'pressure peaks' above a given threshold. This threshold was proposed in the literature as 20 dB below the peak value in the impulse response, meaning pressure peaks must be above this threshold to be counted in the Number of Peaks metric. Values of 20, 25, and 30 dB were utilized in this study, with the same value used within measurement groups. The reason for the threshold variability was to compensate for the strong direct sound experienced in some measurement groups, which varied by as much as 10 dB between microphones positions in identical diffuser configuration setups. For example, the ear of the Kemar Head &

Torso closest to the sound source recorded a much stronger direct sound than the opposing ear (due to head occlusion), and thus would require a larger threshold value to compensate for this level difference to properly calculate the Number of Peaks metric.

The calculation began by taking the impulse response pressure data, computing the absolute value of all data points, and then converting all figures into decibels. Next, the ‘peaks’ in the impulse response were determined by comparing adjacent points within the pressure data. If the sample one before and one after the point of interest were lower in level, a peak was defined. If it exceeded the threshold value for the specific measurement, it was counted in the Number of Peaks metric. Finally, the Number of Peaks was calculated by counting the total number all of the pressure points that were found to be peaks above the given threshold. This method of calculating the Number of Peaks metric was much simpler in formulation than the original literature methodology, as it only looked at peaks from the original signal waveform, without utilizing wavelet analysis or stretching/sectioning any of the data. However, the adjusted method did perform well in the analysis of the MOCAP impulse response data, for which the original methodology was unable to be computed.

Looking at the primary acoustical testing categories, the Wall Tests (for both absorption and reflection setups) were analyzed exactly as described above, which produced accurate results.

The Room Tests were also analyzed as described above, although the results were much poorer. Due to the four speakers used in the Room Tests, as described in Chapter 3, no unique direct sound was present in the impulse responses. An example of this can be seen in the inset of Figure 5.4.2, as numerous independent peaks make up the first 20 ms of the impulse response. An energy time curve such as this indicates that the initial sound was generated from numerous directions or that it was reflected multiple times (or both). The Number of Peaks metric is calculated based on the peak pressure value (which is usually the direct sound), but in this instance the speaker setup employed disrupted this methodology as there was no specific direct sound. It was therefore necessary to time window the data and look at pressure values for the decay range after the peak level in the impulse response. A windowing time of 250 ms was chosen for all measurement (kept constant to maintain consistency between all conditions) to concentrate on the decay range for each of the measurements, as shown in main graphic of Figure 5.4.2. By eliminating the superfluous early data and looking solely on the decay range for the Room Tests, the Number of Peaks metric produced very consistent results.

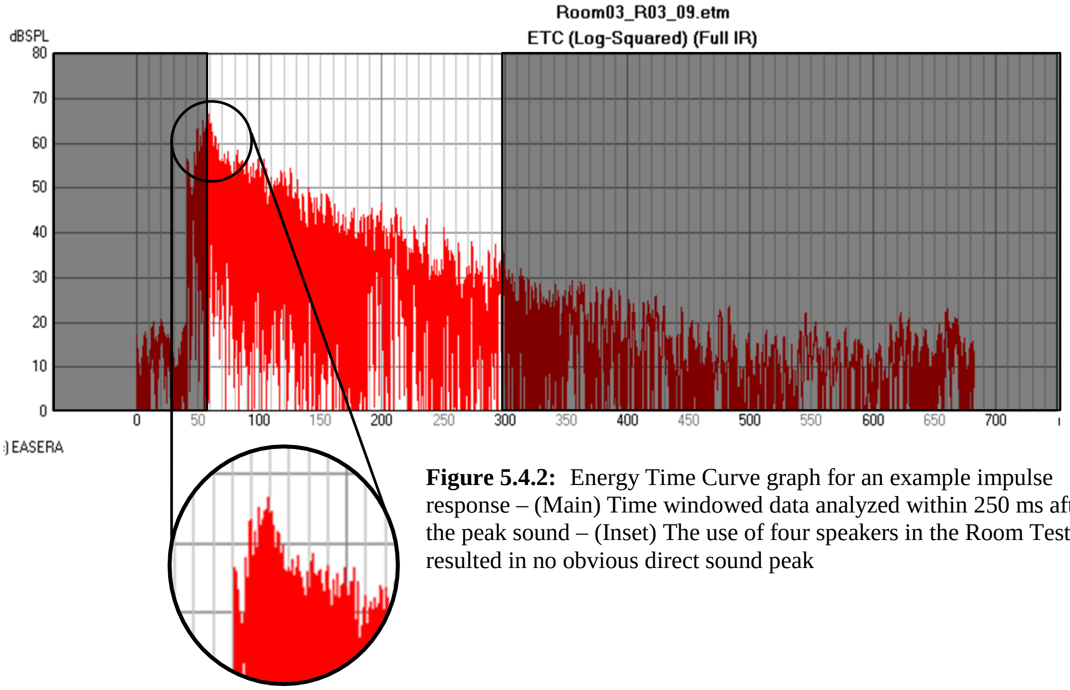


Figure 5.4.2: Energy Time Curve graph for an example impulse response – (Main) Time windowed data analyzed within 250 ms after the peak sound – (Inset) The use of four speakers in the Room Tests resulted in no obvious direct sound peak

Objective Metrics - Data

5.5.1 Analysis Methodologies

The data for all three of the diffusion quantification metrics described above with all threshold values of interest and secondary calculation metrics can be found for all 298 impulse responses in Appendix B. The data has been subdivided first by the three specific metrics: Transition Time, Degree of Time Series Fluctuations, and Number of Peaks. The data was then subdivided a second time into the three different testing configurations that were measured: the Wall Absorption Tests, the Wall Reflection Tests, and the Room Tests. Each column of data represents a particular microphone, a specific threshold, and an individual metric. For example, the first page of Appendix B includes data for the Transition Time metric and the Wall Absorption Tests. Included on the spreadsheet are eight columns, divided by microphone (Earthworks 1 or 2), threshold (11 dB or 9 dB), and metric (Transition Time and Transition-to Reverberation Time Ratio). On the left is a column which indicates the number of diffusers for the given measurement. On the bottom are the statistical test results of the linear regression that were run to compare the particular metrics to the number of diffusers to determine if any correlations were present.

Also included in Appendix B are graphs for the three primary metrics for all testing configurations. The graphs are numbered 1 – 10 for the Wall Tests, with graphs 1 – 5 representing diffusion and absorption measurements and graphs 6 – 10 displaying diffusion and reflection measurements. For the Room Tests, there are four graphs, numbered 1 – 4 for the Transition Time and Degree of Time Series Fluctuations metrics.

For the Number of Peaks metric, there are eight graphs, with the first four showing the unfiltered analysis and the next four displaying the time filtered analysis. The dataset used in each graph is shown beneath each column of the listed spreadsheets.

5.5.2 Statistical Correlations

Values were produced for all three of the metrics in numerous conditions and for all collected impulse responses, but as individual data points they didn’t reveal much information. When the data was viewed as a whole, however, it was possible to discover patterns and correlations between the metrics and the different room configurations. It was necessary to find a way to analyze the large amount of data that was produced which would allow for meaningful conclusions to be generated.

The first step in the analysis process was subdividing the data into the individual metrics, by room configuration, and by the microphone used as described above. It was obvious when looking at the raw data, that this subdivision was required, as large differences were found between microphone positions for the same metric and room configuration. For example, one dataset for the Number of Peaks metric ranged from 22 to 50 (the Earthworks 2 microphone), whereas another ranged from 31 to 100 (the Larson Davis microphone). While both of these groups produced significant findings individually, if the data for both groups was compiled as a whole the resulting tests might not have returned significant results. These types of discrepancies between testing groups were seen for all of the metric/room/microphone configurations, so therefore all statistical tests were run after being subdivided into the described groupings.

The specific statistical tests that were computed for the objective diffusion metric analysis used a linear regression model that would compare the number of diffusers for the specific measurement against the values generated for each metric. The impulse responses were collected with a known number of diffusers for each measurement (0 – 32 for the Wall Tests, 0 – 298 for the Room Tests) and that number was used in each correlation. If there was a relationship between a calculated metric and the number of diffusers, the statistical tests would produce ‘significant’ values ($p < 0.05$); if there was no correlation, the tests would not produce significant values.

The program used to perform the statistical analysis was SAS, Statistical Analytics Software, which was accessed in the Arts & Sciences Hall of the University of Nebraska – Omaha. The software input the data and ran the desired statistical analyses as programmed by the author. All data to be tested was compiled in the manner displayed in Appendix B, with the number of diffusers listed as the first column of the dataset and each subsequent column representing a different metric to be analyzed. Independent linear regressions were run on each metric, for all thresholds, and all impulse responses. Each of these regressions produced statistical values which determined the strength of the correlation between the number of diffusers and the specific metric. The primary statistical data produced in these tests were F*, PRE, and p values; these values are listed beneath each dataset tested in Appendix B. These three quantities rate the statistical significance of the tested correlations, but the p values were the most important to this study, as they were directly used to determine the statistical significance of the performed analysis. With a p value of less than 0.05, a statistical test would be considered significant and therefore identifying a strong correlation between the tested variables. With a p value greater than 0.05, a statistical test would not be considered significant, and thus there would not be a strong correlation between the tested variables.

Once the statistical correlations were completed for all three of the metrics and all of the test groupings, it was possible to look at the data in aggregate. In this way, the three primary test configurations were subdivided by the microphone groups, so the Wall Absorption Tests contained 5 data groupings (for the 5 microphones used in the tests) and the Wall Reflection Tests had the same 5 data groupings. The Room Tests were subdivided twice: by the diffuser configuration (A, B, or C) and by the 4 microphones used. This resulted in 12 data groupings for the Room Tests, for a total of 22 data groupings between all tested conditions.

5.5.3 Transition Time Data

The values produced for each impulse response by the Transition Time metric were time values, measured in milliseconds, between the direct sound and the last reflection that exceed the selected decibel threshold in the Slope Ratio. The threshold level utilized in this analysis was 11 dB. The Transition Time values indicated the point of the impulse response at which diffuse room conditions were met. Thus a lower Transition Time would indicate higher diffusivity within the room because diffuse room conditions would be met earlier within the impulse response.

The Transition Time values that were produced using the data collected in this study ranged between 100 ms and 330 ms for all data points, but the values within testing groups were generally much more consistent. Figure 5.5.1 shows examples of the Transition Times generated for two different test groupings. The graph on the left displays the data from the diffusion and reflection Wall Test for the Earthworks 2 microphone position. All Transition Times for this data grouping were between 125 ms and 145 ms with the majority of the values being approximately 144 ms. This was an example of a statistically non-significant test, where no correlation (F(1,19) = 0.07, p =

0.793) was found between the number of diffusers and the value of the Transition Time metric. Conversely, the graph on the right displays a statistically significant data grouping (F(1,19) = 5.83, p = 0.026) taken from the Wall Reflection Tests for the Larson Davis microphone.

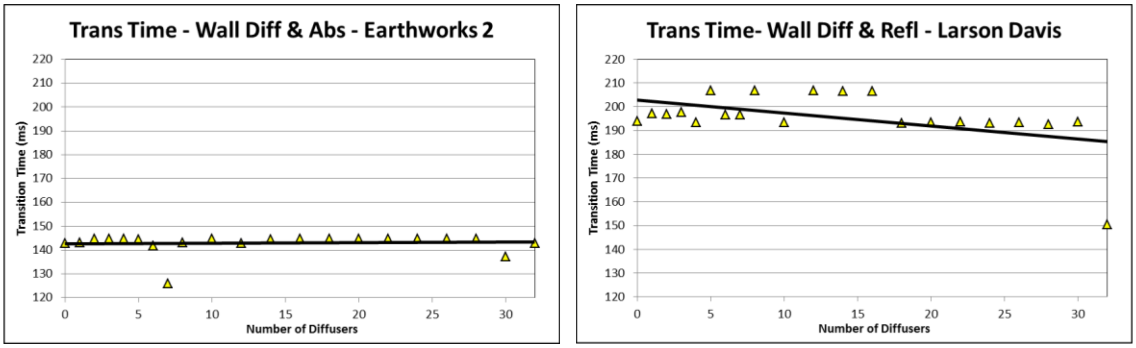


Figure 5.5.1: Transition Time graphs for two Wall Test groupings – (a) Diffusers & Absorbers Wall Tests, Earthworks 2, (b) Diffusers & Reflectors Wall Tests, Larson Davis

One problem that was encountered while implementing the Transition Time metric was finding correlations that were in the reverse direction as expected. For example, Figure 5.5.2 shows two data groupings, one from the Wall Absorption Tests and the other from the Room Tests, where Transition Times rose as the number of diffusers (or diffuser coverage percentage) increased. This goes against the expected nature of the metric, where lower Transition Times were predicted as the diffusive room conditions (and hence the number of diffusers) increased. This phenomenon was likely due to the dependence of the Transition Time metric on other acoustical properties than simply room diffusion. It was clear that the changing the Reverberation Times between impulse responses (as was the case in the Room Tests) affected the Transition Time values. Consequently, the use of a highly absorptive testing facility (which the MOCAP was) must have impacted results, as many potential late reflections were eliminated by the absorption present in the room.

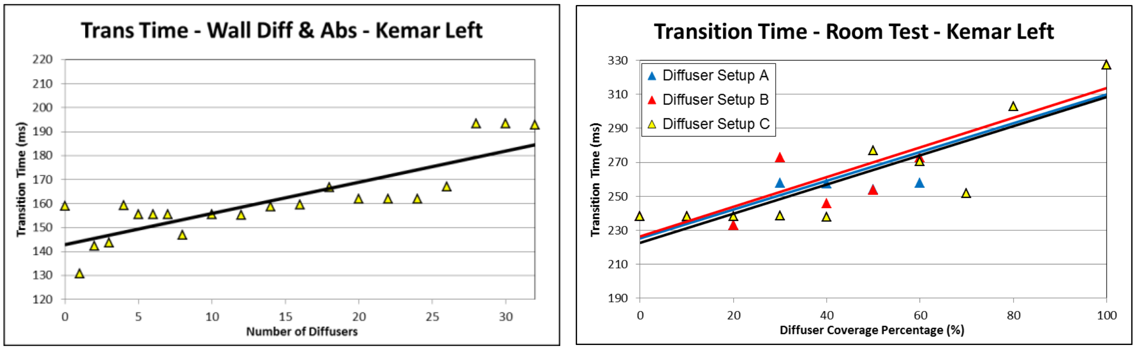


Figure 5.5.2: Transition Time graphs for two test groupings – (a) Diffusers & Absorbers Wall Tests, Kemar Left – (b) Room Tests, Kemar Left

Looking at the testing groups as a whole (Table 5.5.1), 3 of 5 Wall Absorption Tests produced statistically significant results (highlighted yellow). Interestingly, all significant tests generated Transition Times in reverse of the expected downward trend. For the Wall Reflection Tests, only 1 of 5 testing groups produced significant results, with this group showing the downward trend predicted. In the Room Tests, 4 of 12 testing groups proved statistically significant, though all four showed higher Transition Times as the diffusion coverage percentage increased in the room.

Table 5.5.1: Statistical correlations of Transition Times for all test groupings – Statistically significant tests ($p < 0.05$) highlighted yellow

	Diffusion & Absorption Wall Test		Diffusion & Reflection Wall Test	
	F*	p	F*	p
Microphone 1	9.68	0.006	0.22	0.647
Microphone 2	0.07	0.793	0.02	0.899
Microphone 3	3.97	0.061	5.83	0.026
Microphone 4	44.93	<.001	1.98	0.176
Microphone 5	18.59	<.001	0.86	0.365

	Room Test - Config A		Room Test - Config B		Room Test - Config C	
	F*	p	F*	p	F*	p
Microphone 1	0.05	0.835	0.82	0.415	31.88	0.001
Microphone 2	0.00	0.987	22.84	0.009	3.84	0.091
Microphone 3	5.99	0.071	3.01	0.158	23.14	0.001
Microphone 4	0.84	0.412	5.36	0.082	14.97	0.005

In general, the Transition Time metric did not perform well statistically in analyzing the diffusive conditions within the MOCAP facility. Of the 22 testing groups between the two different Wall Tests and the Room Tests, only one group produced statistically significant results consistent with the prescribed function of the metric, namely that more diffusive room conditions predicted lower Transition Times. The other 21 testing groups either showed no statistical correlation or found a relationship opposite of the expected results. The high levels of absorption present in the room along with the changing acoustic conditions certainly contributed to the poor performance of this metric in this study. Based on the data collected, though, the Transition Time metric cannot be recommended for use when assessing the diffusive conditions within a room.

The Slope Ratio, on the other hand, proved to be a useful tool in analyzing the relative strength of reflections in an impulse response. By looking solely at the variation of the reverse Schroeder decay curve, it was possible to measure the value of energy peaks without the influence of the energy time curve which can make these peaks difficult, if not impossible, to detect in the standard pressure graph.

5.5.4 Degree of Time Series Fluctuations Data

There were three values that were produced when calculating the Degree of Time Series Fluctuations for the collected impulse response data: the threshold k (i.e. the Degree of Time Series Fluctuations), the decay rate A, and the estimated Reverberation Time. The threshold k was a single number rating which indicated the amount of fluctuation within the normalized Decay Cancelled Impulse Response, with lower numbers indicating less variation in the sound field and thus more diffuse room conditions. This threshold value did not correlate to a specific acoustic quantity (such as dB, Pa, etc.) because of the data manipulation and normalization procedures, and therefore it was a stand-alone, unitless metric. The decay rate was also computed for the data as described above along with the estimated Reverberation Times. The threshold k value was more consistent when assessing the diffusive room conditions than the calculated decay rate or the estimated Reverberation Times as the metric produced more statistically significant comparisons, indicating a better correlation between k and the number of diffusers. While the data has been included for the decay rate and the estimated Reverberation Times, all subsequent analysis in this study was based on the Degree of Time Series Fluctuations, k.

The k values generated for the impulse response data were wide ranging, and changed depending on the specific testing group. For the Room Tests, the k values spanned between 20 and 70; for some of the Wall Tests the k values ranged from 100 to 300 while others extended much higher, between 400 and 1400. The differences seemed primarily tied to the measurement positions, but because all receivers were Type 1 measurement microphones the generated values were expected to be consistent between instruments, so it was unclear what the true cause of these discrepancies was. Due to the normalization process, the mean value of the normalized Decay Cancelled Impulse Response shifts to 1, which was intended to allow comparison between disparate measurements. For data in this study, this assumption turned out to be incorrect, as the Degree of Time Series Fluctuation values were very different between measurement groups, as can be seen in Y-axis scales of Figure 5.5.3. The analysis was therefore limited to group by group correlations, with each testing group handled separately.

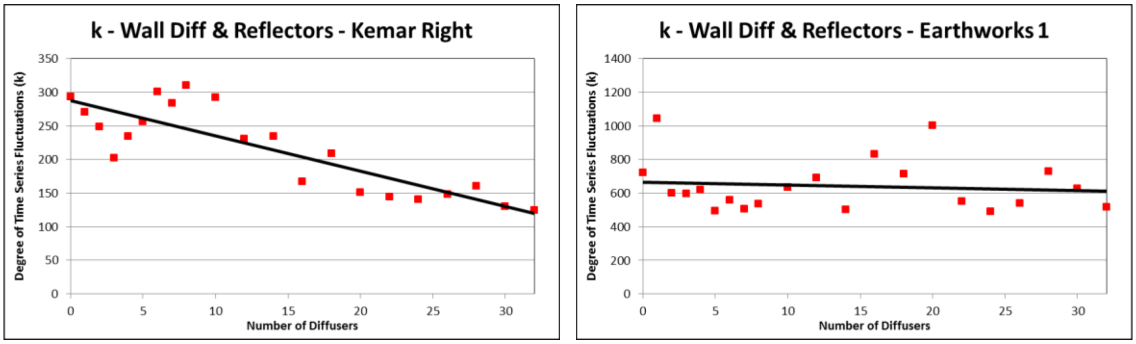


Figure 5.5.3: Degree of Time Series Fluctuations for two Wall Test groupings – (a) Diffusers & Reflectors Wall Tests, Kemar Right, (b) Diffusers & Reflectors Wall Tests, Earthworks 1

The majority of the Wall Tests (9 of 10) for both the diffusion and absorption conditions as well as the diffusion and reflection conditions resulted in statistically significant findings. This meant that as the number of diffusers increased, a lower Degree of Time Series Fluctuations was found as predicted. (Figure 5.5.3 (b)) Only one testing group, shown in Figure 5.5.3 (b), produced a statistically non-significant result.

The Room Tests, on the other hand, did not generate the same consistent results as in the Wall Tests. Here, only 3 of 12 room test groupings proved to be statistically correlated. Figure 5.5.4 (a) shows a few of the Room Test groupings that were significant, while Figure 5.5.4 (b) displays what the majority of the data looked like for the Room Test groupings. The reason behind the ineffectiveness of the Degree of Time Series Fluctuations in the Room Tests was likely due to the changing Reverberation Times (and thus the decay rate) between different measurement conditions. Because the diffuser step size in the Room Tests was 30 diffusers, a difference in Reverberation Time between the impulse responses was created. Because the Degree of Time Series Fluctuations included decay rate as part of the analysis, it might have been expected that the threshold k would be impacted by a change in reverberation. The Wall Tests did not experience this calculation issue because there was very little difference in Reverberation Time between the different measurement conditions.

