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Quantification of Time Varying Directivity of Musical Instruments

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QUANTIFICATION OF TIME VARYING DIRECTIVITY OF MUSICAL INSTRUMENTS

by

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QUANTIFICATION OF TIME VARYING DIRECTIVITY OF MUSICAL INSTRUMENTS

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Static directivity patterns of musical instruments have been mapped somewhat extensively, but little research has been done in analyzing the directivity patterns of musical instruments over time as they play. Directivity patterns can be affected by variables such as instrument, frequency, dynamics, and style. This thesis proposes a set of quantification methods of time varying directivity, all derived from the maximum Directivity Index analyzed at consecutive short-duration time windows comprising the musical excerpt. The instrumental recordings used in this paper are taken in an anechoic chamber using either a 5, 13, or 32 multichannel setup. From the values of maximum Directivity Index evaluated using the windowing technique, quantifiers including Average Maximum Directivity Index, Average Change in Maximum Directivity Index, Location Change Ratio, Dominance Ratio, and Dominating Location are calculated. In addition to establishing time varying directivity metrics, this thesis looks at how factors such as instrument family, orchestral excerpt, and number of microphone channels used in data acquisition affect the values of the proposed metrics. The importance of understanding time varying directivity patterns of musical instruments as well as architectural

acoustic applications connected to this research are also discussed.

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Chapter 1

Introduction

When attending an orchestral concert, a listener is often able to distinguish between the different musical instruments. There are many factors that play into the unique sound of each instrument. One of these is the directivity. The directivity of a source refers to how the energy from a sound source varies with direction. As a musician progresses through a musical piece and changes notes, dynamics, and articulations, the directivity of the instrument is constantly changing. Previously, there has been little research in understanding and quantifying the time-varying aspect of directivity for sound sources. Static directivities are commonly used for source representation in acoustic simulations. However, these are rough estimations of the true nature of a source's directivity. Developments in understanding the time-varying aspect of directivity may improve the accuracy of sources within room acoustic simulations and auralizations which are essential in the field of architectural acoustics.

In Gabriel Weinreich's paper, "Directional Tone Color", it is stated,

> "Above about 1 kHz, the angular radiation pattern of a violin begins to vary rapidly not only with direction but also with frequency, typically changing drastically from one semitone to the next. In an enclosed space, this characteristic, which we have named 'directional tone color', can sometimes produce the illusion that each note played by a solo violin comes from a different direction, endowing fast passages with a special flashing brilliance" (1997).

Weinreich acknowledges the time-varying nature of the violin's directivity. However, he does not propose a way to quantify the time-varying properties of directivity. By quantifying time-varying directivity, comparisons regarding the extent to which different instruments exhibit this "directional tone color" that Weinreich describes are made possible.

This thesis includes a review in Chapter 2 of musical instrument directivity research including studies related to the effects and applications of directivity. Chapter 3 presents a windowing technique utilized to subdivide the musical excerpt into a set of analyzable time windows at which directional characteristics can be calculated. Previous windowing and quantification methods studied at the University of Nebraska - Lincoln have been further developed into the current proposed set of quantifiers for time-varying directivity. These are introduced in Chapter 4. Using this defined set of metrics, 5 channel recordings of each primary instrument part from Mozart

and Brahms symphonies have been analyzed in Chapter 4, in addition to 13 channel and 32 channel excerpts for select solo instruments in Chapter 5. Findings and recommendations for future work are discussed in Chapter 6. By applying the proposed set of quantifiers to a variety of data, this study analyzes the suitability of using these metrics to make comparisons between or within a variety of musical recordings.

Chapter 2

Literature Review

This chapter presents the fundamentals of directivity including its basic definition and quantification. Additionally, it covers previous research on the static directivities of musical instruments as well as some of the effects of directivity in a musical context. Finally, this literature review discusses the time-varying aspect of directivity including multi-channel measurement and quantification approaches.