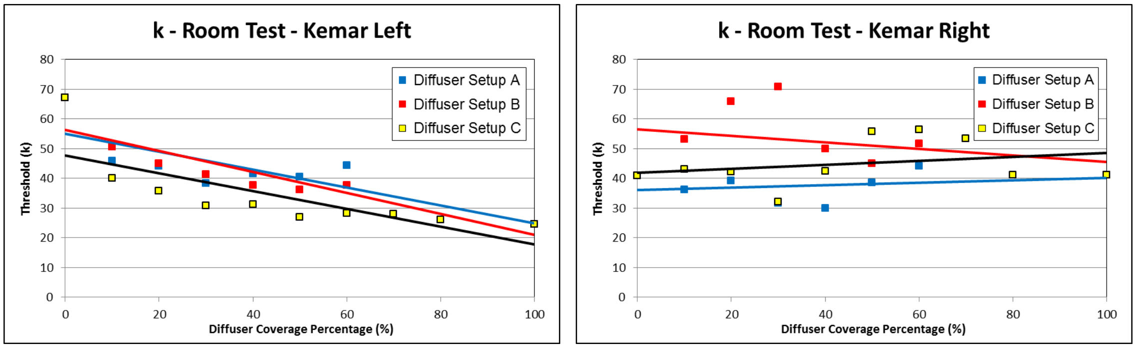


Figure 5.5.4: Degree of Time Series Fluctuations for two Room Test groups – (a) Kemar Left, (b) Kemar Right

In general, the Degree of Time Series Fluctuations proved to be a viable way of looking at the diffusive conditions in a room. It generated consistently accurate results when Reverberation Time was controlled as it was for the Wall Tests, but when reverberation varied, as in the Room Tests, the metric was inconsistent.

Table 5.5.2: Statistical correlations of Degree of Time Series Fluctuations for all test groupings – Statistically significant tests ($p < 0.05$) highlighted yellow

	Diffusion & Absorption Wall Test		Diffusion & Reflection Wall Test	
	F*	p	F*	p
Microphone 1	21.03	<.001	0.23	0.639
Microphone 2	19.29	<.001	21.26	<.001
Microphone 3	8.02	0.011	17.74	0.001
Microphone 4	10.57	0.004	21.48	<.001
Microphone 5	19.72	<.001	49.91	<.001

	Room Test - Config A		Room Test - Config B		Room Test - Config C	
	F*	p	F*	p	F*	p
Microphone 1	7.98	0.048	0.02	0.894	3.29	0.107
Microphone 2	0.22	0.666	7.39	0.053	0.45	0.523
Microphone 3	0.40	0.563	21.81	0.010	10.78	0.011
Microphone 4	0.63	0.472	1.22	0.331	0.65	0.444

5.5.5 Number of Peaks Data

For the Number of Peaks metric, single number values were generated for each collected measurement that counted the number of peaks found in the impulse response above a given threshold. Both the methodology proposed in the literature by Jeon and the alternative method implemented by the author were described above, with the latter way of calculating the metric used in this analysis. It was expected that an increase in the number of diffusers would improve the diffusive conditions within the room and translate to a more fluctuating impulse response, and thus more peaks. Therefore it was predicted that a larger number of diffusers would generate a greater Number of Peaks value.

For both Wall Test configurations, this methodology counted the number of peak pressure samples above thresholds between 20 dB and 30 dB (depending on the test grouping below the peak sound level. Because a standard threshold value was not used for all groupings, the values produced could not be directly compared with other test groups. Figure 5.5.5 displays two of the testing groups for the Wall Tests. The values produced by this metric were consistent between the 10 different Wall Test groupings, with the Number of Peaks ranging from 20 to 120 peaks and generally quite well ordered. In fact, all testing groups for the Wall Tests produced statistically significant results, indicating excellent agreement with the metric. Looking at the values for the fully absorptive and reflective test walls, the reflective condition produced similar or lower peaks than the absorptive condition (when thresholds were the same), meaning the reflective wall created more specular reflections, resulting in lower Number of Peaks.

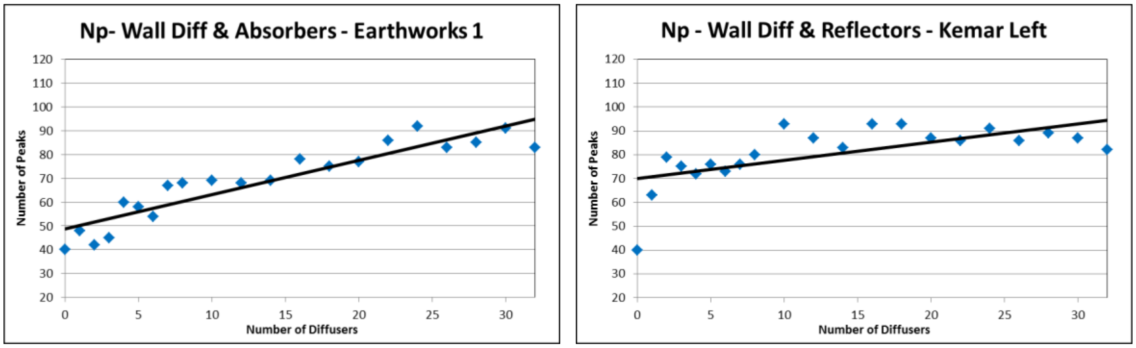


Figure 5.5.5: Number of Peaks for two Wall Test groupings – (a) Diffusers & Absorbers, Earthworks 1 – (b) Diffusers & Reflectors Wall Tests, Kemar Left

In comparison, the Room Tests required more analysis and post processing to accurately assess the Number of Peaks metric. The impulse response data was first analyzed exactly as the Wall Tests described above, but the results were very poor with very little statistical correlation found. Figure 5.5.6 (a) shows the statistically insignificant results of the unfiltered Number of Peaks Room Rest data. These issues were primarily due to the speaker setup issues described above, which were resolved by time windowing the impulse responses to 250 ms after the peak sound level. In this procedure, no alterations were made to modify the impulse response data itself: the time before the peak pressure and the time 250 ms after the peak pressure were simply omitted from the calculation of the Number of Peaks metric. The filtering process also (inadvertently) included a larger threshold value of 50 dB, which artificially increased the Number of Peaks by a factor of around ten.

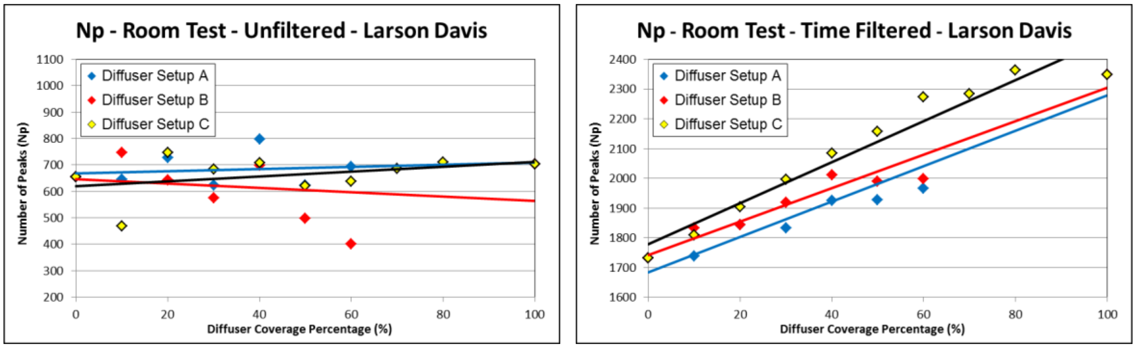


Figure 5.5.6: Number of Peaks for two Room Test groupings – (a) Impulse response data unfiltered, (b) Impulse response data time filtered to analyze only data within 250 ms of the direct sound

By performing this time windowing, statistically significant results were produced for all 12 of 12 Room Test groupings. Figure 5.5.6 (b) shows the same data as the left figure but time windowed to only analyze at the data 250 ms after the peak value. This change in method produced much stronger statistical correlations between the Number of Peaks metric and the diffuser coverage percentages, indicating the time filtering process was useful in analyzing the Room Test data. Ideally, the time windowing would not have been necessary, as the Number of Peaks metric should be calculated without filtering, like the Wall Tests were. Unfortunately, the source issues in the Room Tests necessitated the change in setup procedure which resulted in this alteration to the metric calculation.

Table 5.5.3: Statistical correlations of Number of Peaks for all test groupings – Statistically significant tests ($p < 0.05$) highlighted yellow

	Diffusion & Absorption Wall Test		Diffusion & Reflection Wall Test	
	F*	p	F*	p
Microphone 1	109.17	<.0001	47.86	<.0001
Microphone 2	34.60	<.0001	18.99	0.000
Microphone 3	22.27	<.0001	24.13	<.0001
Microphone 4	52.19	<.0001	13.10	0.002
Microphone 5	100.02	<.0001	98.67	<.0001

	Room Test - Config A		Room Test - Config B		Room Test - Config C	
	F*	p	F*	p	F*	p
Microphone 1	199.33	<.0001	164.21	0.0002	114.51	<.0001
Microphone 2	34.77	0.0041	19.15	0.012	123.46	<.0001
Microphone 3	1012.4	<.0001	49.2	0.0022	104.44	<.0001
Microphone 4	127.14	0.0004	62.76	0.0014	321.7	<.0001

The Number of Peaks metric proved to be the most statistically accurate method out of the three tested in assessing the diffusive conditions of the MOCAP testing facility. The metric analyzed the fine structure of the impulse responses, counting the number of pressure peaks above a given threshold. This assessment methodology seemed to be a more direct way of addressing the issue of diffusion quantification compared with the other two metrics. And due to the strong tie between this metric and the impulse response complexity (as well as the diffusive conditions of the room) the Number of Peaks metric performed very well in assessing the state of diffusiveness in the MOCAP testing facility, and thus can be recommended in the assessment of diffusive room conditions in all rooms.

Objective Metrics - Analysis

5.6.1 Test Groupings

The objective metric analysis of diffusive room conditions was completed for all of the collected measurements and the three selected diffusion quantification methods: Transition Time, Degree of Time Series Fluctuations, and Number of Peaks. Through this process, many interesting discoveries were made regarding the efficacy of these metric, the issues in the use of these methodologies, and other useful information that arose from the analyses. The most important revelation was the confirmation of the most applicable diffusion quantification metric which produced the most statistically accurate results, at least for this dataset. The best methodology of the three was certainly Number of Peaks, as this metric correctly correlated with the number of diffusers for all 22 of the test groupings. The other two metrics simply did not produce as accurate of results when statistical tests were run and thus could not be recommend as highly as the Number of Peaks metric in assessing diffusive room conditions in the MOCAP space.

However, one feature that both the Transition Time and Degree of Time Series Fluctuations metrics possessed that the Number of Peaks metric did not have was the ability to measure relative levels of reflections within an impulse response. This could be very useful, as it would allow for the analysis of reflections without the influence of the energy time curve, which can make looking at the details in the late part of an impulse response difficult. By removing the decay component of the impulse response, the Slope Ratio (for the Transition Time metric) or the normalized Decay Cancelled Impulse Response (for the Degree of Time Series Fluctuations) display the strength of slope differences between adjacent samples, which correlate to energy generated by individual reflections. By studying a graph of either metric, it would be possible to diagnose a late reflection based on the time of arrival and room geometry using only a monaural receiver, as opposed to a multi-channel microphone with more inputs. This analysis method can therefore be a very useful tool in the field of room acoustics and can be implemented without the calculation of the final metrics. It should be noted that while the process for computing the Slope Ratio and the normalized Decay Cancelled Impulse Response were different, the relative values and graphs produced by the two metric were nearly identical. Figure 5.6.1 shows the two metrics computed for the same impulse response measurement: clearly the two data structures are the same for each metric. However, the absolute values are different and can be even more disparate in other instances. So, while the Slope Ratio and the normalized Decay Cancelled Impulse Response can both be used to assess the relative strengths of reflections in an impulse response, values cannot be transferred between the two metrics.

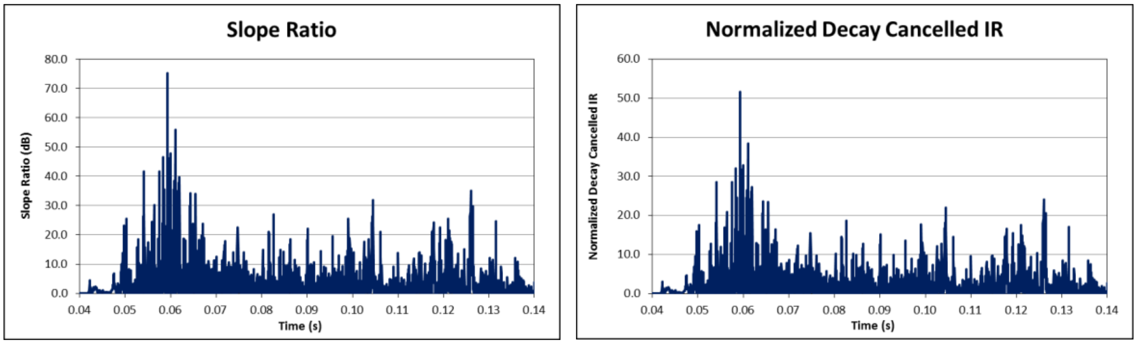


Figure 5.6.1: Example Slope Ratio & Normalized Decay Cancelled Impulse Response graphs which can be used to evaluate reflection strengths of an impulse response

5.6.2 Room Diffuser Configuration Effectiveness

One of the purposes in performing the Room Tests under three different diffuser configurations was to investigate whether the placement of diffusers within the MOCAP testing facility would impact the diffusive conditions measured. For this analysis, only the Room Test data was included and only for the time windowed Number of Peaks data, due to the accuracy of the statistical results. The data groupings were assembled by microphone, with the Earthworks, Larson Davis, Kemar Left, and Kemar Right testing groups all appearing on different graphs. On each of the four graphs below (Figure 5.6.2 (a – d)) diffuser configurations A, B, and C are shown for single microphone setups. Also included were the linear regression lines that were calculated for the different configuration groupings. The blue markers indicate diffuser setup A: the wall midpoints diffuser configuration. The red markers are for diffuser setup B: the random diffuser configuration. The yellow markers with the black border show diffuser setup C: the top-down diffuser configuration, whose trend line is black.

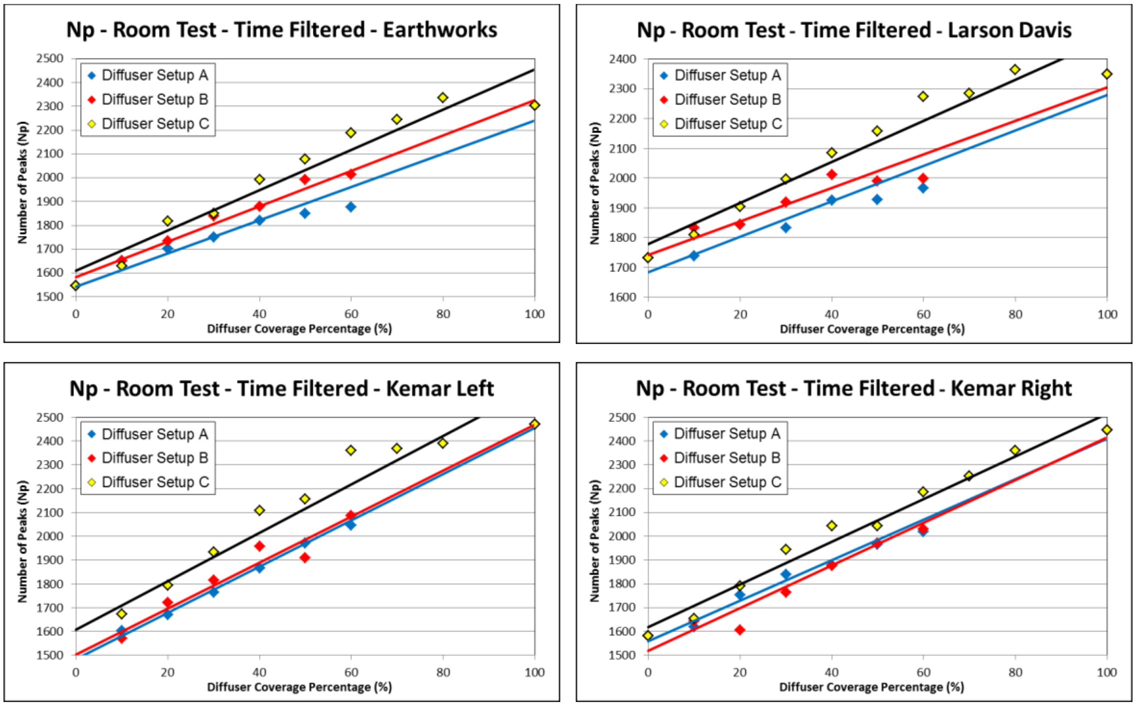


Figure 5.6.2: Number of Peaks data for all conditions of the Room Tests – Diffuser Setup C generated higher Number of Peaks for all microphone positions, indicating higher diffuse room conditions

For all four microphone groupings (the four graphs above) the top-down diffuser configuration (diffuser setup C) produced the highest Number of Peaks at nearly all diffuser coverage percentage levels. At 10% diffuser coverage percentages, setups B and

C were very close in value for several microphones, but above this coverage level, diffuser setup C was clearly higher throughout. When comparing diffuser setups A and B, setup B appears to generate slightly higher Number of Peaks for the Earthworks and Larson Davis microphones, but not for the Left and Right Kemar receivers.

This data indicated that a top-down diffuser configuration generated the most Number of Peaks in the room impulse responses in comparison with the other two diffuser configurations implemented. Because the Number of Peaks metric was shown previously in this study (and in the literature) to accurately correlate with the diffusive room conditions, it could also be utilized in assessing the efficiency of the three tested diffuser configurations. It was therefore concluded that the top-down configuration produced the most diffusive room conditions of the three tested in this study. The reason behind the improved performance of the top-down configuration could be due to the way generated sound was reflected in this setup. Because all of the diffusers in the MOCAP space were aligned horizontally in bands around the room in this configuration, sound waves were reflected back and forth across the room within these bands. As the diffuser coverage percentages increased, the size of these bands grew, increasing the surface area that could potentially create cross reflections. In the other two diffuser configurations, there were no cross-room alignments in relation to the speaker sources, possibly causing the decreased number of subsequent reflections. This effect was likely exacerbated by the high levels of absorption within the testing facility. More research is required to determine whether the banded, top-down diffuser configuration would be the best arrangement in all rooms, but for this study it was the best of the three setups tested, which interestingly disagreed with the subjective perception Room Test findings.

5.6.3 Diffuser Limit of Diminishing Returns

To look at the objective metric data in another way, the effects of increasing the number of diffusers within testing groups was evaluated. Specifically of interest was whether there was a point at which increasing the number of diffusers would not significantly impact the diffusive room conditions, as measured by the Number of Peaks metric. So, the question was posed: Was there a point at which diffusive room conditions would not improve, even when additional diffusion was added? To research this topic, the graphs for the Number of Peaks testing groups were studied for all three room testing conditions: the two Wall Tests and the Room Tests. For the Wall Test data, all testing groups provided statistically significant linear regressions, but the Larson Davis graphs exhibited a more logarithmic shape, where the trend line tapers off around the midpoint of the data. For both the absorption and reflection Wall Test groupings the Larson Davis data displayed a point of diminishing returns between 10 and 15 diffusers, meaning that in this situation, installing more than 15 diffusers would not provide substantive gains for the diffusive room conditions. The other eight testing groups did not exhibit this tapering behavior, as the linear trends continued from zero diffusers all the way to the maximum of 32 diffusers (and possibly beyond). There might have been a point at which the size of the testing wall would produce diminishing returns for all Wall Test conditions, but it appeared that at least in this study, that size limit was not reached.

Looking at the Room Test data for this topic was to some extent more fruitful that the Wall Test data, as there did appear to be a threshold of diminishing returns found for diffusive surface area, at least for one diffuser wall configuration. The top-down diffuser order was the configuration which displayed a diffuser coverage at which diffusive room conditions did not increase, as shown in Figure 5.6.2. At approximately 80% of the total number of diffusers displayed, no increases in the Number of Peaks metric were shown for the measurements taken above this level. In fact, in the Larson Davis and Kemar Left testing groups, this tapering appeared to start around 60% diffuser coverage percentage. Therefore, in this testing configuration a range of diminishing returns was found for the diffuser coverage percentage to be between 60% and 80%. The midpoints of the walls and random diffuser configurations had data collected from diffuser coverage percentages 10% – 60% and did not show any tapering effects, so all data must have been below the threshold of diminishing returns, which was consistent with the findings for the top-down configuration. Additional testing would be required to extrapolate these results to other rooms, but it is evident that a diffuser coverage does exist above which no substantive gains in diffusive room conditions would be expected.

5.6.4 Objective Metrics - Conclusions

From the objective metric analysis of diffuse room conditions several conclusions could be made, not the least of which was the confirmation of the most accurate diffusion quantification metric: Number of Peaks. In addition, the Slope Ratio and the normalized Decay Cancelled Impulse Response (from the Transition Time and the Degree of Time Series Fluctuations metrics, respectively) allowed relative levels of reflections within an impulse response to measured, a property the Number of Peaks metric did not possess. Using the Number of Peaks metric allowed for the diffuser configurations from the Room Tests to be assessed, which revealed that the top-down order produced the highest Number of Peaks in all conditions, and thus the highest diffusive room conditions. Finally, the limit of diminishing returns of diffusive coverage was investigated with some evidence found of a limiting threshold but not enough to deem conclusive.

Chapter 6

Summary & Conclusions

6.1.1 Summary of Completed Study

This study aimed to address the lack of available research on diffusive room conditions by investigating two separate aspects in the assessment of diffusion: human perception and objective metric analysis. It was desired to determine how capable the average person performs at discriminating diffusive room conditions, and also whether diffusive room conditions can be calculated using 'normal' measurement procedures. Information on either of these topics would provide a better understanding of these two different diffusion assessment methodologies. After the completion of both the subjective perception testing and the objective metric analysis, many conclusions were made and the amount of available data regarding diffusion assessment has moved a few steps in the right direction.

It was decided early in the study that all testing data should be collected from a physical space so all diffusion effects would be represented in the measurements. An acoustics testing facility designed to perform diffusion research was found for use, which featured three full walls covered in reversible diffusive/absorptive acoustical panels which could be set up in any configuration imaginable. Utilizing these capabilities, numerous room measurements were collected under various diffuser configurations and subsequently used in both the subjective perception and objective metric analyses. The three primary testing configurations included the Wall Absorption Tests (comparing a diffusive and absorptive test wall), the Wall Reflection Tests (comparing a diffusive and reflective test wall), and the Room Tests (utilizing all diffusers in the space). The Wall Tests addressed the question of how modifying an isolated wall section affected the diffusive room conditions for both the absorptive and reflective comparison conditions. The Room Tests provided information on how diffuser configurations in the test room impacted diffusive room conditions. These measurement groupings formed the basis for both the subjective perception and objective metric analyses that followed.

In testing the subjective perception of diffusion, the average subject's ability to distinguish between diffusive room conditions under many testing configurations was investigated. To implement these tests, auralizations were created to represent a selection of predetermined source material as if it were being played within the tested room under the specific measurement conditions. These auralizations were presented to subjects in comparative listening trials for a wide variety condition pairings, which then allowed questions to be answered regarding the perception of diffusion. For instance, the Just Noticeable Difference between wall states was explored as well as whether diffuser configurations affected discrimination performance. The subjective perception testing was completed for 25 participants, which allowed meaningful conclusions to be made regarding how perceptive participants were at discerning diffusive room conditions.

The objective analysis concentrated on assessing the diffusive conditions within the testing room utilizing standard measurement procedures and the implementation of previously proposed diffusion quantification methods. The same measurement data used in the subjective perception testing was also implemented in the objective metric analysis. Instead of creating auralizations, however, the data was analyzed numerically by studying the fine detail of the collected measurements. Three diffusion quantification metrics (Transition Time, Degree of Time Series Fluctuations, & Number of Peaks) were selected for comparison in this study as they satisfied the desired assessment parameters: all were designed to assess diffuse room conditions utilizing a monaural receiver, all could be computed numerically using standard software, and all produced single number ratings which assessed diffusive room conditions. All three metrics were calculated for the entire set of room measurements and statistical analyses were conducted to determine correlations between the diffusive room conditions and the proposed metrics. Through this process, the Number of Peaks methodology was found to strongly correlate with diffusive room conditions, permitting its use as an assessment tool of diffusion in secondary assessments considered in this research.

It was the goal of this study to further the amount of available information on the assessment of diffusion by researching the human perception of diffusion and objective metrics designed to assess diffusive room conditions using data produced from a physical testing facility. By collecting data from the MOCAP testing facility, involving 25 subjects in a set of subjective perception tests, and analyzing the impulse responses using three different objective methodologies, these study goals were achieved.

6.1.2 Subjective Perception Conclusions

The subjective perception testing phase of this study produced a wide range of information addressing many diffusion perception questions. First of all, Just Noticeable Difference values were found for the four primary Wall Test configurations. The Wall Absorption Tests using Male Speech produced a JND percentage of 51.3% which equated to an equivalent area of 65.6 sq. ft. The Wall Absorption Tests using Violin Music had a JND percentage of 66.7% for an area of 85.3 sq. ft. The Wall Reflection Tests using Male Speech generated a JND percentage of 79.6% with an area of 101.9 sq. ft. Finally, the Wall Reflection Tests using Violin Music had a JND percentage of 80.8% or an area of 103.5 sq. ft. As these values indicate, the Wall Absorption Tests were more discernible than the Wall Reflection Tests for both source materials, much more so when utilizing the Male Speech signal. In the Wall Reflection configuration, the speech and music sources were equally (very) difficult for subjects to discern.

More diffusive coverage was necessary in the JND tests for subjects to be able to discern the diffusive acoustical panel conditions than was expected at the onset of subjective trials. Even for the Wall Absorption Tests using Male Speech, which had the lowest JND, diffusive coverage percentage of more than 50% was necessary for the average subject to be able to discern differences. Therefore, for the average individual a very large surface area (greater than 65 sq. ft.) was required for diffusion to become apparent, even in the most discernable test condition, which was a significant result.

Looking at the demographic information for the JND values, it was found that on average, men performed better than women by 9% overall, and achieved lower JND values on three of the presented testing configurations. However, these differences between men and women were not statistically significant. When grouped by musical experience, there was a clear difference between generated JND values for subjects who were musicians and those who were not: musicians outperformed non-musicians in all testing configurations and by an overall average of 23% (statistically significant).

The Wall Tests also produced data comparing the doubling and quadrupling of diffuser sizes, with varying results. Depending on the testing group, some datasets trended upward, some remained constant, and others trended downward. Also, many of the trial completion percentages were near the random chance threshold of 33%, indicating that in those instances, subjects were essentially guessing on each presentation. The Wall Test diffuser size tests therefore produced inconclusive data comparing the differences between doubled and quadrupled diffuser size combinations.

The Room Tests were the final testing configuration implemented, using both Male Speech and Violin Music source materials. In this configuration, the Male Speech source was more discernible than the Violin Music source in all testing conditions. There was also a slight upward trend to subject completion percentages as the diffuser coverage percentage increased, though this result could have been the result of low statistical power. Looking at the diffuser configurations, when using the Male Speech source, subjects showed no difference in discrimination capabilities, but when the Violin Music source was implemented, the wall midpoints diffuser configuration was more discernable than the other two.

6.1.3 Objective Metric Conclusions

The objective metric analysis of diffuse room conditions produced information upon which several conclusions were made. The first was the confirmation of the most accurate diffusion quantification metric: Number of Peaks. Also, the Slope Ratio and the normalized Decay Cancelled Impulse Response (from the Transition Time and the Degree of Time Series Fluctuations metrics, respectively) were both found to allow relative levels of reflections within an impulse response to be measured, a useful property in assessing the diffusive room conditions within a space. Using the Number of Peaks metric allowed for the diffuser configurations implemented in the Room Tests to be assessed, which revealed that the top-down order produced the highest Number of Peaks in all conditions, and thus the highest diffusive room conditions. Finally, the limit of diminishing returns of diffusive coverage was investigated with some evidence found for a limiting threshold between 60% – 80%, though these results were not fully conclusive.

6.1.4 Discussion of Testing Results

One of the most important aspects to remember about this study is that all of the data generated (including the collected impulse responses, the subjective testing, and the objective analyses) was based on a specific set of testing parameters, and the conclusions made from the subsequent analysis cannot necessarily be extrapolated to other room conditions. This relates back to the complex nature of diffusion which can be affected by numerous factors, such as changing the space in which these tests were conducted, the equipment utilized, or even the setup configurations implemented. Therefore, the JND values reported for the Wall Tests or the determination of the Number of Peaks metric as the best metric in assessing diffusive room conditions were conclusions based on these room, equipment, and testing configurations. This does not preclude the possibility that these results would hold for other spaces, but more data on diffusive room conditions is necessary determine whether extrapolation across any interior space is possible.

What is important to take from this study is that significant amounts of surface diffusion are necessary within a space for the average subject to discern differences in the sound field. In the more applicable Wall Reflection Tests, the test wall needed over 80% diffusive coverage for discrimination, highlighting the similarity in between the reflective and diffusive wall states and thus the need for significant diffusive coverage. The specific values found for this type of diffuser and setup might not be the same for other diffuser types, but what seems clear is that the use of surface diffusion must be maximized to achieve a substantive impact on the resulting sound field.

6.1.5 Suggestions for Future Testing

While this study researched multiple testing conditions to address numerous aspects of diffusion, there are still many directions that future diffusion assessment research could proceed. The current study was based on a specific diffuser type, set up in one room, using a discrete number of equipment and testing configurations. To have the values and conclusions reached in this work applicable to real-world rooms in general, this research would need to be expanded into other testing spaces, using more types of diffusers, and implementing different setup configurations.

The type of diffusers used in this study were 1-dimensional Schroeder-style quadratic residue diffusers (QRD), which was made using a 7-well arrangement designed for mid and high frequency diffusion. If the diffuser tested was changed to a deeper model, designed for lower frequencies, or a shallower model, designed for higher frequencies, vastly different datasets would have been generated. The type of diffuser could have also been changed to be a 2-dimensional QRD, a pyramidal design, a hemispherical arrangement, or any other shape. By testing multiple types of diffusers, it would be possible to rate and compare the individual diffusers based on their resulting performance once installed within a room, in addition to the Diffusion Coefficient and Scattering Coefficient calculations currently performed.

Additional source and receiver combinations could also be investigated in further testing. The orientation of the speakers and microphones in relation to the wall diffusers affected the results for all of the impulse responses collected, so it would be beneficial to expand the number of arrangements tested. For example, it would be helpful to measure the effects of a reflection from a grazing or normal incidence, as all data collected in the wall tests were from reflection angles between 15° – 45°. Other types of sources could also be investigated, especially in the Room Test where the issue of a resonating metal box in the ceiling restricted the use of an Omni-directional source. If the Larson Davis dodecahedron speaker (or similar) could not be used in the MOCAP space, other speaker setups could be tested to achieve impulse responses which included obvious direct sound.

Other rooms could also be used to perform the diffusion testing to compare the results generated in this study with those taken from an entirely different space. Preferably, a room with a longer Reverberation Time would be used to perform additional testing, as it would provide a stark comparison to the low reverberation conditions of the MOCAP space. It would then potentially be possible to extrapolate the data generated from each of the different types of rooms to more generic situations, which could then be used in the design and construction of new buildings.

The ultimate goal (and the impetus) of this study was to better understand the effects of diffusers, specifically how perceptive humans are to changing diffusive conditions and the metrics used to assess diffusive room conditions. This goal has been accomplished for this one room, this one type of diffuser, and the specific setup configurations implemented. There are innumerable other combinations which could be tested in future iterations of this area of research, and this study is but the first link in the chain. To thoroughly investigate this topic, more tests are needed in a wider variety of conditions to more fully understand the complicated subject of acoustic diffusion.

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Appendix A: Subjective Perception Data

A.1 Initial Trial Data

Table A. 1: Initial Trial data & demographic information (Gender, Age, & Musical Experience) for all subjects – ‘Yes’ represents a correct answer

Subject ID

Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Room Absorption Male Speech	Room Diffusion Male Speech	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Room Absorption Violin	Room Diffusion Violin	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes
3	Wall Absorption Male Speech	Wall Diffusion Male Speech	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	Wall Absorption Violin	Wall Diffusion Violin	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5	Wall Reflection Male Speech	Wall Reflection Male Speech	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
6	Wall Reflection Violin	Wall Reflection Violin	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes
			6	5	4	5	5	3	5	5	4	5	5	6	6

Demographics

Gender	M	M	F	M	M	F	F	M	M	F	M	F	M
Age	25	26	23	20	29	22	41	28	24	23	27	25	33

Musical Experience	1	1	4	2	1	1	1	4	1	4	1	4	4

* 1: 0 - 3 Yrs, 2: 3 - 5 Yrs, 3: 5 - 10 Yrs, 4: >10 Yrs

Totals

Test	14	15	16	17	18	19	20	21	22	23	24	25	Subjects	# Correct
1	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	25	24
2	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	25	18
3	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	25	22
4	No	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	25	18
5	Yes	No	No	Yes	No	No	Yes	No	No	No	Yes	Yes	25	14
6	No	No	Yes	No	No	No	Yes	No	No	No	No	No	25	12
	4	3	4	2	4	3	6	2	4	3	4	5	Avg: 4.3	

Gender	M	F	F	M	M	M	M	F	F	M	M	F	Male: 15	Female: 10
Age	26	27	54	23	28	23	22	19	22	23	19	20	Min: 19	Max: 54
													Average: 26.1	

Musical Experience	1	3	1	4	1	3	4	4	1	2	2	2	0 - 3: 11	3 - 5: 4
													5 - 10: 2	>10: 8

A.2 Wall Absorption Tests Data

Table A. 2: Wall Absorption Just Noticeable Difference tests data using Male Speech source material – Numbers indicate the sequence of presented tests for all subjects

Wall Abs Speech **Subject ID**

JND Test			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 0	Diffusers - 32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
2	Diffusers - 0	Diffusers - 24	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
3	Diffusers - 0	Diffusers - 16	24	24	24	32	24	24	24	24	24	24	24	24	24	24	24	24	24	32	24	24	32	32	24	24	32
4	Diffusers - 0	Diffusers - 8	24	24	24	24	24	24	24	24	32	24	24	24	24	24	24	24	32	32	24	24	32	32	24	24	24
5	Diffusers - 0	Diffusers - 7	32	16	32	24	16	16	16	16	32	16	16	16	16	16	16	16	32	32	16	16	32	32	16	32	32
6	Diffusers - 0	Diffusers - 6	32	16	32	16	24	16	16	16	24	16	16	24	16	16	16	16	32	32	16	16	24	32	16	32	32
7	Diffusers - 0	Diffusers - 5	24	8	24	16	32	24	24	8	32	8	8	24	8	8	24	24	32		8	8	24	32	24	24	24
8	Diffusers - 0	Diffusers - 4	24	8	24	8	32	24	24	8	32	8	8	16	8	8	24	24	32		8	8	16		32	24	32
9	Diffusers - 0	Diffusers - 2	16	7	16	8	24	32	16	7		7	7	24	7	7	16	16	32		7	7	24		32	16	
10	Diffusers - 0		16	7	16	7	24	32	24	7		7	7	24	7	7	16	16			7	7	32		24	24	
11	Diffusers - 0		8	6	8	7	16		24	6		6	6	16	6	6	8	24			6	6	32		24	24	
12	Diffusers - 0		8	6	8	8	24		16	6		6	6	16	6	6	8	24			6	7			32	16	
13	Diffusers - 0		16	5	7	8	24		16	5		5	5	8	5	5	7				5	7			32	16	
14	Diffusers - 0		24	5	7	7	16			5		5	6	8	5	5	7				5	6			24		
15	Diffusers - 0		24	4	6	7				4		4	6	7	4	6	6				6	6			24		
16	Diffusers - 0		16	4	6	6				4		4	5	7	4	6	6				7	5			16		
17	Diffusers - 0		16	2	5	6				2		2	5	6	2	5	5				7	5			16		
18	Diffusers - 0			2	5	5				2		2	4	6	2	6	5				6	4					
19	Diffusers - 0			0	4	5				0		0	4	5	0	6	4				6	4					
20	Diffusers - 0				4	4							2	5		5	4				5	2					
21	Diffusers - 0				2	4							2	4			2				6	2					
22	Diffusers - 0				2	5							0	4			2				7	0					
23	Diffusers - 0				0									2			0				7						
24	Diffusers - 0													2							6						
25	Diffusers - 0													0							6						
26	Diffusers - 0																				5						
		Best Completed	**8**	**2**	**2**	**4**	**24**	**16**	**16**	**2**	**32**	**2**	**2**	**2**	**2**	**5**	**2**	**16**	**32**	**32**	**6**	**2**	**24**	**32**	**16**	**16**	**32**

Average: 13.2

Table A. 3: Wall Absorption JND tests data using Male Speech source material – % Correct for each diffuser comparison (Averages in highlighted column)

Diffuser #	% Correct	Individual Percent Correct																								
32	**84.1**	100	100	100	67	100	50	100	100	33	100	100	100	100	100	100	100	63	33	100	100	57	33	100	100	67
24	**78.3**	83	100	75	100	86	75	100	100	33	100	100	100	100	100	100	83	33	33	100	100	33	33	71	83	33
16	**65.7**	40	100	100	100	33	50	60	100	33	100	100	50	100	100	75	50	33	33	100	100	33	33	50	33	33
8	**66.0**	50	100	100	100	33	33	33	100	33	100	100	100	100	100	100	33	33	33	100	100	33	33	33	33	33
7	**64.3**	33	100	100	75	33	33	33	100	33	100	100	100	100	100	100	33	33	33	100	100	33	33	33	33	33
6	**63.0**	33	100	100	100	33	33	33	100	33	100	100	100	100	100	100	33	33	33	75	67	33	33	33	33	33
5	**58.7**	33	100	100	100	33	33	33	100	33	100	67	100	100	33	100	33	33	33	33	100	33	33	33	33	33
4	**58.0**	33	100	100	50	33	33	33	100	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	33	33
2	**57.3**	33	100	100	33	33	33	33	100	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	33	33

Table A. 4: Wall Absorption comparison tests data using Male Speech source material for all subjects – ‘Yes’ equals a correct answer

Wall Abs Speech			**Subject ID**																								
Test	**Duplicated Audio File**	**Different Audio File**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
1	Diffusers - 2	Diffusers - 4	Yes	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No
2	Diffusers - 4	Diffusers - 2	Yes	Yes	Yes	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	Yes	Yes
3	Diffusers - 2	Diffusers - 8	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	Yes	No	Yes	No	No	No
4	Diffusers - 8	Diffusers - 2	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	No	Yes	No
5	Diffusers - 4	Diffusers - 8	Yes	No	Yes	No	No	No	No	No	No	No	Yes	No	No	Yes	No	Yes	Yes	No	No	Yes	No	No	No	No	Yes
6	Diffusers - 8	Diffusers - 4	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes
7	Diffusers - 4	Diffusers - 16	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	No
8	Diffusers - 16	Diffusers - 4	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No
9	Diffusers - 8	Diffusers - 16	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No
10	Diffusers - 16	Diffusers - 8	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	No	No	Yes	No	Yes	No	No	Yes	No
11	Diffusers - 8	Diffusers - 32	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
12	Diffusers - 32	Diffusers - 8	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes
			8	**9**	**10**	**10**	**4**	**5**	**7**	**9**	**5**	**8**	**12**	**9**	**9**	**8**	**9**	**9**	**6**	**1**	**8**	**9**	**3**	**5**	**6**	**10**	**5**
																							Average: 7.4				

Table A. 5: Wall Absorption comparison tests compiled data using Male Speech source material

Test Performance					**Comparisons**			
Test	**Test Group**	**Subjects**	**# Correct**	**% Correct**	**Combined Tests**	**% Correct Combined**	**Double**	**Quadruple**
1	2 vs 4	25	10	40.0	2 vs 4	50.0	50.0	72.7
2	4 vs 2	25	15	60.0				
3	2 vs 8	25	15	60.0	2 vs 8	58.0		
4	8 vs 2	25	14	56.0				
5	4 vs 8	25	8	32.0	4 vs 8	50.0		
6	8 vs 4	25	17	68.0				
7	4 vs 16	25	20	80.0	4 vs 16	78.0		
8	16 vs 4	25	19	76.0				
9	8 vs 16	25	14	56.0	8 vs 16	50.0		
10	16 vs 8	25	11	44.0				
11	8 vs 32	25	20	80.0	8 vs 32	82.0		
12	32 vs 8	25	21	84.0				

Table A. 6: Wall Absorption Just Noticeable Difference tests data using Violin Music source material

Wall Abs Music **Subject ID**

JND Test			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 0	Diffusers - 32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
2	Diffusers - 0	Diffusers - 24	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
3	Diffusers - 0	Diffusers - 16	24	24	24	24	32	24	24	24	32	24	24	24	24	32	24	24	32	24	24	32	32	32	32	24	32
4	Diffusers - 0	Diffusers - 8	24	24	24	24	32	24	32	32	32	24	24	24	24	24	24	24	32	24	32	24	32	24	32	24	32
5	Diffusers - 0	Diffusers - 7	16	32	16	32	32	32	32	32	32	16	16	16	16	24	16	32	32	32	32	24	32	24	24	16	32
6	Diffusers - 0	Diffusers - 6	16	32	24	32	32	32	32	24	32	16	16	16	16	32	16	32	32	32	24	16	32	32	24	16	32
7	Diffusers - 0	Diffusers - 5	24	24	24	32	32	32	32	32	32	8	8	8	8	32	8	24	32	32	24	16	24	32	32	8	32
8	Diffusers - 0	Diffusers - 4	32	24	16	32		32	24	32	24	8	8	8	8	32	8	32		32	32	8		32	32	8	32
9	Diffusers - 0	Diffusers - 2	32	16	24	32		32	32		24	7	7	7	7	32	7	32		24	32	8			32	7	24
10	Diffusers - 0		24	16	32						16	7	7	7	7	32	7	24		24	32	7				7	24
11	Diffusers - 0		32	8	32						16	6	6	6	6	24	6			32	24	7				6	16
12	Diffusers - 0		32	8							8	6	6	6	6		6					6				6	16
13	Diffusers - 0		24	7							8	5	5	5	5		5					6				7	8
14	Diffusers - 0		24	8								5	5	5	5		5					5				7	8
15	Diffusers - 0		16	16								4	4	4	4		4					5				6	
16	Diffusers - 0		16	24								4	4	4	4		4					4				6	
17	Diffusers - 0		8	32								2	2	2	2		2					4				5	
18	Diffusers - 0		8	32								2	2	2	2		2					2				5	
19	Diffusers - 0		7									0	0	0	0		0					2				4	
20	Diffusers - 0		7																			0				4	
21	Diffusers - 0		6																							2	
22	Diffusers - 0																									2	
23	Diffusers - 0																									0	
24	Diffusers - 0																										
25	Diffusers - 0																										
26	Diffusers - 0																										
		Best Completed	**7**	**8**	**24**	**24**	**32**	**24**	**32**	**32**	**8**	**2**	**2**	**2**	**2**	**24**	**2**	**24**	**32**	**24**	**24**	**2**	**32**	**24**	**24**	**2**	**8**
																					Average: 16.8						