2.1 Directivity of a Simple Source

In Long's book on architectural acoustics (2005), Long explains that for a given source, the sound pressure level at a given distance is not necessarily the same in every direction from the source center. This property of how the sound pressure level is varied with direction is called directionality. The directionally dependent changes in sound level based on the particular radiation behavior of a source are known as the directivity. Long explains that the directionality of a source may cause considerable effects, since two sources

with the same sound pressure level may have completely different sound fields due to the directivity patterns. Figure 2.1 shows the polar plot of an arbitrary sound source. The plot represents the level of radiated sound with angular direction, where each line represents a decibel difference relative to the on-axis sound level. Polar plots are commonly used to show the directivity of a source in either the horizontal or vertical plane (Long 2005). While radiation of sound from a monopole is directionally independent, many sources may radiate energy in a particular direction more substantially than others. This effect is known as directivity (Wilson 2006).

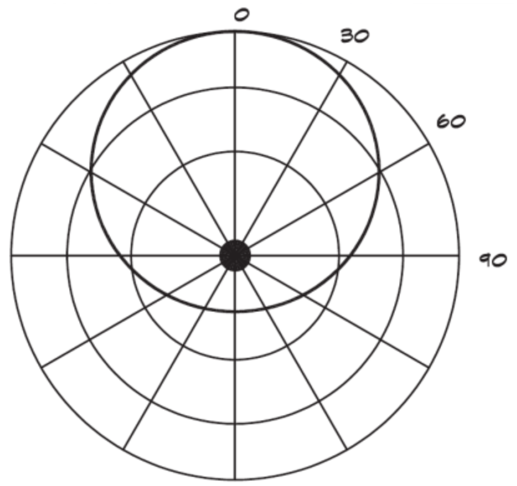

Figure 2.1: Polar directivity plot (Source: Long 2006)

2.1.1 Quantification of Directivity

Polar directivity diagrams such as the one shown in Figure 2.1 are created by plotting the relative sound pressure level in decibels as a function of angle for a specific frequency. Various methods of static directivity quantification are described by Meyer (2009). One way of defining directivity in a quantifiable sense is by specifying the difference in level between the highest and lowest

value on a polar diagram. Alternatively, the angular region corresponding to either halving the energy or halving the loudness may be reported as a method of directivity quantification. The angular region that is within 3 dB of the maximum directivity corresponds to halving the maximum energy while the 10 dB region corresponds to halving the loudness (Meyer 2009).

Another way to quantify static directivity is the front back factor. This is the difference in sound level in decibels between the radiated sound towards the back and towards the front. The front and back values are calculated by taking a mean of the sound levels within 10 degrees of the 0 and 180 degree directions within the polar diagram. Similarly, a front to side factor can also be calculated (Meyer 2009).

The directivity factor, Q, is a very common way to quantify directivity. The directivity factor can be described as "the relation between the sound pressure which is in fact present and that which would be present if the source were replaced by one of the same total output at the same distance but having an omnidirectional characteristic" (Meyer 2009). An alternate way to describe the directivity factor is by Equation 2.1 where directivity factor is a ratio of intensity in a specific direction to the average intensity (Long 2005). In directionality discussions, it is usually the directivity factor for the primary direction of radiation that defines the directionality of a source. However, directivity factor can be reported as a function of angle and applied to any direction of radiation (Meyer 2009).

$$Q(\theta, \phi) = I(\theta, \phi)/I_ave \tag{2.1}$$

In the presented research, the fundamental quantifier for directivity used is the Directivity Index (DI). The Directivity Index is defined as the difference between the sound pressure level measured in a particular direction from a given source and the sound pressure level for an omnidirectional source with an equivalent average sound pressure level such that

$$D(\theta, \phi) = L_p(\theta, \phi) - \bar{L}_p \tag{2.2}$$

where

$D(\theta, \phi)$ is the directivity index (gain) for a given direction (dB)

$L_p(\theta, \phi)$ is the sound pressure level for a given direction (dB)

$\bar{L}_p$ is the sound pressure level averaged over all angles (dB)

θ, ϕ specifies a specific direction in polar coordinates

In terms of directivity factor, the directivity index can be written as

$$D(\theta, \phi) = 10logQ(\theta, \phi) \tag{2.3}$$

where $Q(\theta, \phi)$ is the directivity factor for a given direction (θ, ϕ) (Long 2005).