Table A. 7: Wall Absorption JND tests data using Violin Music source material

Diffuser #	% Correct	Individual Percent Correct																							
32	**69.9**	100	67	75	43	29	57	71	83	43	100	100	100	100	38	100	100	33	67	86	67	33	50	57	100	50
24	**64.9**	67	60	80	50	33	50	33	33	100	100	100	100	100	33	100	33	33	50	33	100	33	50	50	100	100
16	**60.3**	75	67	33	33	33	33	33	33	100	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	100
8	**56.0**	100	33	33	33	33	33	33	33	50	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	50
7	**54.7**	100	33	33	33	33	33	33	33	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	33
6	**51.0**	33	33	33	33	33	33	33	33	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	75	33
5	**52.0**	33	33	33	33	33	33	33	33	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	33
4	**52.0**	33	33	33	33	33	33	33	33	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	33
2	**52.0**	33	33	33	33	33	33	33	33	33	100	100	100	100	33	100	33	33	33	33	100	33	33	33	100	33

Table A. 8: Wall Absorption comparison tests data using Violin Music source material for all subjects

Wall Abs Music **Subject ID**

Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 2	Diffusers - 4	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No	No
2	Diffusers - 4	Diffusers - 2	No	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	No	No	Yes	Yes	No
3	Diffusers - 2	Diffusers - 8	No	No	No	No	No	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes	No
4	Diffusers - 8	Diffusers - 2	Yes	Yes	No	No	No	No	No	No	No	Yes	No	Yes	Yes	No	Yes	No	No	No	Yes	Yes	No	No	Yes	Yes	No
5	Diffusers - 4	Diffusers - 8	No	No	Yes	Yes	No	No	No	Yes	No	No	No	Yes	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	No	Yes
6	Diffusers - 8	Diffusers - 4	No	Yes	No	No	No	No	No	No	Yes	No	No	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	No	Yes	Yes	No
7	Diffusers - 4	Diffusers - 16	Yes	No	No	No	No	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No
8	Diffusers - 16	Diffusers - 4	Yes	Yes	Yes	No	Yes	No	Yes	No	No	Yes	No	Yes	No	No	No	No	Yes	No	No	No	No	No	No	Yes	Yes
9	Diffusers - 8	Diffusers - 16	No	No	No	No	Yes	No	No	Yes	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
10	Diffusers - 16	Diffusers - 8	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	No	No	No	Yes	No	No	No
11	Diffusers - 8	Diffusers - 32	Yes	No	No	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No
12	Diffusers - 32	Diffusers - 8	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No	No	Yes	No	No
			6	3	4	2	3	0	2	7	8	7	5	8	8	7	9	5	4	3	6	9	4	3	8	8	3
																						Average: 5.3					

Table A. 9: Wall Absorption comparison tests compiled data using Violin Music source material

Test Performance **Comparisons**

Test	Test Group	Subjects	# Correct	% Correct	Combined Tests	% Correct Combined	Double	Quadruple
1	2 vs 4	25	13	52.0	2 vs 4	52.0	42.7	45.3
2	4 vs 2	25	13	52.0				
3	2 vs 8	25	9	36.0	2 vs 8	38.0		
4	8 vs 2	25	10	40.0				
5	4 vs 8	25	10	40.0	4 vs 8	38.0		
6	8 vs 4	25	9	36.0				
7	4 vs 16	25	11	44.0	4 vs 16	42.0		
8	16 vs 4	25	10	40.0				
9	8 vs 16	25	11	44.0	8 vs 16	38.0		
10	16 vs 8	25	8	32.0				
11	8 vs 32	25	15	60.0	8 vs 32	56.0		
12	32 vs 8	25	13	52.0				

A.3 Wall Reflection Tests Data

Table A. 10: Wall Reflection Just Noticeable Difference tests data using Male Speech source material

Wall Refl Speech **Subject ID**

JND Test			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 0	Diffusers - 32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
2	Diffusers - 0	Diffusers - 24	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
3	Diffusers - 0	Diffusers - 16	32	32	32	24	32	32	32	24	24	24	32	24	24	32	24	24	32	32	32	24	24	32	32	32	24
4	Diffusers - 0	Diffusers - 8	32	32	24	24	32	32	32	24	32	24	24	32	24	32	24	24	32	32	32	24	24	24	32	32	32
5	Diffusers - 0	Diffusers - 7	32	24	24	16	32	32	24	16	32	32	32	32	16	32	32	32	32	32	32	16	32	24	32	24	32
6	Diffusers - 0	Diffusers - 6		32	16	24	32	32	32	16	24	32	32	24	16	32	32	32	32	32	24	16	32	16	32	32	32
7	Diffusers - 0	Diffusers - 5		32	16	24	32		32	8	32	32	24	24	8	32	24	24		24	32	8	32	16	32	32	32
8	Diffusers - 0	Diffusers - 3		24	8	16	32		24	8	32	24	32	32	8	32	24	24			32	8	32	24		32	
9	Diffusers - 0	Diffusers - 2		32	8	16	24		24	16	24	32		32	7		16	16			32	7	32	32			
10	Diffusers - 0				7	8	24		32	16	24	32		24	7		16	24				7		32			
11	Diffusers - 0				7	16				8	16	32		24	6		8	24				6		24			
12	Diffusers - 0				6	24				8				16	6		16					6		24			
13	Diffusers - 0				6	32				7				16	5		16					5		16			
14	Diffusers - 0				5	32				7				8	5		8					5		16			
15	Diffusers - 0				6	32				8				8	3		8					4		8			
16	Diffusers - 0				7					8				7	3		7					4		16			
17	Diffusers - 0				7					7				7	2		7					2					
18	Diffusers - 0				6					7				6	2		6					2					
19	Diffusers - 0				6					6				6	0		6					0					
20	Diffusers - 0				5					6				5			5										
21	Diffusers - 0				6					5				5			5										
22	Diffusers - 0													4			4										
23	Diffusers - 0													4			4										
24	Diffusers - 0													2			2										
25	Diffusers - 0													2			2										
26	Diffusers - 0													0			0										
		Best Completed	**32**	**32**	**6**	**16**	**24**	**32**	**24**	**6**	**24**	**24**	**32**	**2**	**2**	**32**	**2**	**24**	**32**	**32**	**32**	**2**	**24**	**16**	**32**	**32**	**32**
																					Average: 21.9						

Table A. 11: Wall Reflection JND tests data using Male Speech source material

Diffuser #	% Correct	Individual Percent Correct																								
32	**67.2**	33	71	67	60	50	33	86	100	100	63	67	100	100	38	100	100	83	67	50	100	57	80	33	43	33
24	**53.6**	33	33	100	80	50	33	67	100	25	67	33	60	100	33	75	67	33	33	33	100	50	80	33	33	33
16	**49.0**	33	33	100	50	33	33	33	100	33	33	33	100	100	33	100	33	33	33	33	100	33	60	33	33	33
8	**45.1**	33	33	100	33	33	33	33	83	33	33	33	100	100	33	67	33	33	33	33	100	33	33	33	33	33
7	**46.2**	33	33	100	33	33	33	33	75	33	33	33	100	100	33	100	33	33	33	33	100	33	33	33	33	33
6	**45.8**	33	33	67	33	33	33	33	100	33	33	33	100	100	33	100	33	33	33	33	100	33	33	33	33	33
5	**41.7**	33	33	33	33	33	33	33	33	33	33	33	100	100	33	100	33	33	33	33	100	33	33	33	33	33
3	**41.7**	33	33	33	33	33	33	33	33	33	33	33	100	100	33	100	33	33	33	33	100	33	33	33	33	33
2	**41.7**	33	33	33	33	33	33	33	33	33	33	33	100	100	33	100	33	33	33	33	100	33	33	33	33	33

Table A. 12: Wall Reflection comparison tests data using Male Speech source material for all subjects

Wall Refl Speech **Subject ID**

Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 2	Diffusers - 3	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
2	Diffusers - 3	Diffusers - 2	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes
3	Diffusers - 2	Diffusers - 8	No	No	Yes	No	No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes
4	Diffusers - 8	Diffusers - 2	No	No	No	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	No	Yes	No	No
5	Diffusers - 5	Diffusers - 8	Yes	Yes	Yes	No	No	Yes	No	Yes	No	Yes	No	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No	No	No	No	No
6	Diffusers - 8	Diffusers - 5	No	No	Yes	Yes	Yes	No	Yes	No	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	Yes
7	Diffusers - 5	Diffusers - 16	Yes	No	No	No	Yes	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes
8	Diffusers - 16	Diffusers - 5	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes
9	Diffusers - 8	Diffusers - 16	No	No	No	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	No	No	Yes
10	Diffusers - 16	Diffusers - 8	Yes	No	No	No	No	Yes	No	Yes	No	No	No	Yes	No	No	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	No
11	Diffusers - 8	Diffusers - 32	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No
12	Diffusers - 32	Diffusers - 8	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	No
			6	6	8	5	5	6	7	10	6	9	6	10	10	4	10	8	6	5	7	10	7	1	8	5	7
																						Average: 6.9					

Table A. 13: Wall Reflection comparison tests compiled data using Male Speech source material

Test Performance **Comparisons**

Test	Test Group	Subjects	# Correct	% Correct	Combined Tests	% Correct Combined	Double	Quadruple
1	2 vs 4	25	19	76.0	2 vs 4	70.0	54.0	60.7
2	4 vs 2	25	16	64.0				
3	2 vs 8	25	14	56.0	2 vs 8	50.0		
4	8 vs 2	25	11	44.0				
5	4 vs 8	25	12	48.0	4 vs 8	52.0		
6	8 vs 4	25	14	56.0				
7	4 vs 16	25	14	56.0	4 vs 16	64.0		
8	16 vs 4	25	18	72.0				
9	8 vs 16	25	11	44.0	8 vs 16	40.0		
10	16 vs 8	25	9	36.0				
11	8 vs 32	25	19	76.0	8 vs 32	68.0		
12	32 vs 8	25	15	60.0				

Table A. 14: Wall Reflection Just Noticeable Difference tests data using Violin Music source material

Wall Refl Music **Subject ID**

JND Test			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 0	Diffusers - 32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
2	Diffusers - 0	Diffusers - 24	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
3	Diffusers - 0	Diffusers - 16	32	24	32	32	32	32	32	24	24	32	32	24	24	24	32	32	32	24	32	24	32	32	24	32	32
4	Diffusers - 0	Diffusers - 8	32	24	32	32	32	32	32	24	24	32	24	24	24	24	24	32	32	32	32	32	32	32	32	24	32
5	Diffusers - 0	Diffusers - 7	32	16	32	32	24	32	32	32	16	24	24	16	16	32	24	32	32	32	32	32	32	32	32	24	32
6	Diffusers - 0	Diffusers - 6	32	16	32	32	32		32	32	16	24	16	16	16	32	16	24	24	24	32	24	32		32	16	32
7	Diffusers - 0	Diffusers - 5		8	32	24	32		24	24	8	32	16	24	8	24	16	32	32	32	24	32			24	16	24
8	Diffusers - 0	Diffusers - 3		8	32	24			32	24	8	32	8	24	8	24	8	32	32	32	24	32			32	24	32
9	Diffusers - 0	Diffusers - 2		7		32				32	16	24	8	32	7	16	16	24			32	24			32	32	
10	Diffusers - 0			7						32	24		7	32	7	16	16	24			32	24			32	32	
11	Diffusers - 0			6						24	32		7	24	6	8	8	16			24	16			24	24	
12	Diffusers - 0			6						24	32		6	24	6	16	16	16			24	16			24	24	
13	Diffusers - 0			7						16	32		6	16	7	24		8			16	8			16	16	
14	Diffusers - 0			8							32		5	16	7	24		8			16				16	16	
15	Diffusers - 0			16									5		6			7			8				8	8	
16	Diffusers - 0			16									3		6			7								16	
17	Diffusers - 0			8									3		5			6									
18	Diffusers - 0			8									2		5			6									
19	Diffusers - 0			7									3		3			5									
20	Diffusers - 0			7									5		5			5									
21	Diffusers - 0			8									5		5			4									
22	Diffusers - 0			8									6		3			4									
23	Diffusers - 0			7											3			2									
24	Diffusers - 0														2			2									
25	Diffusers - 0														2			0									
26	Diffusers - 0														0												
		Best Completed	**32**	**8**	**32**	**24**	**32**	**32**	**32**	**24**	**8**	**24**	**5**	**16**	**2**	**16**	**16**	**2**	**32**	**32**	**16**	**16**	**32**	**32**	**16**	**16**	**32**
																					Average: 21.2						

Table A. 15: Wall Reflection JND tests data using Male Speech source material

Diffuser #	% Correct	Individual Percent Correct																								
32	**64.7**	33	100	38	57	50	33	57	100	33	67	67	100	100	100	67	71	57	83	75	100	33	33	75	80	43
24	**55.1**	33	100	33	50	33	33	33	67	67	33	100	83	100	67	100	67	33	33	75	50	33	33	50	80	33
16	**54.4**	33	100	33	33	33	33	33	33	67	33	100	50	100	67	80	100	33	33	100	100	33	33	50	60	33
8	**41.8**	33	86	33	33	33	33	33	33	50	33	100	33	100	33	33	100	33	33	33	33	33	33	33	33	33
7	**39.6**	33	50	33	33	33	33	33	33	33	33	100	33	100	33	33	100	33	33	33	33	33	33	33	33	33
6	**39.6**	33	50	33	33	33	33	33	33	33	33	100	33	75	33	33	100	33	33	33	33	33	33	33	33	33
5	**37.8**	33	33	33	33	33	33	33	33	33	33	75	33	100	33	33	100	33	33	33	33	33	33	33	33	33
3	**36.1**	33	33	33	33	33	33	33	33	33	33	33	33	67	33	33	100	33	33	33	33	33	33	33	33	33
2	**36.1**	33	33	33	33	33	33	33	33	33	33	33	33	100	33	33	100	33	33	33	33	33	33	33	33	33

Table A. 16: Wall Reflection comparison tests data using Violin Music source material for all subjects

Wall Refl Music			Subject ID																							
Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Diffusers - 2	Diffusers - 3	No	Yes	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No	Yes	Yes	No	No	No	Yes	No
2	Diffusers - 3	Diffusers - 2	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes	No	No	No	Yes	Yes
3	Diffusers - 2	Diffusers - 8	No	No	Yes	No	No	No	No	No	No	No	Yes	No	Yes	No	Yes	No	No	No	No	Yes	No	No	No	No	No
4	Diffusers - 8	Diffusers - 2	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No
5	Diffusers - 5	Diffusers - 8	No	No	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No	No
6	Diffusers - 8	Diffusers - 5	No	Yes	No	No	No	No	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	Yes	Yes	No
7	Diffusers - 5	Diffusers - 16	Yes	No	Yes	No	Yes	No	No	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	No
8	Diffusers - 16	Diffusers - 5	No	Yes	Yes	No	No	Yes	No	Yes	No	Yes	Yes	No	Yes	No	Yes	No	Yes	No	Yes	Yes	Yes	No	No	No	No
9	Diffusers - 8	Diffusers - 16	No	Yes	Yes	No	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	Yes	Yes	No
10	Diffusers - 16	Diffusers - 8	No	Yes	No	Yes	No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	No
11	Diffusers - 8	Diffusers - 32	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No
12	Diffusers - 32	Diffusers - 8	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
			2	8	9	4	5	3	3	6	3	6	7	6	11	4	10	5	8	6	7	12	6	1	7	8	2
																											Average: 6

Table A. 17: Wall Reflection comparison tests compiled data using Violin Music source material

Test Performance					Comparisons			
Test	Test Group	Subjects	# Correct	% Correct	Combined Tests	% Correct Combined	Double	Quadruple
1	2 vs 4	25	8	32.0	2 vs 4	38.0	45.3	54.0
2	4 vs 2	25	11	44.0				
3	2 vs 8	25	5	20.0	2 vs 8	38.0		
4	8 vs 2	25	14	56.0				
5	4 vs 8	25	13	52.0	4 vs 8	48.0		
6	8 vs 4	25	11	44.0				
7	4 vs 16	25	13	52.0	4 vs 16	50.0		
8	16 vs 4	25	12	48.0				
9	8 vs 16	25	12	48.0	8 vs 16	50.0		
10	16 vs 8	25	13	52.0				
11	8 vs 32	25	18	72.0	8 vs 32	74.0		
12	32 vs 8	25	19	76.0				

A.4 Room Tests Data

Table A. 18: Room Tests data using Male Speech source material for all subjects – ‘Yes’ equals a correct answer

Room Speech **Subject ID**

Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Room A - 10	Room B - 10	No	Yes	No	No	No	No	No	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes	Yes	No
2	Room B - 10	Room A - 10	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
3	Room A - 10	Room C - 10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No	Yes	Yes
4	Room C - 10	Room A - 10	Yes	Yes	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No
5	Room B - 10	Room C - 10	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
6	Room C - 10	Room B - 10	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
7	Room A - 20	Room B - 20	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes	Yes
8	Room B - 20	Room A - 20	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No
9	Room A - 20	Room C - 20	Yes	No	No	Yes	No	Yes	No	No	Yes	No	Yes	Yes	Yes	No	No	No	Yes	No	No	Yes	No	No	No	Yes	Yes
10	Room C - 20	Room A - 20	No	No	Yes	Yes	No	No	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No	No	No	Yes	No	No	Yes	No	No
11	Room B - 20	Room C - 20	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
12	Room C - 20	Room B - 20	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes
13	Room A - 30	Room B - 30	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
14	Room B - 30	Room A - 30	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
15	Room A - 30	Room C - 30	Yes	Yes	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	No	Yes	No
16	Room C - 30	Room A - 30	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No
17	Room B - 30	Room C - 30	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
18	Room C - 30	Room B - 30	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
19	Room A - 50	Room B - 50	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes	No	No	Yes	No
20	Room B - 50	Room A - 50	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
21	Room A - 50	Room C - 50	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
22	Room C - 50	Room A - 50	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
23	Room B - 50	Room C - 50	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
24	Room C - 50	Room B - 50	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
25	Room A - 60	Room B - 60	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes
26	Room B - 60	Room A - 60	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes
27	Room A - 60	Room C - 60	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
28	Room C - 60	Room A - 60	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
29	Room B - 60	Room C - 60	Yes	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	No	Yes	No
30	Room C - 60	Room B - 60	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	No	No	Yes	No
		Number Correct:	23	27	28	25	16	17	16	22	19	25	21	27	29	24	29	27	13	15	21	28	21	12	22	28	18
																							Average: 22.1				

Table A. 19: Room Tests compiled data using Male Speech source material

Trial Setup		Test Performance			Comparisons		
Test %	**Test Group**	**Subjects**	**# Correct**	**% Correct**	**Combined Tests**	**% Correct Combined**	**Group %**
10 %	10 - A vs B	25	11	44.0	10 - A vs B	56.0	69.3
	10 - B vs A	25	17	68.0			
	10 - A vs C	25	20	80.0	10 - A vs C	78.0	
	10 - C vs A	25	19	76.0			
	10 - B vs C	25	18	72.0	10 - B vs C	74.0	
	10 - C vs B	25	19	76.0			
20 %	20 - A vs B	25	16	64.0	20 - A vs B	66.0	60.0
	20 - B vs A	25	17	68.0			
	20 - A vs C	25	11	44.0	20 - A vs C	40.0	
	20 - C vs A	25	9	36.0			
	20 - B vs C	25	17	68.0	20 - B vs C	74.0	
	20 - C vs B	25	20	80.0			
30 %	30 - A vs B	25	20	80.0	30 - A vs B	84.0	78.7
	30 - B vs A	25	22	88.0			
	30 - A vs C	25	16	64.0	30 - A vs C	68.0	
	30 - C vs A	25	18	72.0			
	30 - B vs C	25	22	88.0	30 - B vs C	84.0	
	30 - C vs B	25	20	80.0			
50 %	50 - A vs B	25	16	64.0	50 - A vs B	72.0	84.0
	50 - B vs A	25	20	80.0			
	50 - A vs C	25	24	96.0	50 - A vs C	94.0	
	50 - C vs A	25	23	92.0			
	50 - B vs C	25	20	80.0	50 - B vs C	86.0	
	50 - C vs B	25	23	92.0			
60 %	60 - A vs B	25	20	80.0	60 - A vs B	82.0	76.7
	60 - B vs A	25	21	84.0			
	60 - A vs C	25	22	88.0	60 - A vs C	90.0	
	60 - C vs A	25	23	92.0			
	60 - B vs C	25	15	60.0	60 - B vs C	58.0	
	60 - C vs B	25	14	56.0			
			Min	**36.0**			
			Max	**96.0**			

A vs B	**B vs A**
66.4	77.6
Combined	
72.0	
A vs C	**C vs A**
74.4	73.6
Combined	
74.0	
B vs C	**C vs B**
73.6	76.8
Combined	
75.2	

Table A. 20: Room Tests data using Violin Music source material for all subjects

Room Music **Subject ID**

Test	Duplicated Audio File	Different Audio File	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Room A - 10	Room B - 10	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	No	No
2	Room B - 10	Room A - 10	No	No	Yes	No	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes
3	Room A - 10	Room C - 10	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes
4	Room C - 10	Room A - 10	No	Yes	Yes	No	No	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No	No	No	Yes	No	No	Yes	Yes	Yes
5	Room B - 10	Room C - 10	No	No	Yes	No	No	No	No	Yes	No	No	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No
6	Room C - 10	Room B - 10	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes
7	Room A - 20	Room B - 20	No	Yes	Yes	Yes	No	Yes	No	Yes	No	No	No	Yes	Yes	Yes	No	No	No	No	No	Yes	No	Yes	Yes	Yes	Yes
8	Room B - 20	Room A - 20	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
9	Room A - 20	Room C - 20	No	No	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	No	Yes	No	Yes
10	Room C - 20	Room A - 20	No	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
11	Room B - 20	Room C - 20	No	No	Yes	Yes	No	Yes	Yes	No	No	No	No	No	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No
12	Room C - 20	Room B - 20	Yes	No	Yes	No	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No	No	Yes	No	Yes	No	Yes	No	Yes	Yes
13	Room A - 30	Room B - 30	No	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
14	Room B - 30	Room A - 30	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
15	Room A - 30	Room C - 30	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes
16	Room C - 30	Room A - 30	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	No	Yes	No
17	Room B - 30	Room C - 30	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No
18	Room C - 30	Room B - 30	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	No	No	Yes	No	No
19	Room A - 50	Room B - 50	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	Yes	Yes
20	Room B - 50	Room A - 50	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No
21	Room A - 50	Room C - 50	No	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No
22	Room C - 50	Room A - 50	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	No	Yes	Yes	Yes
23	Room B - 50	Room C - 50	No	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No
24	Room C - 50	Room B - 50	Yes	No	Yes	Yes	No	Yes	No	No	No	No	No	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	No	No	No
25	Room A - 60	Room B - 60	No	No	No	Yes	Yes	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	No	Yes	Yes	No
26	Room B - 60	Room A - 60	No	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No
27	Room A - 60	Room C - 60	Yes	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	No	Yes	Yes	No
28	Room C - 60	Room A - 60	Yes	No	No	No	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
29	Room B - 60	Room C - 60	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes	No	No	No	No	Yes	Yes	Yes	No	No	No	Yes	No
30	Room C - 60	Room B - 60	No	Yes	No	No	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	No	No	No
	Number Correct:		**11**	**16**	**23**	**15**	**19**	**18**	**13**	**16**	**15**	**16**	**11**	**23**	**29**	**25**	**21**	**16**	**10**	**16**	**14**	**26**	**15**	**12**	**22**	**23**	**15**

Average: 17.6

Table A. 21: Room Tests compiled data using Violin Music source material

Trial Setup		Test Performance			Comparisons		
Test %	**Test Group**	**Subjects**	**# Correct**	**% Correct**	**Combined Tests**	**% Correct Combined**	**Group %**
10 %	10 - A vs B	25	11	44.0	10 - A vs B	54.0	52.7
	10 - B vs A	25	16	64.0			
	10 - A vs C	25	18	72.0	10 - A vs C	58.0	
	10 - C vs A	25	11	44.0			
	10 - B vs C	25	9	36.0	10 - B vs C	46.0	
	10 - C vs B	25	14	56.0			
20 %	20 - A vs B	25	13	52.0	20 - A vs B	62.0	57.3
	20 - B vs A	25	18	72.0			
	20 - A vs C	25	15	60.0	20 - A vs C	60.0	
	20 - C vs A	25	15	60.0			
	20 - B vs C	25	11	44.0	20 - B vs C	50.0	
	20 - C vs B	25	14	56.0			
30 %	30 - A vs B	25	17	68.0	30 - A vs B	80.0	68.0
	30 - B vs A	25	23	92.0			
	30 - A vs C	25	16	64.0	30 - A vs C	60.0	
	30 - C vs A	25	14	56.0			
	30 - B vs C	25	17	68.0	30 - B vs C	64.0	
	30 - C vs B	25	15	60.0			
50 %	50 - A vs B	25	16	64.0	50 - A vs B	68.0	62.7
	50 - B vs A	25	18	72.0			
	50 - A vs C	25	16	64.0	50 - A vs C	70.0	
	50 - C vs A	25	19	76.0			
	50 - B vs C	25	15	60.0	50 - B vs C	50.0	
	50 - C vs B	25	10	40.0			
60 %	60 - A vs B	25	13	52.0	60 - A vs B	60.0	52.7
	60 - B vs A	25	17	68.0			
	60 - A vs C	25	15	60.0	60 - A vs C	56.0	
	60 - C vs A	25	13	52.0			
	60 - B vs C	25	10	40.0	60 - B vs C	42.0	
	60 - C vs B	25	11	44.0			
			Min	**36.0**			
			Max	**92.0**			

A vs B	**B vs A**
56.0	73.6
Combined	
64.8	
A vs C	**C vs A**
64.0	57.6
Combined	
60.8	
B vs C	**C vs B**
49.6	51.2
Combined	
50.4	

Appendix B: Objective Metric Data

B.1 Transition Time – Wall Tests

Table B. 1: Diffusers & Absorbers Wall Test Transition Time data – Receivers: Earthworks 1 & Earthworks 2

Values Generated for All Diffuser Orientations & Microphone Positions

Number of Diffusers in Test Wall

Receiver	**Earthworks 1**				**Earthworks 2**			
Threshold	**11 dB Threshold**		**9 dB Threshold**		**11 dB Threshold**		**9 dB Threshold**	
Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran./RT Ratio	Trans. Time	Tran./RT Ratio	Trans. Time
Units	-	s	-	s	-	s	-	s
0	0.33	147.3	0.38	168.5	0.41	143.0	0.41	144.8
1	0.29	128.3	0.33	149.6	0.41	143.0	0.41	143.1
2	0.28	125.1	0.28	128.1	0.43	144.6	0.43	144.8
3	0.28	128.2	0.29	128.3	0.43	144.8	0.43	144.9
4	0.28	125.0	0.29	128.1	0.44	144.6	0.44	144.7
5	0.34	147.7	0.38	168.5	0.45	144.6	0.45	144.7
6	0.38	168.5	0.38	168.9	0.44	141.8	0.45	142.8
7	0.39	168.4	0.39	168.4	0.38	125.9	0.43	142.9
8	0.34	147.6	0.38	168.4	0.46	143.0	0.47	144.7
10	0.33	147.4	0.38	166.2	0.47	144.8	0.47	145.8
12	0.30	131.3	0.38	168.4	0.46	142.8	0.46	142.8
14	0.30	131.3	0.31	137.5	0.45	144.6	0.45	144.7
16	0.38	166.3	0.38	168.3	0.45	144.7	0.45	144.8
18	0.39	168.3	0.39	168.3	0.43	144.7	0.43	144.8
20	0.40	168.4	0.40	168.4	0.43	144.8	0.43	144.9
22	0.39	168.3	0.39	168.4	0.43	144.7	0.43	144.8
24	0.40	168.2	0.40	168.3	0.41	144.8	0.41	144.8
26	0.39	168.2	0.39	168.2	0.39	144.6	0.45	165.5
28	0.31	137.3	0.38	168.3	0.39	144.8	0.39	144.8
30	0.38	168.0	0.38	168.0	0.37	137.3	0.45	166.9
32	0.38	168.4	0.38	168.4	0.40	142.9	0.40	142.9
F*	**10.11**	**9.68**	**6.82**	**5.59**	**4.65**	**0.07**	**1.07**	**5.17**
PRE/R^2	**0.347**	**0.338**	**0.264**	**0.227**	**0.197**	**0.004**	**0.053**	**0.214**
p	**0.005**	**0.006**	**0.017**	**0.029**	**0.044**	**0.793**	**0.315**	**0.035**
Graph #:	**1**				**2**			

Trans Time = Transition Time Determined by the Chosen Threshold
Tran/RT Ratio = Ratio of Computed Transition Time & Measured Reverb Time (at 500 Hz)

Table B. 2: Diffusers & Absorbers Wall Test Transition Time data – Receiver: Larson Davis

	Receiver	**Larson Davis**			
	Threshold	**11 dB Threshold**		**9 dB Threshold**	
	Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time
	Units	-	s	-	s
Number of Diffusers in Test Wall	0	0.46	193.0	0.46	193.3
	1	0.45	188.9	0.45	189.0
	2	0.45	188.9	0.46	192.9
	3	0.46	193.2	0.46	193.8
	4	0.46	192.9	0.46	193.7
	5	0.46	193.9	0.46	193.9
	6	0.46	193.2	0.46	193.8
	7	0.46	193.1	0.46	193.7
	8	0.47	193.2	0.47	193.7
	10	0.45	188.9	0.46	193.1
	12	0.46	192.4	0.46	193.1
	14	0.46	193.0	0.46	193.4
	16	0.45	193.0	0.45	193.4
	18	0.46	193.4	0.46	193.4
	20	0.46	193.2	0.46	193.4
	22	0.46	193.4	0.46	193.7
	24	0.46	193.3	0.46	193.7
	26	0.47	193.0	0.47	193.3
	28	0.47	193.6	0.47	194.1
	30	0.46	193.2	0.46	193.9
	32	0.45	193.4	0.49	211.9
	F*	**1.05**	**3.97**	**7.13**	**5.48**
	PRE/R^2	**0.053**	**0.173**	**0.273**	**0.224**
	p	**0.317**	**0.061**	**0.015**	**0.030**

Graph #: **3**

Table B. 3: Diffusers & Absorbers Wall Test Transition Time data – Receivers: Kemar Left & Kemar Right

Number of Diffusers in Test Wall

Receiver	**Kemar Left**				**Kemar Right**			
Threshold	**11 dB Threshold**		**9 dB Threshold**		**11 dB Threshold**		**9 dB Threshold**	
Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran./RT Ratio	Trans. Time	Tran./RT Ratio	Trans. Time
Units	-	s	-	s	-	s	-	s
0	0.42	159.1	0.42	159.1	0.34	129.4	0.38	142.7
1	0.35	130.7	0.38	142.3	0.37	139.2	0.38	143.2
2	0.38	142.4	0.43	159.2	0.39	142.8	0.39	142.8
3	0.39	143.6	0.39	143.9	0.37	141.6	0.38	142.8
4	0.44	159.3	0.44	159.3	0.40	146.2	0.40	146.2
5	0.44	155.5	0.44	155.5	0.40	143.2	0.41	145.9
6	0.44	155.6	0.44	155.6	0.41	142.7	0.41	143.4
7	0.44	155.6	0.45	159.2	0.40	143.4	0.41	146.0
8	0.42	146.9	0.45	159.2	0.42	143.3	0.43	144.6
10	0.46	155.5	0.46	155.5	0.42	143.3	0.43	145.9
12	0.44	155.3	0.45	158.6	0.43	146.0	0.43	146.0
14	0.45	158.9	0.48	167.1	0.41	146.0	0.41	146.0
16	0.44	159.5	0.49	176.4	0.41	146.0	0.41	146.0
18	0.48	166.9	0.48	166.9	0.41	146.0	0.41	146.3
20	0.46	161.9	0.57	199.0	0.42	146.3	0.42	146.3
22	0.46	161.9	0.46	161.9	0.42	146.4	0.42	148.4
24	0.45	162.0	0.46	167.1	0.41	148.3	0.41	148.3
26	0.45	167.1	0.54	200.7	0.41	146.2	0.46	165.6
28	0.51	193.4	0.53	200.8	0.41	146.6	0.42	150.4
30	0.52	193.3	0.54	199.1	0.41	146.3	0.46	165.8
32	0.51	193.0	0.51	193.0	0.46	165.6	0.46	165.7
F*	**39.85**	**44.93**	**41.44**	**47.76**	**14.07**	**18.59**	**34.23**	**31.51**
PRE/R^2	**0.677**	**0.703**	**0.686**	**0.715**	**0.425**	**0.495**	**0.643**	**0.624**
p	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.001**	**0.0004**	**<.0001**	**<.0001**

Graph #: **4** **5**

Table B. 4: Diffusers & Reflectors Wall Test Transition Time data – Receivers: Earthworks 1 & Earthworks 2

Values Generated for All Diffuser Orientations & Microphone Positions

Number of Diffusers in Test Wall

Receiver	**Earthworks 1**				**Earthworks 2**			
Threshold	**11 dB Threshold**		**9 dB Threshold**		**11 dB Threshold**		**9 dB Threshold**	
Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran./RT Ratio	Trans. Time	Tran./RT Ratio	Trans. Time
Units	-	s	-	s	-	s	-	s
0	0.40	149.6	0.40	149.6	0.42	142.9	0.42	142.9
1	0.35	131.2	0.39	149.6	0.39	132.1	0.43	144.8
2	0.36	137.8	0.39	149.6	0.43	144.8	0.43	144.8
3	0.36	135.0	0.36	135.0	0.43	144.9	0.43	145.1
4	0.39	149.3	0.39	149.3	0.38	130.0	0.38	130.1
5	0.37	149.7	0.37	149.7	0.38	130.3	0.43	144.9
6	0.38	147.3	0.38	149.3	0.43	144.8	0.43	145.0
7	0.38	147.3	0.38	147.5	0.43	145.4	0.43	145.4
8	0.36	135.0	0.37	135.1	0.43	144.9	0.43	145.2
10	0.36	131.4	0.37	131.4	0.38	131.9	0.41	145.0
12	0.36	131.4	0.36	131.5	0.43	145.3	0.43	146.8
14	0.40	147.5	0.40	147.5	0.43	146.7	0.43	147.0
16	0.35	128.1	0.35	128.1	0.43	145.0	0.43	146.6
18	0.35	131.4	0.39	149.5	0.44	144.9	0.44	145.0
20	0.33	128.2	0.33	128.2	0.45	144.8	0.45	145.1
22	0.38	147.4	0.43	166.3	0.45	145.2	0.45	145.4
24	0.37	149.5	0.37	149.5	0.36	126.2	0.41	143.4
26	0.37	149.7	0.41	168.4	0.39	144.5	0.46	170.3
28	0.32	131.7	0.32	131.7	0.39	144.8	0.39	144.8
30	0.32	131.6	0.41	168.3	0.40	144.8	0.40	144.9
32	0.39	166.6	0.39	166.8	0.35	130.3	0.36	133.9
F*	**3.23**	**0.22**	**0.04**	**2.38**	**1.05**	**0.02**	**0.58**	**0.65**
PRE/R^2	**0.145**	**0.011**	**0.002**	**0.111**	**0.052**	**0.001**	**0.030**	**0.033**
p	**0.088**	**0.647**	**0.841**	**0.139**	**0.319**	**0.899**	**0.456**	**0.430**
Graph #:	6				7			

Trans Time = Transition Time Determined by the Chosen Threshold
Tran/RT Ratio = Ratio of Computed Transition Time & Measured Reverb Time (at 500 Hz)

Table B. 5: Diffusers & Reflectors Wall Test Transition Time data – Receiver: Larson Davis

	Receiver	**Larson Davis**			
	Threshold	**11 dB Threshold**		**9 dB Threshold**	
	Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time
	Units	-	s	-	s
Number of Diffusers in Test Wall	0	0.51	193.9	0.52	196.9
	1	0.52	197.0	0.52	198.2
	2	0.53	197.0	0.56	206.9
	3	0.52	197.6	0.55	207.5
	4	0.50	193.3	0.50	196.6
	5	0.50	206.9	0.50	206.9
	6	0.49	196.7	0.52	206.9
	7	0.49	196.6	0.52	206.8
	8	0.53	206.9	0.53	207.0
	10	0.47	193.4	0.50	206.8
	12	0.50	206.9	0.50	206.9
	14	0.48	206.6	0.48	206.6
	16	0.47	206.6	0.47	207.0
	18	0.44	193.3	0.47	207.1
	20	0.44	193.4	0.44	194.1
	22	0.44	193.8	0.47	207.2
	24	0.46	193.1	0.49	207.2
	26	0.46	193.3	0.46	194.0
	28	0.47	192.7	0.47	193.3
	30	0.47	193.7	0.47	194.0
	32	0.36	150.5	0.46	193.1
	F*	**32.25**	**5.83**	**38.62**	**4.48**
	PRE/R^2	**0.629**	**0.235**	**0.670**	**0.191**
	p	**<.0001**	**0.026**	**<.0001**	**0.048**

Graph #: 8

Table B. 6: Diffusers & Reflectors Wall Test Transition Time data – Receivers: Kemar Left & Kemar Right

Wall Test - Diffusers & Reflectors Comparison

	Receiver	**Kemar Left**				**Kemar Right**			
	Threshold	**11 dB Threshold**		**9 dB Threshold**		**11 dB Threshold**		**9 dB Threshold**	
	Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran./RT Ratio	Trans. Time	Tran./RT Ratio	Trans. Time
	Units	-	s	-	s	-	s	-	s
Number of Diffusers in Test Wall	0	0.51	193.4	0.51	193.9	0.39	145.9	0.41	150.5
	1	0.51	193.7	0.51	193.7	0.39	138.7	0.41	146.5
	2	0.52	193.9	0.52	193.9	0.40	143.1	0.43	154.0
	3	0.54	195.7	0.55	196.3	0.39	142.7	0.40	146.5
	4	0.53	195.2	0.53	195.2	0.41	142.9	0.41	142.9
	5	0.53	195.6	0.53	195.6	0.42	143.2	0.42	143.2
	6	0.54	200.5	0.54	200.5	0.50	170.5	0.50	170.5
	7	0.53	196.3	0.54	200.6	0.43	146.4	0.43	146.4
	8	0.55	196.3	0.56	200.7	0.41	142.5	0.49	170.5
	10	0.54	195.8	0.54	195.8	0.40	142.5	0.40	143.1
	12	0.53	191.8	0.53	191.8	0.40	143.2	0.53	191.8
	14	0.55	192.1	0.55	192.1	0.37	140.9	0.38	142.5
	16	0.55	198.2	0.56	201.2	0.38	143.3	0.50	191.9
	18	0.55	198.0	0.55	198.0	0.41	146.0	0.47	167.8
	20	0.57	192.4	0.57	193.5	0.49	167.8	0.49	167.8
	22	0.57	192.5	0.57	192.5	0.43	146.0	0.43	146.0
	24	0.55	192.4	0.55	193.2	0.42	146.4	0.42	146.4
	26	0.39	142.9	0.52	192.2	0.40	146.3	0.40	146.3
	28	0.52	197.2	0.52	197.2	0.41	146.4	0.42	150.3
	30	0.52	193.2	0.52	193.4	0.43	154.3	0.46	165.9
	32	0.48	193.4	0.50	199.1	0.41	146.1	0.48	173.9
	F*	**1.05**	**1.98**	**0.00**	**0.18**	**0.25**	**0.86**	**0.75**	**1.01**
	PRE/R^2	**0.053**	**0.094**	**0.000**	**0.010**	**0.013**	**0.043**	**0.038**	**0.050**
	p	**0.318**	**0.176**	**0.975**	**0.672**	**0.625**	**0.365**	**0.399**	**0.329**

Graph #: **9** **10**

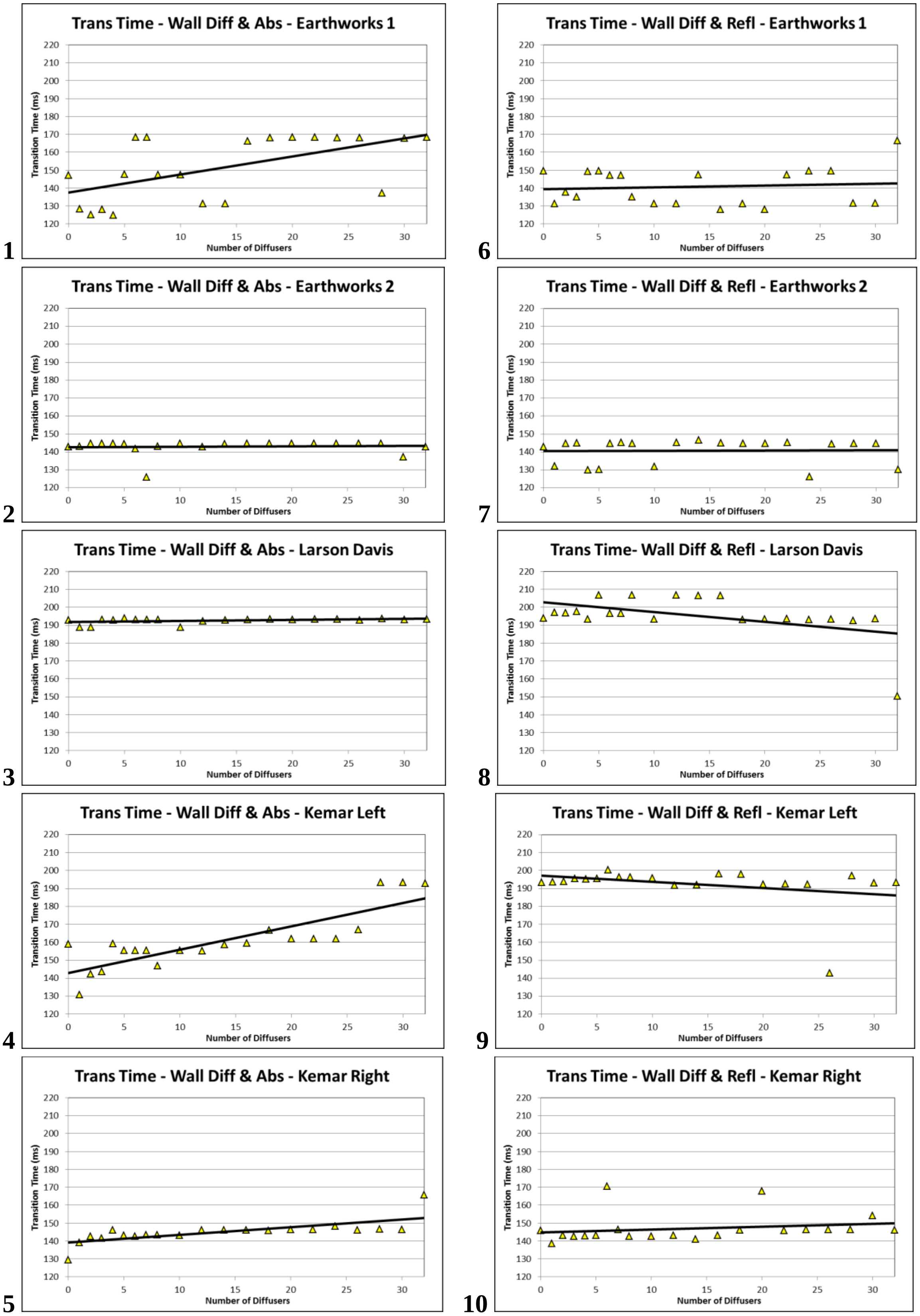

Figure B. 1: Transition Times for all Wall Tests – (Left) Diffusers & Absorbers – (Right) Diffusers & Reflectors