A spherical sound source that expands and contracts symmetrically is described as having an omnidirectional characteristic. The directivity factor for such a source suspended in a free field is 1 while the directivity index is 0 dB. For general sources, this type of directionality generally only holds at low frequencies for which the sound source is small compared to the wavelength

the source is radiating (Meyer 2009). At higher frequencies, omnidirectionality no longer holds, and directional patterns become more apparent.

2.2 Directivities of Musical Instruments

The complexity of musical source directivity through time is acknowledged by Chiang et al. through the explanation that there is a great deal of difficulty in considering the fine details associated with the directional patterns of true musical sources since the directivity may change along with variance in factors such as frequency range, dynamic levels, and tones that are played (Chiang et al. 2008). In research application, Chiang et al. greatly simplify musical directivities using directivity factors. Their analysis of directivity factors indicates that directivity generally increases with increasing frequency. The directivity factor for high frequency components for strings, woodwinds, and vocalists is around 2 or 3 in the primary direction of radiation while it is generally greater than 4 for brass instruments.

Meyer described qualities of orchestral instruments including dynamics and timbre in addition to directionality (1993). Directionality can be largely affected by variables such as dynamics and tone quality. Dynamics and tone color of musical instruments are also directly related to room acoustics, since room absorption is frequency dependent, as are timbre and dynamics. Regarding dynamics, Meyer explains that dynamic range of a musical instrument depends on the particular playing technique. For example, a fast passage has different dynamic range limits than a long, held note. Strings are

typically softer than both woodwinds and brass, while woodwinds are generally about 10 dB softer than brass instruments. Higher pitched instruments have stronger overtones relative to the main components, especially the violin and the oboe. Timbre of an instrument changes as the overall dynamic level varies. This effect is most prominent in brass instruments. An increase in 1 dB of overall dynamic level results in a level difference of more than 3 dB between 3000 Hz components and the strongest components, while the same overall level increase in dynamic level results in a 1.2 to 2 dB component difference for woodwinds. The component level difference is even smaller for strings, about 1.1 dB. Meyer also discusses how directivities of musical instruments affect the overall sound of the orchestra. Essentially, omnidirectional radiation patterns disappear for orchestral instruments above 500 Hz, and the omnidirectional radiation spans about one octave for each instrument at the lowest frequencies. The specific omnidirectional radiation frequency ranges by instrument are shown in Figure 2.2 (Meyer 1993). Within this region of omnidirectionality, time-varying properties are somewhat negligible and of little interest to an investigation of time-varying directivity.

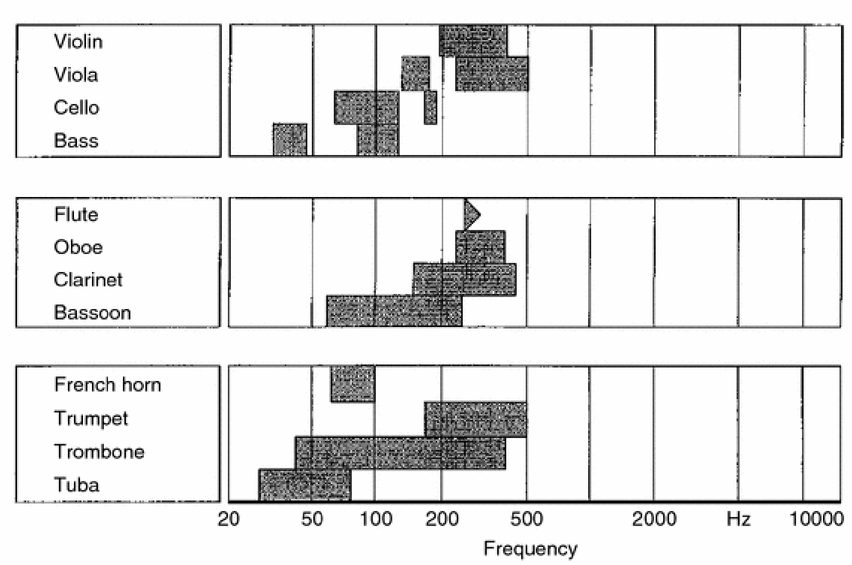

Figure 2.2: Frequency range of omnidirectional sound radiation by instrument (Source: Meyer 1993)

Extensive research has been conducted on the static directional properties of specific musical instruments as well as general instrument groups for different frequency ranges. Meyer only specifies that his measurements were made in an anechoic chamber using a microphone distance of 3.5 meters. Results were plotted using angular radiation plots (Figure 2.3) as well as histograms corresponding to the radiation directions (Figure 2.4) (Meyer 2009).