B.2 Transition Time – Room Tests

Table B. 7: Room Test Transition Time data – Receivers: Earthworks & Larson Davis

Values Generated for All Diffuser Orientations & Microphone Positions

Receiver	Earthworks				Larson Davis			
Threshold	11 dB Threshold		9 dB Threshold		11 dB Threshold		9 dB Threshold	
Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time
Units	-	s	-	s	-	s	-	s
Room A 10	0.55	212.65	0.55	212.77	0.59	265.63	0.59	265.92
Room A 20	0.55	212.79	0.55	212.81	0.54	261.56	0.55	261.60
Room A 30	0.63	252.94	0.63	253.35	0.50	261.40	0.50	261.69
Room A 40	0.52	212.38	0.55	227.35	0.48	261.50	0.53	285.48
Room A 50	0.48	212.77	0.58	253.65	0.47	261.92	0.47	265.48
Room A 60	0.46	227.52	0.51	251.19	0.47	265.46	0.50	285.73
F*	**2.73**	**0.05**	**0.17**	**5.94**	**35.04**	**0.00**	**8.82**	**2.59**
PRE/R^2	**0.406**	**0.012**	**0.041**	**0.598**	**0.898**	**0.000**	**0.688**	**0.393**
p	**0.174**	**0.835**	**0.701**	**0.072**	**0.004**	**0.987**	**0.041**	**0.183**
Room B 10	0.53	212.33	0.53	212.42	0.49	221.38	0.63	285.56
Room B 20	0.54	212.35	0.55	212.58	0.49	221.33	0.59	265.88
Room B 30	0.59	212.21	0.59	212.31	0.48	220.83	0.58	265.67
Room B 40	0.54	212.06	0.54	212.31	0.56	265.21	0.57	265.67
Room B 50	0.54	227.17	0.54	227.38	0.54	265.48	0.58	285.83
Room B 60	0.45	212.83	0.48	227.58	0.58	285.60	0.58	285.73
F*	**1.60**	**0.82**	**1.08**	**8.55**	**10.46**	**22.84**	**3.09**	**0.39**
PRE/R^2	**0.286**	**0.171**	**0.213**	**0.681**	**0.723**	**0.851**	**0.436**	**0.088**
p	**0.2742**	**0.4153**	**0.3567**	**0.0431**	**0.0319**	**0.009**	**0.153**	**0.568**
Room Empty	0.61	212.48	0.61	212.73	0.49	221.63	0.59	265.88
Room C 10	0.53	212.54	0.53	212.90	0.47	221.56	0.61	285.81
Room C 20	0.51	215.54	0.51	215.56	0.53	261.83	0.54	265.46
Room C 30	0.55	212.81	0.56	216.85	0.54	265.75	0.54	266.15
Room C 40	0.55	215.98	0.58	224.63	0.53	265.85	0.53	265.98
Room C 50	0.50	215.77	0.53	227.19	0.54	265.69	0.54	265.81
Room C 60	0.56	251.23	0.56	253.88	0.58	285.35	0.58	285.40
Room C 70	0.55	251.33	0.55	251.48	0.52	262.00	0.53	267.46
Room C 80	0.49	251.73	0.49	251.73	0.54	285.44	0.54	285.69
Room Diffuse	0.47	292.75	0.48	299.21	0.43	265.23	0.47	285.58
F*	**5.78**	**31.88**	**4.93**	**45.33**	**0.29**	**3.84**	**6.14**	**1.21**
PRE/R^2	**0.419**	**0.799**	**0.382**	**0.850**	**0.039**	**0.354**	**0.467**	**0.148**
p	**0.043**	**0.001**	**0.057**	**0.000**	**0.609**	**0.091**	**0.0423**	**0.307**

Graph #: 1 2

Table B. 8: Room Test Transition Time data – Kemar Left & Kemar Right values displayed

Room Test - Diffuser Arrangements A, B, & C

Receiver	Kemar Left				Kemar Right			
Threshold	11 dB Threshold		9 dB Threshold		11 dB Threshold		9 dB Threshold	
Metric	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time	Tran/RT Ratio	Trans Time
Units	-	s	-	s	-	s	-	s
Room A 10	0.52	237.96	0.53	245.83	0.59	237.94	0.60	238.33
Room A 20	0.53	232.94	0.56	246.04	0.48	197.04	0.58	237.77
Room A 30	0.60	257.77	0.60	257.90	0.63	237.52	0.63	237.52
Room A 40	0.55	257.58	0.55	257.71	0.60	232.79	0.61	237.63
Room A 50	0.55	254.04	0.56	258.04	0.57	237.90	0.57	240.31
Room A 60	0.50	257.92	0.50	257.92	0.53	240.19	0.62	276.92
F*	**0.07**	**5.99**	**0.63**	**9.08**	**0.03**	**0.84**	**0.08**	**3.42**
PRE/R^2	**0.017**	**0.600**	**0.135**	**0.694**	**0.006**	**0.173**	**0.020**	**0.461**
p	**0.804**	**0.071**	**0.473**	**0.039**	**0.880**	**0.412**	**0.788**	**0.138**
Room B 10	0.51	238.04	0.51	238.44	0.48	203.54	0.55	232.79
Room B 20	0.53	232.90	0.54	238.10	0.55	232.65	0.57	237.81
Room B 30	0.63	272.71	0.63	272.73	0.53	233.00	0.54	238.31
Room B 40	0.57	245.71	0.60	257.33	0.46	215.56	0.46	215.56
Room B 50	0.54	253.73	0.58	272.75	0.54	237.98	0.54	237.98
Room B 60	0.54	272.96	0.54	272.96	0.58	253.44	0.58	253.46
F*	**0.08**	**3.01**	**0.27**	**8.47**	**0.85**	**5.36**	**0.02**	**0.58**
PRE/R^2	**0.019**	**0.430**	**0.064**	**0.679**	**0.176**	**0.573**	**0.004**	**0.126**
p	**0.7967**	**0.1577**	**0.6288**	**0.0436**	**0.4080**	**0.082**	**0.908**	**0.490**
Room Empty	0.52	238.31	0.52	238.35	0.57	237.98	0.57	238.08
Room C 10	0.53	238.27	0.53	238.29	0.58	232.69	0.60	238.19
Room C 20	0.54	238.31	0.54	238.35	0.58	237.90	0.58	237.94
Room C 30	0.53	238.73	0.53	238.75	0.55	238.42	0.55	238.44
Room C 40	0.51	237.79	0.55	257.29	0.55	237.90	0.55	238.52
Room C 50	0.62	276.96	0.62	276.96	0.61	268.40	0.62	272.92
Room C 60	0.59	270.56	0.64	293.56	0.58	267.96	0.58	267.96
Room C 70	0.51	251.73	0.51	251.73	0.50	238.00	0.53	253.58
Room C 80	0.59	303.08	0.59	303.10	0.55	272.67	0.60	300.40
Room Diffuse	0.55	327.29	0.55	327.29	0.52	300.35	0.58	334.46
F*	**1.38**	**23.14**	**1.27**	**26.42**	**3.41**	**14.97**	**0.00**	**24.33**
PRE/R^2	**0.147**	**0.743**	**0.137**	**0.768**	**0.299**	**0.652**	**0.000**	**0.753**
p	**0.274**	**0.001**	**0.292**	**0.001**	**0.102**	**0.005**	**0.9672**	**0.001**

Graph #: **3** **4**

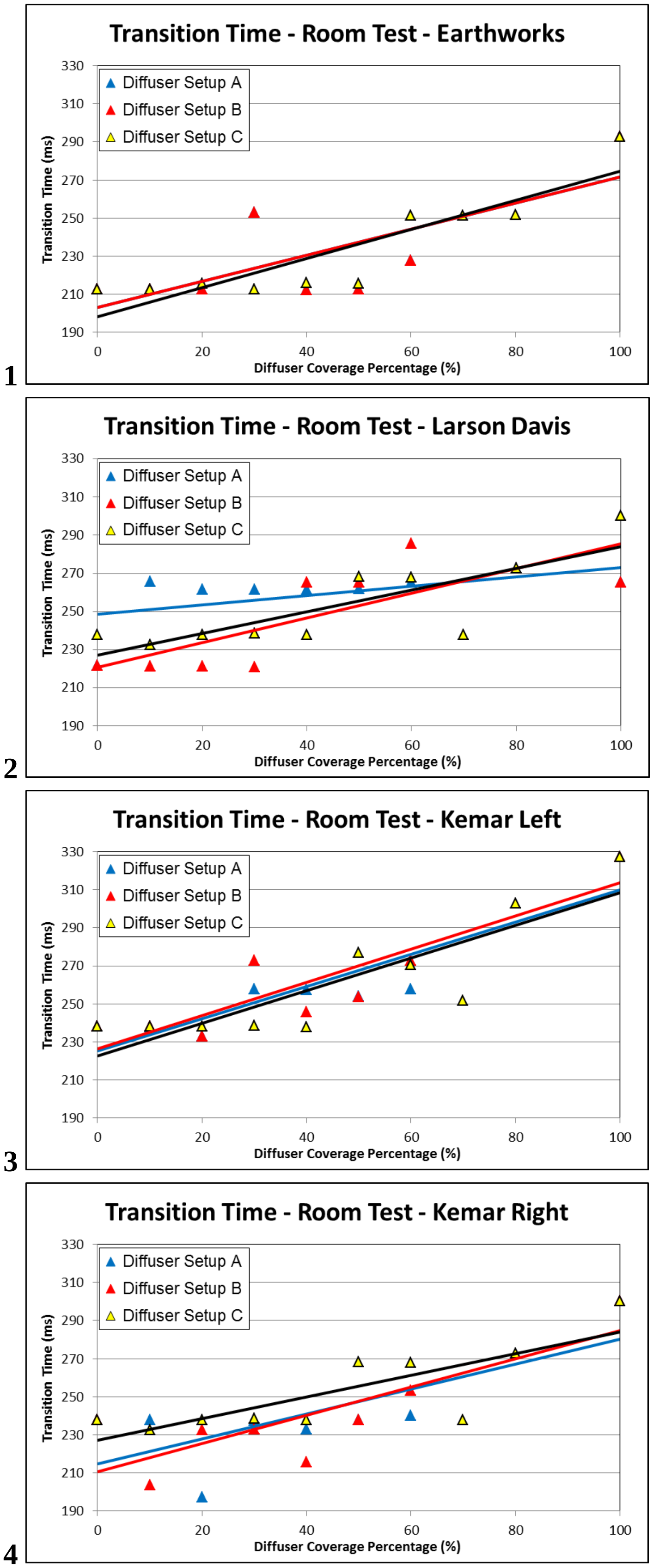

Figure B. 2: Transition Times for all Room Tests – Each graph represents data from one microphone position

B.3 Degree of Time Series Fluctuations – Wall Tests

Table B. 9: Diffusers & Absorbers Wall Test Degree of Time Series Fluctuation data – Receivers: Earthworks 1, Earthworks 2, & Larson Davis

Values Generated for All Diffuser Orientations & Microphone Positions

	Receiver	**Earthworks 1**			**Earthworks 2**			**Larson Davis**		
	Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
	Units	-	s	-	-	s	-	-	s	-
Number of Diffusers in Test Wall	0	19.21	0.72	859.9	15.39	0.90	45.6	15.99	0.86	249.2
	1	16.35	0.85	1004.1	14.74	0.94	66.5	14.14	0.98	268.8
	2	12.09	1.14	1320.8	14.62	0.94	77.0	16.36	0.84	205.7
	3	14.92	0.93	1059.7	15.05	0.92	88.6	19.08	0.72	191.2
	4	12.95	1.07	1104.0	15.22	0.91	91.4	18.37	0.75	181.7
	5	19.79	0.70	755.1	14.35	0.96	83.2	19.47	0.71	137.2
	6	19.42	0.71	709.8	12.34	1.12	125.8	19.71	0.70	137.9
	7	19.64	0.70	662.5	10.75	1.29	160.4	18.96	0.73	143.4
	8	18.17	0.76	668.0	15.27	0.90	134.2	19.49	0.71	163.3
	10	19.49	0.71	650.5	16.76	0.82	135.0	18.70	0.74	144.0
	12	17.41	0.79	765.9	13.26	1.04	165.3	17.93	0.77	187.5
	14	16.62	0.83	758.9	15.85	0.87	175.2	20.25	0.68	257.6
	16	20.42	0.68	544.4	16.50	0.84	183.2	18.13	0.76	185.1
	18	18.32	0.75	644.1	16.77	0.82	130.2	20.02	0.69	199.4
	20	18.51	0.75	689.1	16.05	0.86	156.1	19.39	0.71	175.3
	22	18.16	0.76	615.1	17.46	0.79	128.7	19.84	0.70	131.3
	24	19.25	0.72	538.1	15.35	0.90	162.4	19.60	0.71	152.5
	26	19.23	0.72	627.2	16.54	0.84	161.1	18.25	0.76	161.2
	28	18.05	0.77	619.7	14.70	0.94	173.5	20.05	0.69	129.5
	30	20.59	0.67	471.7	16.15	0.86	164.0	19.99	0.69	105.9
	32	19.27	0.72	606.2	16.75	0.83	138.3	26.46	0.52	133.3
	F*	**5.20**	**5.11**	**21.03**	**5.50**	**4.19**	**19.29**	**13.93**	**13.51**	**8.02**
	PRE/R^2	**0.215**	**0.212**	**0.525**	**0.224**	**0.181**	**0.504**	**0.423**	**0.416**	**0.297**
	p	**0.034**	**0.036**	**0.0002**	**0.030**	**0.055**	**0.0003**	**0.001**	**0.002**	**0.0106**
	Graph #:			**1**			**2**			**3**

k = Degree of Time Series Fluctuations
RT = Estimated RT as Computed by This Methodology
Mean $g^2(t)$ = Mean Decay Slope of the Impulse Response

Table B. 10: Diffusers & Absorbers Wall Test Degree of Time Series Fluctuation data – Receivers: Kemar Left & Kemar Right

	Receiver	**Kemar Left**			**Kemar Right**		
	Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
	Units	-	s	-	-	s	-
Number of Diffusers in Test Wall	0	20.74	0.67	132.2	16.08	0.86	211.1
	1	16.96	0.81	102.5	16.46	0.84	358.7
	2	22.17	0.62	159.9	16.26	0.85	261.2
	3	22.51	0.61	110.3	17.47	0.79	263.0
	4	24.44	0.57	103.0	17.89	0.77	219.9
	5	23.74	0.58	128.7	18.36	0.75	185.3
	6	22.66	0.61	130.5	18.01	0.77	215.0
	7	25.38	0.54	58.6	18.19	0.76	155.7
	8	22.93	0.60	84.6	18.41	0.75	131.6
	10	24.45	0.57	84.5	18.65	0.74	126.3
	12	23.63	0.58	97.5	19.07	0.72	226.6
	14	24.87	0.56	69.1	18.01	0.77	217.6
	16	24.86	0.56	92.6	19.00	0.73	187.9
	18	24.80	0.56	133.0	19.32	0.72	138.9
	20	25.40	0.54	93.1	19.50	0.71	137.4
	22	24.45	0.57	81.6	19.67	0.70	129.8
	24	24.50	0.56	82.4	18.66	0.74	138.7
	26	24.24	0.57	73.6	20.05	0.69	140.3
	28	25.60	0.54	74.1	19.87	0.70	129.7
	30	25.55	0.54	68.4	20.29	0.68	119.0
	32	25.77	0.54	75.9	20.52	0.67	126.6
	F*	**15.76**	**11.32**	**10.57**	**81.56**	**64.14**	**19.72**
	PRE/R^2	**0.453**	**0.373**	**0.358**	**0.811**	**0.772**	**0.509**
	p	**0.001**	**0.003**	**0.0042**	**<.0001**	**<.0001**	**0.0003**

Graph #: **4** **5**

Table B. 11: Diffusers & Reflectors Wall Test Degree of Time Series Fluctuation data – Receivers: Earthworks 1, Earthworks 2, & Larson Davis

Values Generated for All Diffuser Orientations & Microphone Positions

Number of Diffusers in Test Wall

Receiver	**Earthworks 1**			**Earthworks 2**			**Larson Davis**		
Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
Units	-	s	-	-	s	-	-	s	-
0	19.95	0.69	723.3	14.83	0.93	635.9	19.20	0.72	505.8
1	17.74	0.78	1043.2	14.26	0.97	678.2	19.74	0.70	618.6
2	18.18	0.76	600.8	14.81	0.93	496.6	21.31	0.65	295.5
3	17.18	0.80	597.6	16.93	0.82	273.6	20.05	0.69	275.7
4	19.18	0.72	617.4	12.41	1.11	291.4	19.00	0.73	294.0
5	20.65	0.67	493.1	13.55	1.02	246.7	19.70	0.70	255.6
6	18.71	0.74	560.2	16.15	0.86	227.8	19.71	0.70	190.8
7	18.13	0.76	507.1	17.26	0.80	246.6	19.60	0.70	266.0
8	17.68	0.78	536.3	17.27	0.80	332.9	20.09	0.69	216.1
10	15.90	0.87	633.3	15.32	0.90	253.5	19.67	0.70	245.4
12	16.11	0.86	691.9	16.41	0.84	168.5	19.25	0.72	157.8
14	20.13	0.69	502.4	16.37	0.84	189.0	19.79	0.70	141.0
16	10.91	1.27	831.5	15.62	0.88	153.0	19.64	0.70	162.8
18	16.96	0.81	712.4	17.02	0.81	165.4	18.94	0.73	212.2
20	11.86	1.17	1003.8	15.25	0.91	171.7	19.57	0.71	148.2
22	19.26	0.72	552.4	16.53	0.84	142.0	20.01	0.69	175.5
24	20.24	0.68	490.0	12.64	1.09	159.3	19.38	0.71	130.4
26	20.27	0.68	539.0	16.36	0.84	120.6	20.06	0.69	151.0
28	15.65	0.88	730.4	15.56	0.89	147.9	19.82	0.70	164.9
30	16.44	0.84	626.3	19.61	0.70	155.0	19.56	0.71	139.8
32	18.84	0.73	517.8	10.57	1.31	156.3	24.18	0.57	155.0
F*	**0.51**	**0.55**	**0.23**	**0.01**	**0.13**	**21.26**	**2.08**	**1.85**	**17.74**
PRE/R^2	**0.026**	**0.028**	**0.012**	**0.001**	**0.007**	**0.528**	**0.099**	**0.089**	**0.483**
p	**0.484**	**0.468**	**0.6389**	**0.922**	**0.724**	**0.0002**	**0.166**	**0.190**	**0.0005**

Graph #: **6** **7** **8**

k = Degree of Time Series Fluctuations
RT = Estimated RT as Computed by This Methodology
Mean $g^2(t)$ = Mean Decay Slope of the Impulse Response

Table B. 12: Diffusers & Reflectors Wall Test Degree of Time Series Fluctuation data – Receivers: Kemar Left & Kemar Right

	Receiver	**Kemar Left**			**Kemar Right**		
	Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
	Units	-	s	-	-	s	-
Number of Diffusers in Test Wall	0	24.41	0.57	177.6	21.26	0.65	293.1
	1	21.35	0.65	179.9	18.63	0.74	270.5
	2	21.64	0.64	151.5	19.23	0.72	248.5
	3	22.32	0.62	124.2	19.86	0.70	202.3
	4	18.41	0.75	97.3	17.76	0.78	234.8
	5	20.32	0.68	123.6	18.92	0.73	255.9
	6	23.95	0.58	127.3	19.99	0.69	300.9
	7	23.32	0.59	167.3	17.95	0.77	283.4
	8	23.62	0.58	198.0	20.18	0.68	310.3
	10	22.51	0.61	148.5	18.54	0.75	292.3
	12	16.47	0.84	172.0	18.92	0.73	230.7
	14	17.35	0.80	143.7	16.77	0.82	234.9
	16	23.76	0.58	130.0	19.61	0.70	166.7
	18	24.05	0.57	62.6	18.62	0.74	208.9
	20	24.86	0.56	76.0	19.95	0.69	151.3
	22	24.28	0.57	74.6	19.41	0.71	143.9
	24	23.19	0.60	101.4	20.10	0.69	140.9
	26	20.49	0.67	80.1	20.11	0.69	148.1
	28	25.58	0.54	61.1	19.86	0.70	160.1
	30	24.42	0.57	88.5	20.38	0.68	130.4
	32	25.47	0.54	84.4	20.32	0.68	124.3
	F*	**2.99**	**2.05**	**21.48**	**1.67**	**1.66**	**49.91**
	PRE/R^2	**0.136**	**0.097**	**0.531**	**0.081**	**0.081**	**0.724**
	p	**0.100**	**0.169**	**0.0002**	**0.211**	**0.213**	**<.0001**

Graph #: **9** **10**

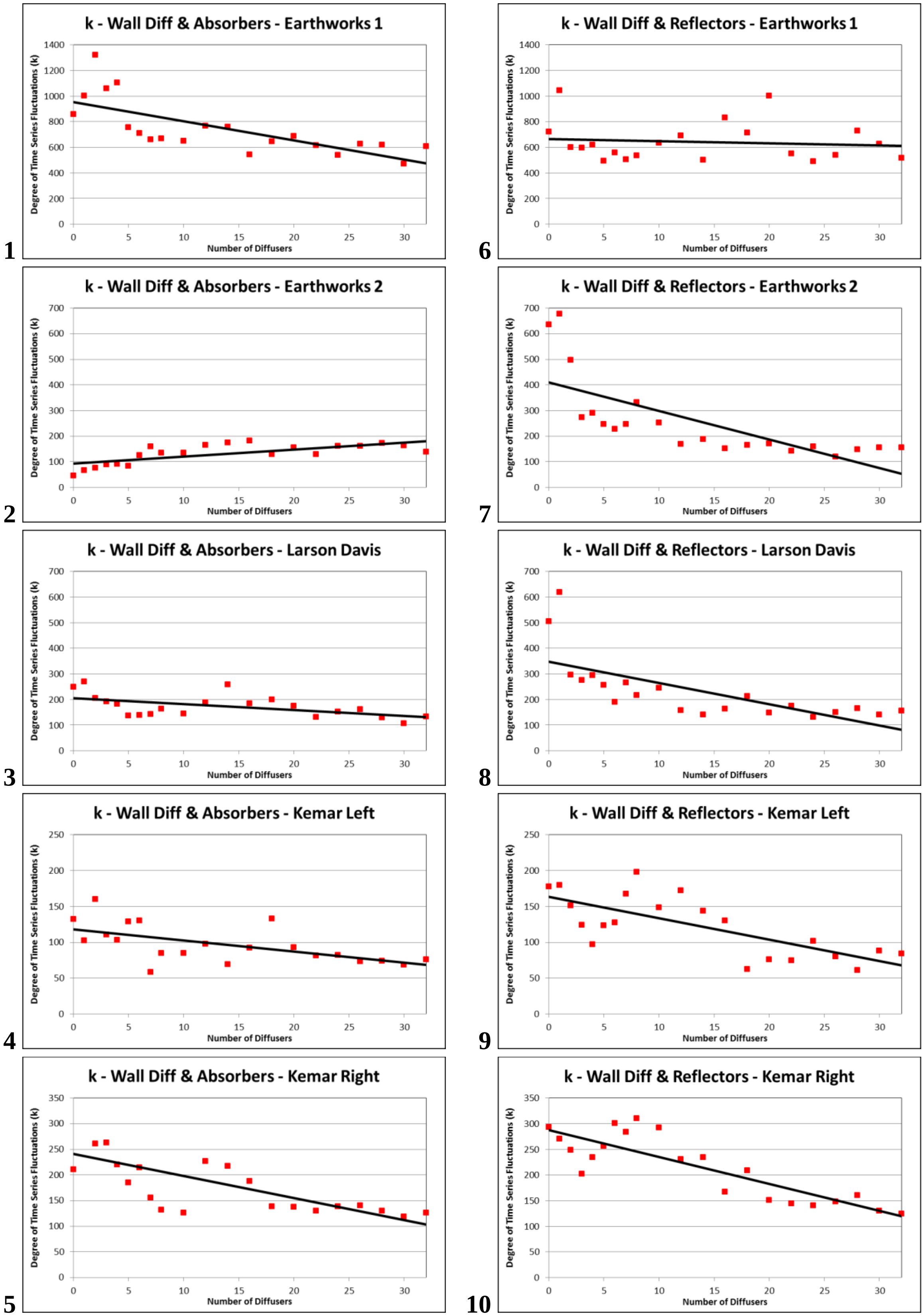

Figure B. 3: Degree of Time Series Fluctuations for all Wall Tests – (Left) Diffusers & Absorbers – (Right) Diffusers & Reflectors

B.4 Degree of Time Series Fluctuations – Room Tests

Table B. 13: Room Test Degree of Time Series Fluctuation data – Receivers: Earthworks & Larson Davis

Values Generated for All Diffuser Orientations & Microphone Positions

Receiver	**Earthworks**			**Larson Davis**		
Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
Units	-	s	-	-	s	-
Room A 10	11.88	1.16	35.33	13.54	1.02	19.51
Room A 20	13.53	1.02	28.28	12.59	1.10	23.74
Room A 30	13.11	1.05	27.96	13.47	1.03	21.19
Room A 40	11.35	1.22	24.56	14.23	0.97	19.67
Room A 50	11.51	1.20	28.39	14.21	0.97	20.83
Room A 60	12.64	1.09	22.77	14.53	0.95	20.25
F*	**0.25**	**0.24**	**7.98**	**6.92**	**6.06**	**0.22**
PRE/R^2	**0.059**	**0.056**	**0.666**	**0.634**	**0.603**	**0.051**
p	**0.644**	**0.651**	**0.048**	**0.058**	**0.070**	**0.666**
Room B 10	12.49	1.11	28.33	13.48	1.03	24.39
Room B 20	12.04	1.15	44.33	12.98	1.06	29.44
Room B 30	11.84	1.17	47.61	12.46	1.11	30.10
Room B 40	12.56	1.10	43.83	14.37	0.96	24.20
Room B 50	11.44	1.21	33.15	14.70	0.94	41.61
Room B 60	11.02	1.25	37.76	14.43	0.96	44.05
F*	**5.27**	**5.72**	**0.02**	**3.81**	**3.37**	**7.39**
PRE/R^2	**0.569**	**0.588**	**0.005**	**0.488**	**0.457**	**0.649**
p	**0.083**	**0.075**	**0.894**	**0.123**	**0.140**	**0.053**
Room Empty	12.21	1.13	46.54	12.59	1.10	23.48
Room C 10	11.98	1.15	42.92	13.70	1.01	29.52
Room C 20	12.83	1.08	25.26	13.23	1.04	25.63
Room C 30	11.16	1.24	29.11	13.22	1.05	30.67
Room C 40	12.51	1.11	27.22	13.91	0.99	26.82
Room C 50	13.11	1.05	30.45	14.72	0.94	41.05
Room C 60	13.00	1.06	32.92	14.82	0.93	28.85
Room C 70	13.48	1.03	32.35	13.75	1.00	39.21
Room C 80	13.46	1.03	29.17	15.28	0.90	34.55
Room Diffuse	13.35	1.04	28.67	15.24	0.91	27.16
F*	**8.82**	**7.38**	**3.29**	**12.43**	**11.92**	**0.45**
PRE/R^2	**0.524**	**0.480**	**0.291**	**0.640**	**0.630**	**0.061**
p	**0.018**	**0.026**	**0.107**	**0.010**	**0.011**	**0.523**
Graph #:			**1**			**2**

Table B. 14: Room Test Degree of Time Series Fluctuation data – Receivers: Kemar Left & Kemar Right

Receiver	**Kemar Left**			**Kemar Right**		
Metric	Mean $g^2(t)$	RT	k	Mean $g^2(t)$	RT	k
Units	-	s	-	-	s	-
Room A 10	15.16	0.91	45.85	15.04	0.92	36.12
Room A 20	15.58	0.89	44.12	13.43	1.03	39.21
Room A 30	16.33	0.85	38.27	14.44	0.96	31.58
Room A 40	15.60	0.89	41.60	14.03	0.98	29.98
Room A 50	14.38	0.96	40.40	14.87	0.93	38.49
Room A 60	15.54	0.89	44.24	15.95	0.87	44.03
F*	**0.17**	**0.18**	**0.40**	**1.47**	**1.38**	**0.63**
PRE/R^2	**0.040**	**0.043**	**0.090**	**0.268**	**0.256**	**0.136**
p	**0.703**	**0.694**	**0.563**	**0.293**	**0.306**	**0.472**
Room B 10	14.51	0.95	50.57	14.12	0.98	53.03
Room B 20	15.14	0.91	45.07	14.76	0.94	65.89
Room B 30	17.43	0.79	41.42	15.18	0.91	70.76
Room B 40	16.52	0.84	37.65	12.88	1.07	49.90
Room B 50	16.80	0.82	36.14	15.50	0.89	45.01
Room B 60	17.04	0.81	37.62	16.82	0.82	51.60
F*	**6.04**	**6.67**	**21.81**	**1.65**	**1.16**	**1.22**
PRE/R^2	**0.602**	**0.625**	**0.845**	**0.292**	**0.225**	**0.234**
p	**0.070**	**0.061**	**0.010**	**0.269**	**0.342**	**0.331**
Room Empty	14.25	0.97	67.16	14.23	0.97	40.92
Room C 10	14.62	0.95	40.10	14.22	0.97	43.01
Room C 20	14.73	0.94	35.79	12.58	1.10	42.23
Room C 30	16.11	0.86	30.88	14.54	0.95	32.01
Room C 40	14.91	0.93	31.22	13.46	1.03	42.33
Room C 50	16.64	0.83	26.81	17.86	0.77	55.62
Room C 60	16.46	0.84	28.18	17.05	0.81	56.39
Room C 70	18.98	0.73	28.08	15.78	0.88	53.41
Room C 80	18.02	0.77	26.06	17.90	0.77	41.04
Room Diffuse	17.85	0.77	24.63	17.21	0.80	41.14
F*	**28.42**	**32.54**	**10.78**	**10.52**	**9.75**	**0.65**
PRE/R^2	**0.780**	**0.803**	**0.574**	**0.568**	**0.549**	**0.075**
p	**0.001**	**0.001**	**0.011**	**0.012**	**0.014**	**0.444**
Graph #:			**3**			**4**

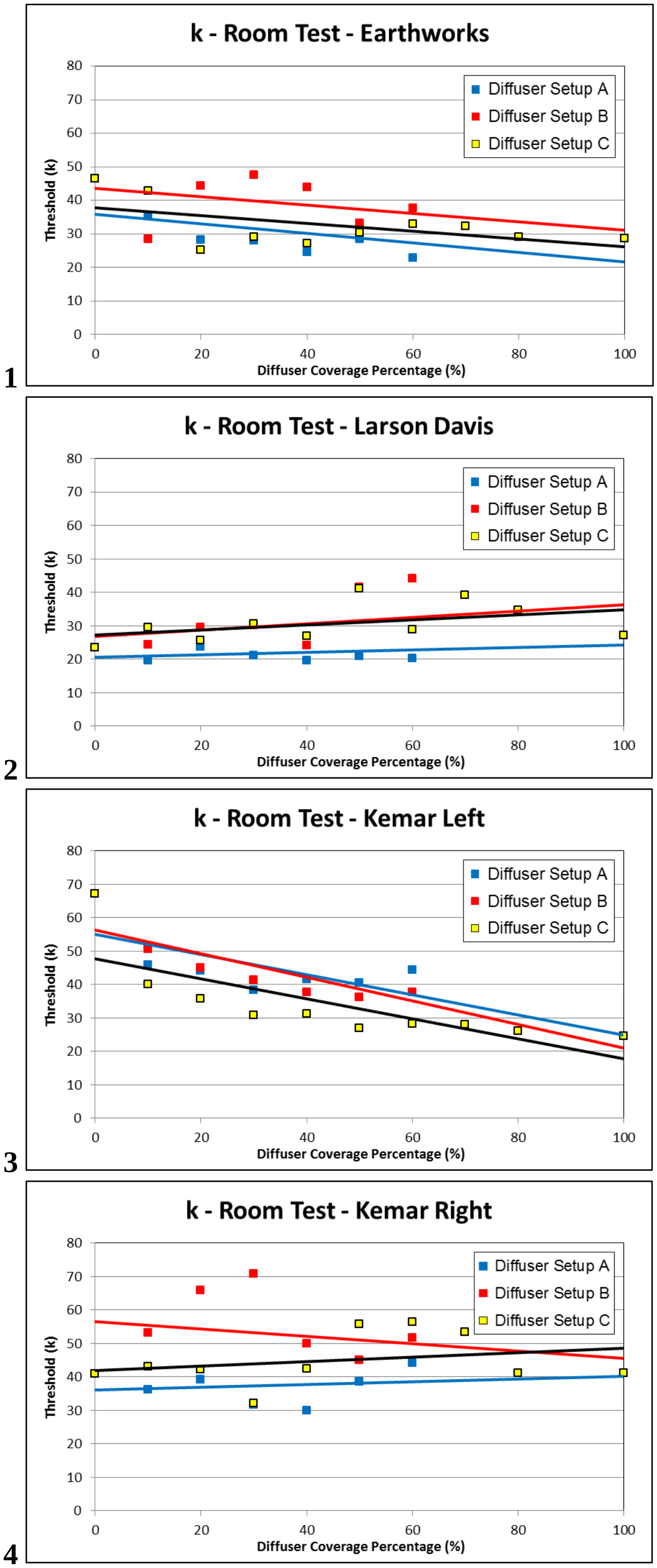

Figure B. 4: Degree of Time Series Fluctuations for all Room Tests – Each graph shows data from one mic

B.5 Number of Peaks – Wall Tests

Table B. 15: Diffusers & Absorbers Wall Test Number of Peaks data – Receivers: Earthworks 1, Earthworks 2, Larson Davis, Kemar Left, & Kemar Right

Values Generated for All Diffuser Orientations & Microphone Positions

Number of Diffusers in Test Wall

Receiver	**Earthworks 1**	**Earthworks 2**	**Larson Davis**	**Kemar Left**	**Kemar Right**
Metric	Np	Np	Np	Np	Np
Threshold	- 25 dB	- 25 dB	- 20 dB	- 20 dB	- 30 dB
0	40	31	79	42	51
1	48	46	83	53	47
2	42	45	87	53	52
3	45	54	83	60	45
4	60	51	92	71	55
5	58	52	101	69	57
6	54	60	97	68	54
7	67	64	99	64	56
8	68	70	102	66	59
10	69	66	104	72	60
12	68	56	109	78	63
14	69	65	108	82	62
16	78	71	114	87	79
18	75	71	106	77	72
20	77	67	111	88	69
22	86	65	110	84	68
24	92	69	112	80	69
26	83	75	112	82	83
28	85	80	106	85	87
30	91	68	107	89	76
32	83	73	101	85	79
F*	**109.17**	**34.60**	**22.27**	**52.19**	**100.02**
PRE/R^2	**0.852**	**0.646**	**0.540**	**0.733**	**0.840**
p	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Graph #:	**1**	**2**	**3**	**4**	**5**

Table B. 16: Diffusers & Reflectors Wall Test Number of Peaks data – Receivers: Earthworks 1, Earthworks 2, Larson Davis, Kemar Left, & Kemar Right

Values Generated for All Diffuser Orientations & Microphone Positions

Number of Diffusers in Test Wall

Receiver	**Earthworks 1**	**Earthworks 2**	**Larson Davis**	**Kemar Left**	**Kemar Right**
Metric	Np	Np	Np	Np	Np
Threshold	- 20 dB	- 20 dB	- 20 dB	- 20 dB	- 30 dB
0	22	23	31	40	57
1	21	22	32	63	57
2	30	26	44	79	64
3	27	26	75	75	59
4	29	26	52	72	61
5	33	27	89	76	64
6	28	27	105	73	65
7	37	33	71	76	63
8	38	28	93	80	65
10	35	29	87	93	66
12	35	27	104	87	62
14	35	32	98	83	67
16	40	37	122	93	71
18	34	31	122	93	78
20	32	29	123	87	73
22	46	31	113	86	74
24	44	32	109	91	75
26	40	28	108	86	77
28	38	33	114	89	76
30	47	31	108	87	74
32	50	36	101	82	76
F*	**47.86**	**18.99**	**24.13**	**13.10**	**98.67**
PRE/R^2	**0.716**	**0.500**	**0.560**	**0.408**	**0.839**
p	**<.0001**	**0.000**	**<.0001**	**0.002**	**<.0001**
Graph #:	**6**	**7**	**8**	**9**	**10**

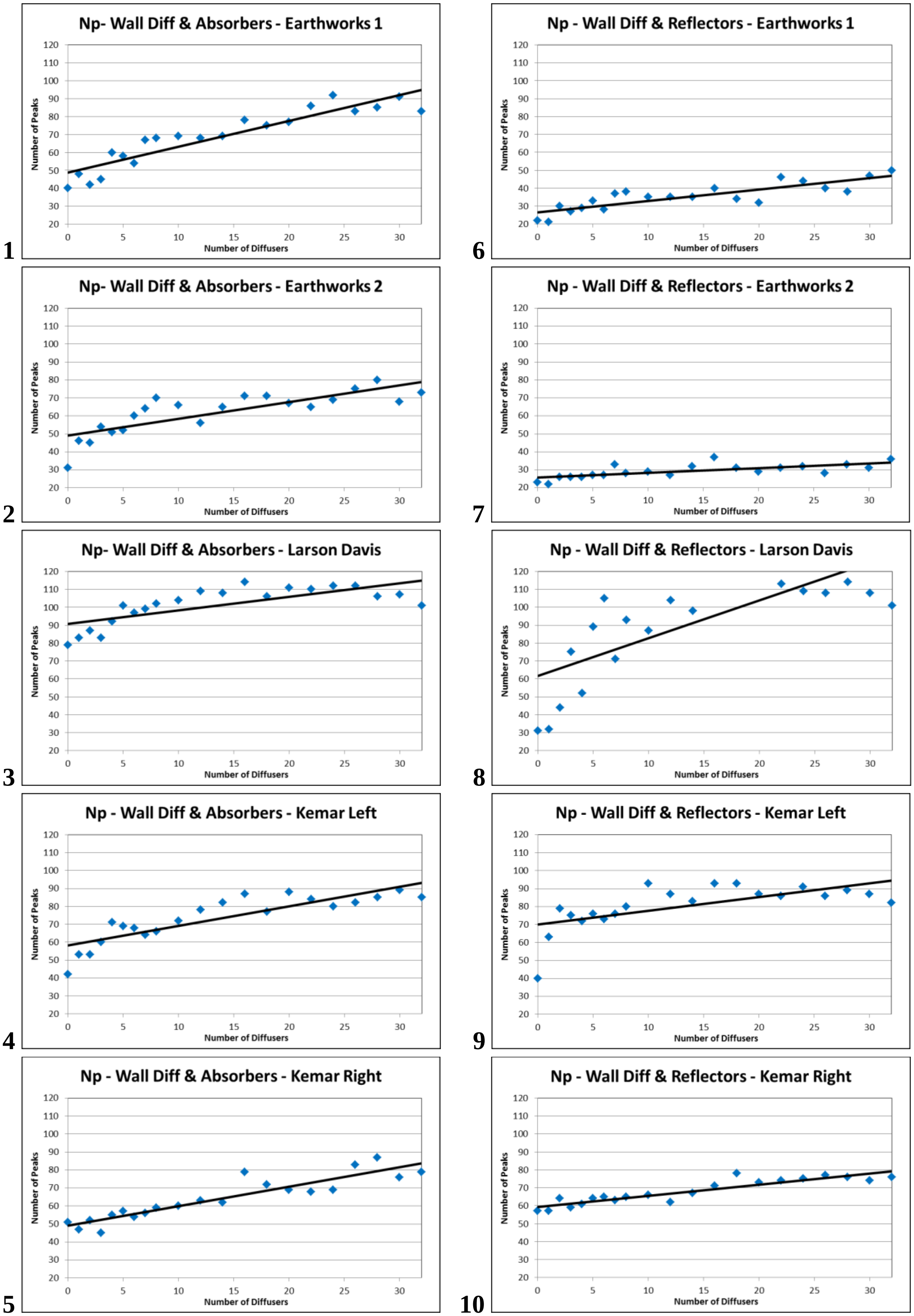

Figure B. 5: Number of Peaks for all Wall Tests – (Left) Diffusers & Absorbers – (Right) Diffusers & Reflectors

Table B. 17: Room Test Number of Peaks unfiltered data – Receivers: Earthworks 1, Earthworks 2, Larson Davis, Kemar Left, & Kemar Right

Values Generated for All Diffuser Orientations & Microphone Positions

Receiver	**Earthworks**	**Larson Davis**	**Kemar Left**	**Kemar Right**
Metric	Np	Np	Np	Np
Units	- 20 dB	- 20 dB	- 20 dB	- 20 dB
Room A 10	529	646	430	453
Room A 20	533	727	372	523
Room A 30	564	624	405	552
Room A 40	671	797	412	587
Room A 50	630	623	403	462
Room A 60	674	694	448	404
F*	**17.05**	**0.02**	**0.73**	**0.41**
PRE/R^2	**0.810**	**0.006**	**0.154**	**0.093**
p	**0.015**	**0.882**	**0.442**	**0.556**

Room B 10	622	746	353	345
Room B 20	574	643	399	387
Room B 30	569	576	385	372
Room B 40	588	699	460	475
Room B 50	603	499	321	357
Room B 60	651	401	346	334
F*	**0.91**	**9.84**	**0.19**	**0.01**
PRE/R^2	**0.185**	**0.711**	**0.044**	**0.002**
p	**0.395**	**0.035**	**0.689**	**0.934**

Room Empty	459	654	363	441
Room C 10	559	469	410	424
Room C 20	651	746	441	457
Room C 30	631	685	423	552
Room C 40	650	708	544	554
Room C 50	629	622	570	301
Room C 60	680	639	485	364
Room C 70	642	686	520	352
Room C 80	692	711	551	379
Room Diffuse	664	704	619	460
F*	**9.65**	**1.36**	**27.96**	**0.78**
PRE/R^2	**0.547**	**0.146**	**0.778**	**0.089**
p	**0.015**	**0.277**	**0.0007**	**0.403**
Graph #:	**1**	**2**	**3**	**4**