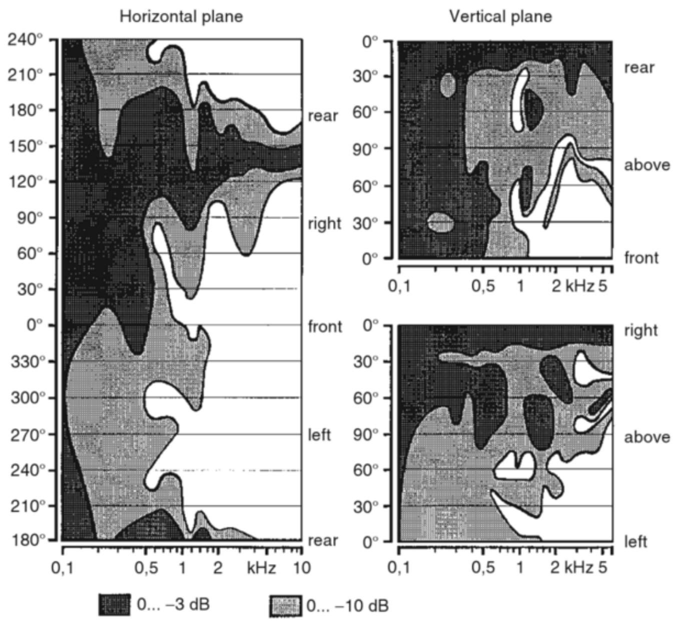

Figure 2.3: Angular radiation of the principal radiation regions for the French horn with player (Source: Meyer (2009)

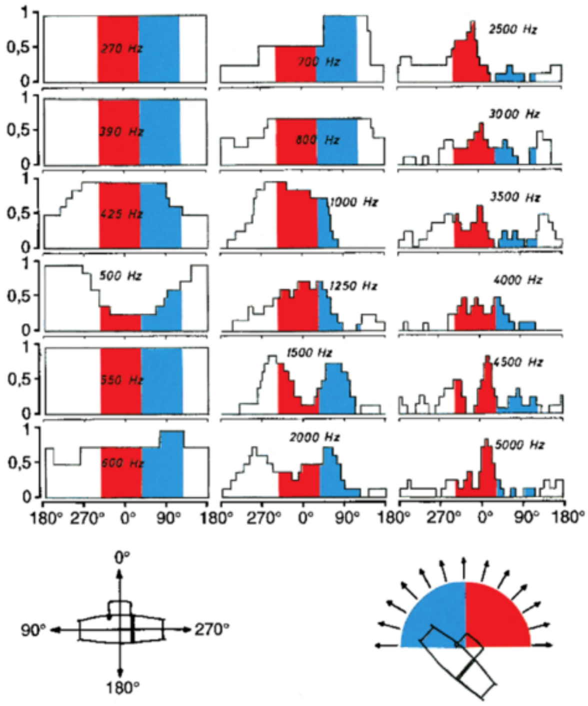

Figure 2.4: Histogram of principal radiation regions for the violin (0-3 dB) (Source: Meyer 2009)

For Pätynen and Lokki's measurements (2010), 14 orchestral instruments were recorded in an anechoic chamber using 22 microphones such that 20 of the microphones were positioned in a dodecahedron shape around the instrumentalist, and the other two microphones were positioned above and in front of the musician. The average distance between each microphone and the center of the room was 2.13 m. Pätynen and Lokki emphasize the importance of the musician's effect on the instrument's radiation pattern in their measurements. Pätynen and Lokki plotted radiation of single tones and normalized sound levels to 0 dB to illustrate average instrument directivities of all tones recorded (Figure 2.5). Additionally, octave bands in median, lateral, and transverse planes were plotted for each instrument to illustrate the overall directivity (Figure 2.6).

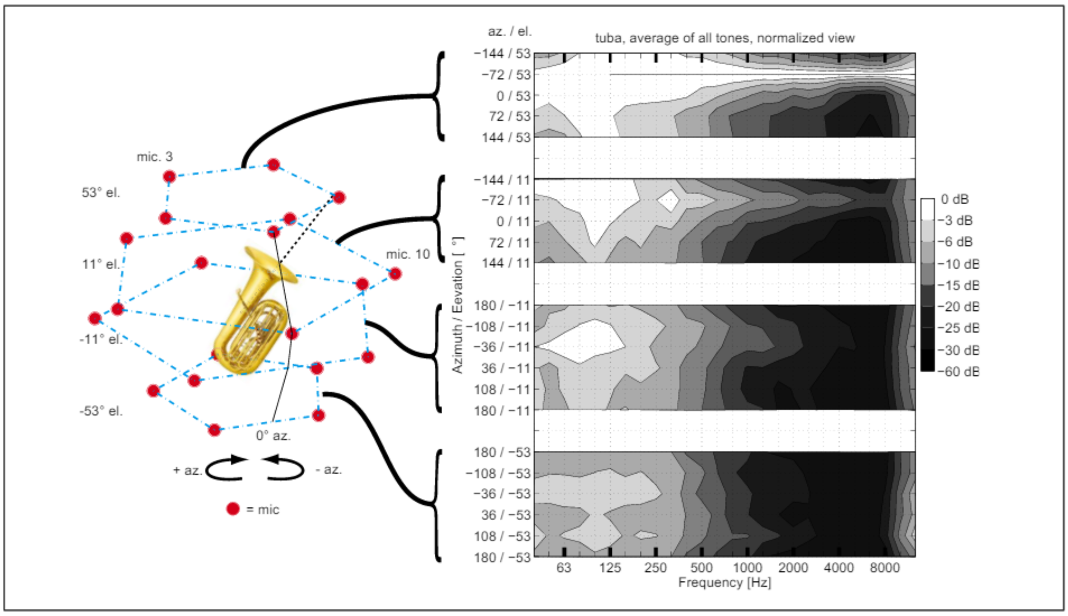

Figure 2.5: One-third octave band instrumental radiation with 0 dB normalization for the tuba (Source: Pätynen and Lokki 2010)

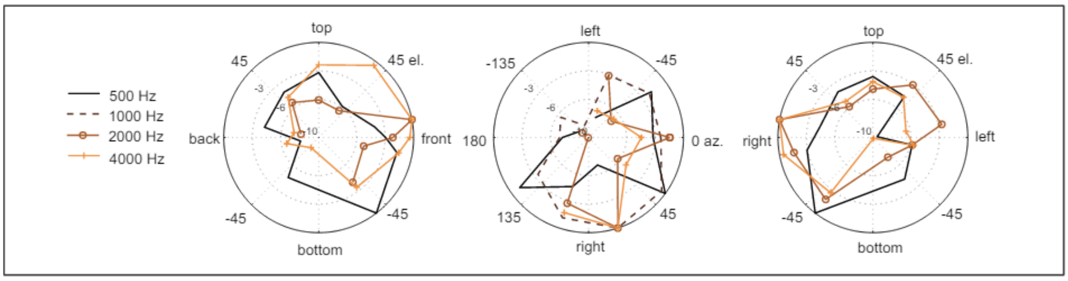

Figure 2.6: Polar directivity plots in median, lateral, and transverse planes for the flute (Source: Pätynen and Lokki 2010)

The overall static directivity conclusions made about the orchestral instruments are nearly the same for the research done by both Meyer (2009) and Pätynen & Lokki(2010), and are described in detail in the following sections.