Table B. 18: Room Test Number of Peaks time filtered, 250 ms after max peak data – Receivers: Earthworks 1, Earthworks 2, Larson Davis, Kemar Left, & Kemar Right

Values Generated for All Diffuser Orientations & Microphone Positions

Receiver	**Earthworks**	**Larson Davis**	**Kemar Left**	**Kemar Right**
Metric	Np	Np	Np	Np
Units	- 50 dB	- 50 dB	- 50 dB	- 50 dB
Room A 10	1651	1737	1602	1619
Room A 20	1703	1843	1670	1754
Room A 30	1750	1832	1764	1839
Room A 40	1821	1926	1867	1878
Room A 50	1849	1928	1972	1965
Room A 60	1878	1966	2047	2018
F*	**199.33**	**34.77**	**1012.40**	**127.14**
PRE/R^2	**0.980**	**0.897**	**0.996**	**0.970**
p	**<.0001**	**0.004**	**<.0001**	**0.000**
Room B 10	1651	1833	1570	1642
Room B 20	1735	1844	1720	1606
Room B 30	1840	1919	1814	1764
Room B 40	1880	2012	1958	1877
Room B 50	1993	1989	1908	1972
Room B 60	2014	1999	2086	2031
F*	**164.21**	**19.15**	**49.20**	**62.76**
PRE/R^2	**0.976**	**0.827**	**0.925**	**0.940**
p	**0.0002**	**0.012**	**0.002**	**0.001**
Room Empty	1547	1731	1490	1581
Room C 10	1629	1809	1673	1654
Room C 20	1817	1903	1794	1792
Room C 30	1849	1996	1933	1944
Room C 40	1992	2083	2108	2043
Room C 50	2078	2157	2156	2044
Room C 60	2188	2273	2359	2185
Room C 70	2245	2283	2368	2252
Room C 80	2335	2363	2389	2361
Room Diffuse	2304	2348	2470	2447
F*	**114.51**	**123.46**	**104.44**	**321.70**
PRE/R^2	**0.935**	**0.939**	**0.929**	**0.976**
p	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Graph #:	**5**	**6**	**7**	**8**

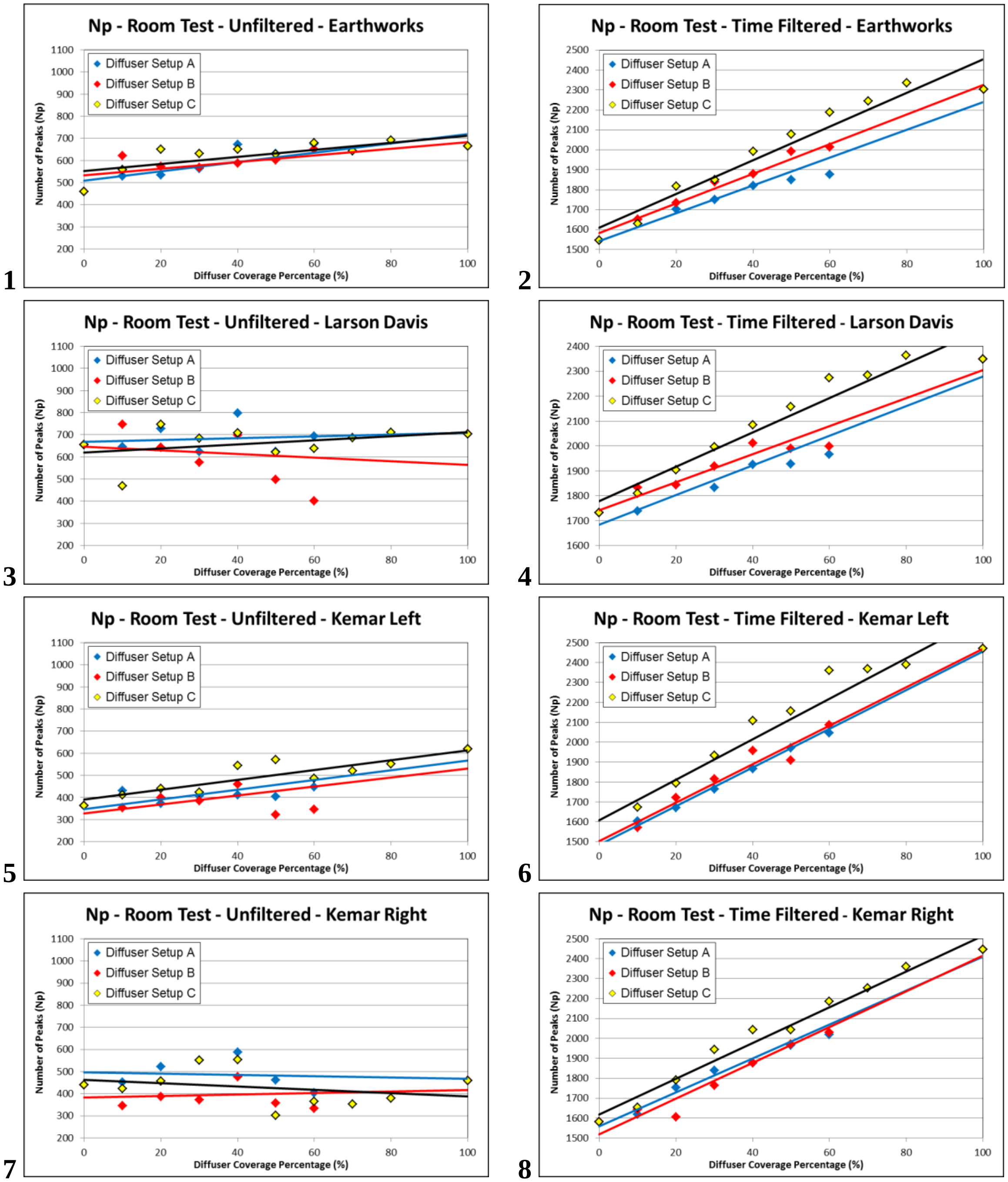

Figure B. 6: Number of Peaks for all Room Tests – (Left) Unfiltered impulse response data – (Right) Time filtered impulse response data, analyzing only data within 250 ms of the direct sound

Appendix C: Objective Metric Visual Basic Code

C.1 Transition Time

```
Public StartRow As Integer
Public EndRow As Long
Public NumRows As Long
Public SamplingRate As Variant
Public SchroederSum As Variant
Public PSquaredMax As Variant
Public PSquaredMin As Variant
Public SlopeAverage As Variant
Public TransitionTime11 As Variant
Public TransitionTime9 As Variant

Sub TransitionTime()
   'Define Variables
   Dim Row As Long
   StartRow = 7
   SamplingRate = Sheets("Room Data").Cells(19, 6).Value
   TransitionTime11 = 0
   TransitionTime9 = 0
   SchroederSum = 0

   'Fill Time, Pressure, & Squared Pressure and Define NumRows & EndRow
   Row = StartRow
   Do
      Sheets("Slope Ratio").Cells(Row, 1).Value = Sheets("Room Data").Cells(Row, 1).Value
      Sheets("Slope Ratio").Cells(Row, 2).Value = Sheets("Room Data").Cells(Row, 2).Value
      Sheets("Slope Ratio").Cells(Row, 3).Value = Sheets("Slope Ratio").Cells(Row, 2).Value * Sheets("Slope Ratio").Cells(Row, 2).Value
      Row = Row + 1
   Loop Until IsEmpty(Sheets("Room Data").Cells(Row, 1).Value) = True
   NumRows = Row - 7
   EndRow = Row - 1

   'Fill Normalized Pressure
   PSquaredMax = Application.WorksheetFunction.Max(Range(Sheets("Slope Ratio").Cells(StartRow, 3), Sheets("Slope
                              Ratio").Cells(EndRow, 3)))
   PSquaredMin = Application.WorksheetFunction.Min(Range(Sheets("Slope Ratio").Cells(StartRow, 3), Sheets("Slope
                              Ratio").Cells(EndRow, 3)))
   Row = StartRow
   Do
      Sheets("Slope Ratio").Cells(Row, 4).Value = (Sheets("Slope Ratio").Cells(Row, 3).Value - PSquaredMin) / (PSquaredMax -
                              PSquaredMin)
      Row = Row + 1
   Loop Until Row = EndRow + 1

   'Fill Schroeder Decay Curve
   Row = EndRow
    SchroederSum = Application.WorksheetFunction.Average(Range(Sheets("Slope Ratio").Cells(Sheets("Slope Ratio").Cells(17, 11).Value, 4),
                              Sheets("Slope Ratio").Cells(EndRow, 4)))
   Do
      SchroederSum = SchroederSum + (Sheets("Slope Ratio").Cells(Row, 4).Value / SamplingRate)
      Sheets("Slope Ratio").Cells(Row, 5).Value = SchroederSum
      Sheets("Slope Ratio").Cells(Row, 6).Value = 10 * Log(Sheets("Slope Ratio").Cells(Row, 5).Value / (0.00002 * 0.00002)) / Log(10)
      Row = Row - 1
   Loop Until Row = 6
```

```
   'Calculate Instantaneous Slope
   Row = StartRow
   Do
      Sheets("Slope Ratio").Cells(Row, 7).Value = -(Sheets("Slope Ratio").Cells(Row + 1, 6).Value - Sheets("Slope Ratio").Cells(Row,
                              6).Value) * SamplingRate
      Row = Row + 1
   Loop Until Row = EndRow
   Sheets("Slope Ratio").Cells(EndRow, 7).Value = Sheets("Slope Ratio").Cells(EndRow - 1, 7).Value

   'Calculate Slope Ratio
   Row = StartRow
    SlopeAverage = Application.WorksheetFunction.Average(Range(Sheets("Slope Ratio").Cells(StartRow, 7), Sheets("Slope
                              Ratio").Cells(EndRow, 7)))
   Do
      Sheets("Slope Ratio").Cells(Row, 8).Value = Sheets("Slope Ratio").Cells(Row, 7).Value / SlopeAverage
      Row = Row + 1
   Loop Until Row = EndRow + 1

   'Calculate Transition Time
   Row = StartRow
   Do
      If Sheets("Slope Ratio").Cells(Row, 8).Value > Sheets("Slope Ratio").Cells(16, 11).Value Then
         TransitionTime11 = Sheets("Slope Ratio").Cells(Row, 1).Value
      End If
      If Sheets("Slope Ratio").Cells(Row, 8).Value > Sheets("Slope Ratio").Cells(16, 12).Value Then
         TransitionTime9 = Sheets("Slope Ratio").Cells(Row, 1).Value
      End If
      Row = Row + 1
   Loop Until Row = EndRow + 1
   Sheets("Slope Ratio").Cells(5, 11).Value = TransitionTime11 * 1000
   Sheets("Slope Ratio").Cells(6, 11).Value = TransitionTime11 / Sheets("Room Data").Cells(13, 6).Value
   Sheets("Slope Ratio").Cells(5, 12).Value = TransitionTime9 * 1000
   Sheets("Slope Ratio").Cells(6, 12).Value = TransitionTime9 / Sheets("Room Data").Cells(13, 6).Value
End Sub
```

C.2 Degree of Time Series Fluctuations

```
Public StartRow As Integer
Public EndRow As Long
Public NumRows As Long
Public SamplingRate As Variant
Public SchroederSum As Variant
Public GSquaredSum As Variant
Public HSquaredSum As Variant
Public RTotal As Variant

Sub DecayCancelled()
   'Define Variables
   Dim Row As Long
   StartRow = 7
   SamplingRate = Sheets("Room Data").Cells(19, 6).Value
   GSquaredSum = 0
   RTotal = 0
   SchroederSum = 0

   'Fill Time, Pressure, & Squared Pressure and Define NumRows & EndRow
   Row = StartRow
   Do
      Sheets("Decay Cancelled IR").Cells(Row, 1).Value = Sheets("Room Data").Cells(Row, 1).Value
      Sheets("Decay Cancelled IR").Cells(Row, 2).Value = Sheets("Room Data").Cells(Row, 2).Value
      Sheets("Decay Cancelled IR").Cells(Row, 3).Value = (Sheets("Decay Cancelled IR").Cells(Row, 2).Value * Sheets("Decay Cancelled
                              IR").Cells(Row, 2).Value)
      Row = Row + 1
   Loop Until IsEmpty(Sheets("Room Data").Cells(Row, 1).Value) = True
   NumRows = Row - 7
   EndRow = Row - 1
```

```
  'Set Start & End Row Times
  Sheets("Decay Cancelled IR").Cells(8, 10).Value = Sheets("Decay Cancelled IR").Cells(26, 9).Value
  Sheets("Decay Cancelled IR").Cells(9, 10).Value = Sheets("Decay Cancelled IR").Cells(27, 9).Value
  Sheets("Decay Cancelled IR").Cells(10, 10).Value = Sheets("Decay Cancelled IR").Cells(9, 10).Value - Sheets("Decay Cancelled
                    IR").Cells(8, 10).Value + 1
  Sheets("Decay Cancelled IR").Cells(8, 9).Value = Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(8, 10).Value,
                    1).Value
  Sheets("Decay Cancelled IR").Cells(9, 9).Value = Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(9, 10).Value,
                    1).Value
  Sheets("Decay Cancelled IR").Cells(10, 9).Value = Sheets("Decay Cancelled IR").Cells(10, 10).Value / SamplingRate
  Sheets("Decay Cancelled IR").Cells(13, 9).Value = Sheets("Decay Cancelled IR").Cells(28, 9).Value

  'Fill Schroeder Decay Curve & G Squared
  Row = EndRow
  SchroederSum = Application.WorksheetFunction.Average(Range(Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled
                    IR").Cells(27, 9).Value, 3),
                    Sheets("Decay Cancelled IR").Cells(EndRow, 3)))
  Do
    SchroederSum = SchroederSum + (Sheets("Decay Cancelled IR").Cells(Row, 3).Value / SamplingRate)
    Sheets("Decay Cancelled IR").Cells(Row, 4).Value = SchroederSum
    Sheets("Decay Cancelled IR").Cells(Row, 5).Value = Sheets("Decay Cancelled IR").Cells(Row, 3).Value / Sheets("Decay Cancelled
                    IR").Cells(Row, 4).Value
    Row = Row - 1
  Loop Until Row = 6
  'Calculate Mean G Squared & RT
  Row = Sheets("Decay Cancelled IR").Cells(8, 10).Value
  Do
     GSquaredSum = GSquaredSum + Sheets("Decay Cancelled IR").Cells(Row, 5).Value
     Row = Row + 1
  Loop Until Row = Sheets("Decay Cancelled IR").Cells(9, 10).Value + 1
  Sheets("Decay Cancelled IR").Cells(3, 9).Value = GSquaredSum / Sheets("Decay Cancelled IR").Cells(10, 10).Value
  Sheets("Decay Cancelled IR").Cells(5, 9).Value = 13.82 / Sheets("Decay Cancelled IR").Cells(3, 9).Value

  'Fill H Squared & Calculate Mean H Squared, RTotal, & R(k)
  Row = StartRow
  Do
    Sheets("Decay Cancelled IR").Cells(Row, 6).Value = Sheets("Decay Cancelled IR").Cells(Row, 5).Value / Sheets("Decay Cancelled
                    IR").Cells(3, 9).Value
    If Row >= Sheets("Decay Cancelled IR").Cells(8, 10).Value And Row <= Sheets("Decay Cancelled IR").Cells(9, 10).Value Then
      RTotal = RTotal + Sheets("Decay Cancelled IR").Cells(Row, 6).Value
    End If
    Row = Row + 1
  Loop Until Row = EndRow + 1
  Sheets("Decay Cancelled IR").Cells(4, 9).Value = RTotal / Sheets("Decay Cancelled IR").Cells(10, 10).Value
  Sheets("Decay Cancelled IR").Cells(12, 9).Value = RTotal / SamplingRate
  Sheets("Decay Cancelled IR").Cells(14, 9).Value = (RTotal / SamplingRate) * Sheets("Decay Cancelled IR").Cells(13, 9).Value

  CalculateK
End Sub

Sub CalculateK()
  'Define Variables
  Dim Row As Long
  Dim k As Variant
  Dim kSum As Variant
  Dim EndLoop As Integer
  Dim TempMax As Variant
  Dim TempMin As Variant
  Dim TempSum As Variant
  Dim TempK As Variant
  Dim Interval As Variant
  TempMax = Application.WorksheetFunction.Max(Range(Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(8,
                    10).Value, 6),
                    Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(9, 10).Value, 6)))
  TempMin = Application.WorksheetFunction.Min(Range(Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(8,
                    10).Value, 6),
                    Sheets("Decay Cancelled IR").Cells(Sheets("Decay Cancelled IR").Cells(9, 10).Value, 6)))
```

```
   EndLoop = 0
   TempSum = -100
   k = (TempMax + TempMin) / 2
   TempK = k
   Interval = (TempMax - TempMin) / 200

   'Calculate Minimum k Value
   Do
      kSum = 0
      Row = Sheets("Decay Cancelled IR").Cells(8, 10).Value
      Do
         If Sheets("Decay Cancelled IR").Cells(Row, 6).Value > k Then
            kSum = kSum + (Sheets("Decay Cancelled IR").Cells(Row, 6).Value / SamplingRate)
         End If
         Row = Row + 1
      Loop Until Row = Sheets("Decay Cancelled IR").Cells(9, 10).Value + 1
      If Abs(TempSum - Sheets("Decay Cancelled IR").Cells(14, 9).Value) < Abs(kSum - Sheets("Decay Cancelled IR").Cells(14, 9).Value)
                              Then
         EndLoop = 100
      ElseIf kSum > Sheets("Decay Cancelled IR").Cells(14, 9).Value Then
         TempK = k
         k = k + Interval
         TempSum = kSum
         EndLoop = EndLoop + 1
      Else
         TempK = k
         k = k - Interval
         TempSum = kSum
         EndLoop = EndLoop + 1
      End If
   Loop Until EndLoop = 100
   Sheets("Decay Cancelled IR").Cells(16, 9).Value = TempK
End Sub
```

C.3 Number of Peaks

```
Public StartRow As Integer
Public EndRow As Long
Public NumRows As Long
Public SamplingRate As Variant
Public MaxLevel As Variant
Public MaxLevelTime As Variant
Public MaxLevelRow As Long
Public NumberOfPeaks As Long

Sub NumberPeaks()
   'Define Variables
   Dim Row As Long
   StartRow = 7
   SamplingRate = Sheets("Room Data").Cells(19, 6).Value
   MaxLevel = 0
   MaxLevelTime = 0
   MaxLevelRow = 0
   NumberOfPeaks = 0

   'Fill Time, Pressure, Absolute Value Pressure, & Level and Define NumRows, EndRow, MaxLevel, MaxLevelTime, & MaxLevelRow
   Row = StartRow
   Do
      Sheets("Number of Peaks").Cells(Row, 1).Value = Sheets("Room Data").Cells(Row, 1).Value
      Sheets("Number of Peaks").Cells(Row, 2).Value = Sheets("Room Data").Cells(Row, 2).Value
      Sheets("Number of Peaks").Cells(Row, 3).Value = Abs(Sheets("Number of Peaks").Cells(Row, 2).Value)
      If 20 * Log(Sheets("Number of Peaks").Cells(Row, 3).Value / 0.00002) / Log(10) > 0 Then
         Sheets("Number of Peaks").Cells(Row, 4).Value = 20 * Log(Sheets("Number of Peaks").Cells(Row, 3).Value / 0.00002) / Log(10)
      Else
         Sheets("Number of Peaks").Cells(Row, 4).Value = 0
      End If
```

```
    If Sheets("Number of Peaks").Cells(Row, 4).Value > MaxLevel Then
      MaxLevel = Sheets("Number of Peaks").Cells(Row, 4).Value
      MaxLevelTime = Sheets("Number of Peaks").Cells(Row, 1).Value
      MaxLevelRow = Row
    End If
    Row = Row + 1
  Loop Until IsEmpty(Sheets("Room Data").Cells(Row, 1).Value) = True
  NumRows = Row - 7
  EndRow = Row - 1
  Sheets("Number of Peaks").Cells(4, 8).Value = MaxLevel
  Sheets("Number of Peaks").Cells(4, 9).Value = MaxLevelTime
  Sheets("Number of Peaks").Cells(4, 10).Value = MaxLevelRow

  'Calculate Number of Peaks Below Cutoff Level
  Row = StartRow
  EndRow = MaxLevelRow + (48 * Sheets("Number of Peaks").Cells(15, 8).Value)
  Do
    LocalMax = Sheets("Number of Peaks").Cells(Row, 4).Value
    If Row < MaxLevelRow Or Row > EndRow Or Sheets("Number of Peaks").Cells(Row, 4).Value < (MaxLevel - Sheets("Number of
                    Peaks").Cells(16, 8).Value) Then
      Sheets("Number of Peaks").Cells(Row, 5).Value = 0
    ElseIf Sheets("Number of Peaks").Cells(Row, 4).Value > Sheets("Number of Peaks").Cells(Row - 1, 4).Value And Sheets("Number
                    of
                              Peaks").Cells(Row, 4).Value > Sheets("Number of Peaks").Cells(Row + 1, 4).Value Then
      Sheets("Number of Peaks").Cells(Row, 5).Value = Sheets("Number of Peaks").Cells(Row, 4).Value
      NumberOfPeaks = NumberOfPeaks + 1
    Else
      Sheets("Number of Peaks").Cells(Row, 5).Value = 0
    End If
    Row = Row + 1
  Loop Until IsEmpty(Sheets("Number of Peaks").Cells(Row, 4).Value) = True
  Sheets("Number of Peaks").Cells(6, 8).Value = NumberOfPeaks
End Sub
```