2.2.1 Woodwinds

The woodwind group is unique in that the sound production device varies widely within this group. The major similarity is that the pitch is changed by altering the effective length of the instrument pipe. The flute behaves as a dipole with energy mainly radiating from the mouthpiece and the first additional open hole on the instrument. Thus, sound is produced by forming a Helmholtz resonator within the instrument. The open finger holes radiate the majority of the sound at mid frequencies while the open end of the instrument is the main radiator of the sound for higher frequencies. The piccolo behaves similarly to the flute in its radiation characteristics. With the oboe, the reed is not a sound radiator. Because of this, the oboe does not act as a dipole like the flute does. One major feature of the oboe's directivity pattern is a four

leaf clover directional characteristic in certain regions. Another major feature of the oboe's directional patterns is the large amount of screening of the sound by the player due to the small size and the particular playing position of the instrument. The clarinet has similar directional characteristics to the oboe. One of the main differences between the clarinet and the oboe is that the clarinet is cylindrical while the oboe is conical. Thus, the even harmonics of the clarinet are attenuated. Another difference with the clarinet compared to the oboe is that the clarinet experiences less screening from the player, as the clarinet is larger and held at a steeper angle compared to the oboe. The bassoon has some similarities to the oboe, as it is also a double reed instrument. This includes the clover-like radiation patterns present in some frequency regions. In general, the overall characteristics present in the oboe directionality patterns are shifted to lower frequencies for the bassoon (Pätynen & Lokki 2010, Meyer 2009).

2.2.2 Brass

Directivity indices for brass instruments generally reach much higher values than for woodwinds, notably in upper frequency regions. For most brass instruments, the directional effects are primarily based on the shape and size of the bell of the instrument. For the trumpet, the directional characteristics exhibit rotational symmetry around the axis of the bell. Above 2000 Hz, the trumpet has very directional, well-defined energy propagation on the axis of the instrument along with minor lobes to the back and sides. The trombone exhibits directional characteristics that are generally very similar to those of

the trumpet. However, due to the larger bell size, these characteristics are shifted slightly downward. Overall, the trombone is less directional than the trumpet. The tuba exhibits spherical directional patterns only below 75 Hz. The directionality tendencies of the French horn are more complex than other brass instruments. The sound of the French horn is determined not only by the bell shape and size, but also by the hand of the player in the instrument. Also, the instrument itself is held close to the body of the player which adds more diffraction. Unlike other brass instruments, the French horn is held to the side. Thus, the energy to the back is greater than the energy to the front. When the bell of the horn is stopped with the player's hand, the instrument is less directional than when played unstopped. Because of the complexity of the instrument in playing position, the instrument and the player are considered as one unit in discussions of directionality patterns. In general, changes in dynamics have a relatively large effect on the spectrum of brass instruments, as louder dynamics excite more overtones. Thus, played dynamics may have a significant effect on the directional characteristics of brass instruments (Pätynen & Lokki 2010, Meyer 2009).

2.2.3 Strings

Stringed instruments are generally more complicated than woodwinds and brass when it comes to discussing their directivity patterns. Unlike many of the wind instruments, the stringed instruments are not shaped such that the sound is necessarily directed in a certain way. Directivity tendencies of a stringed instrument are largely dependent on the wood and how the

instrument is constructed, which can lead to significant differences in directivity patterns from instrument to instrument. As Meyer points out, the directional characteristics of stringed instruments do not have directivity patterns that align with certain frequencies as clearly as found with brass instruments (2009). Additionally, angular changes in directivity are extremely prevalent as the frequency of interest changes. Within the frequency range of about 400 to 550 Hz, the violin can have main radiation directions upwards, downwards, and equally to the sides depending on slight frequency changes. Unlike the brass instruments, dynamics have little effect on directivity for the string instruments. As one would expect, the viola has similar directional characteristics to the violin. At high frequencies, the cello has two narrow principal lobes of radiation. The double bass shows definite directional characteristics even at very low frequencies (Meyer 2009).

Some of Meyer's research involves stringed instruments in particular (1972). Directivity and instrument placement affects the ratio of reverberant to direct sound. This preferred ratio differs depending on the type of music. Directionality measurements of stringed instruments were taken in an anechoic chamber by standing the instrument on a turntable, damping the strings, and exciting the body of the instrument using an electrodynamic oscillation system with a sinusoidal voltage. The system used a vibrating needle pressed into the bridge of the instrument such that the needle vibrates as the bow of the player would in a typical playing situation. The sound pressure level radiated from the instrument was then measured using a microphone placed 1 meter

from the violins and violas and 3.5 meters from the lower strings. By coupling the recorder with the turntable that the instrument was standing on, polar diagrams were created (Meyer 1972). Data obtained from this experiment was initially analyzed by examining the 3 dB angular range, or the angular range where the sound pressure level from the instrument is within 3 dB of the maximum level recorded. According to Meyer, although a 3 dB difference in loudness is hardly perceptible and seems insignificant, a 3 dB variation can influence the timbre of an instrument. Additionally, a difference in 3 dB can be the difference between whether or not an instrument is masked within an ensemble. Radiation direction was plotted using angular radiation histograms much like the plot shown in Figure 2.4 using angular measurements in the plane of the bridge. At low frequencies, all of the stringed instruments exhibited omnidirectional propagation patterns. Directional results characteristic to the physical violin help explain the difference in sound between the first and second violins in a concert setting (Meyer 1972).

As mentioned in Chapter 1, Weinreich (1997) describes the violin as having flashing brilliance and directional tone color as the violin plays. Weinreich goes into some detail regarding factors that may affect the directivity of an instrument over time, particularly for the violin. One of the musical elements influencing directivity patterns is vibrato, which involves modulation of both frequency and amplitude of the played note. On a violin, this is achieved by a rocking motion of the left wrist on the neck of the violin. As Weinreich explains, “since the peak-to-peak frequency range covered by a typical vibrato

can exceed three-quarters of a semitone, we now see that the result will be a strong modulation of the directional radiation pattern as well" (Weinreich 1997).

A discussion of experimentally measured instrumental static directivity patterns provides background about what is currently known about the directional characteristics of individual musical instruments across different frequencies. This brings up questions regarding the effects of directivity on topics such as musical performance quality and room acoustics.

2.3 Effects of Directivity in a Musical Context

Changes in directivity cause variation in overall perceived loudness, spectrum, and timbre at a receiver position (Meyer 2009). These characteristics may impact acoustical parameter values such as clarity, strength, and early decay time as well as the preferred relative placement of instrumental sections on the stage. Additionally, the application of directivity characteristics can affect the realism of computer simulations.

2.3.1 Acoustical Parameters

In studying the acoustics of a built performing arts space, there are usually multiple measurements taken for metrics such as Reverberation Time (RT), Clarity Index (C80), and Interaural Cross Correlation (IACC) at several receiver positions around the hall with respect to a few onstage source locations. Prince and Talaske (1994) tested specific source directivities and

stage locations to examine their effect on room acoustic measurements. In the study, 54 source locations based on typical instrument locations were used. Both omnidirectional and directional loudspeakers were tested at each location with a Maximum Length Sequence. In addition to these, a "measurement violin" was used to represent a more realistic instrumental source. The responses were measured at two receiver locations, which showed the same order of variance in the results of measured parameters. The room acoustic metrics evaluated included Reverberation Time (RT), Early Decay Time (EDT), Clarity Index (C80), Early Reverberation Time (ERT), Middle Reverberation Time (MRT), and Later Reverberation Time (LRT). The measured RT values showed no significant variation with source position and type. However, unlike measurement results for the omnidirectional source, early reflections were greater than or equal to the level of direct sound in the room for the directional source (Prince & Talaske 1994). With the measurement violin, the C80 was about 1.5 dB lower than the C80 with the omnidirectional source. This difference can be attributed to the lower direct sound energy level of the measurement violin in the direction of the receiver. Prince and Talaske conclude that the effects of directionality as well as spatial separation of sources are necessary factors to take into account in simulation of musical sources, as the results from their tests suggest that differences in source and position are easily perceptible.

Martín et al. examined the influence of source orientation on acoustical parameters derived from room impulse responses (RIR) (2007). In practice,

RIRs are made using a loudspeaker that is as omnidirectional as possible. While the speakers chosen to carry out these tests should fall within constraints outlined by the ISO 3382 standard (ISO3382), the loudspeakers tend to still have slight directional deviations. As Martín et al. explain, while reverberation time is unaffected by slight directional differences, other acoustic parameters related to the time structure of the RIR may be affected by source orientation to a greater extent. The study aimed not to propose a new way to measure halls, but rather to show that measurements taken with directional sources may introduce differences in measurements that are not the result of random effects. For each source-receiver combination, 24 different source orientations were assessed using two dodecahedron omni-directional loudspeakers. Acoustic parameters examined included Reverberation Time, Early Decay Time, Clarity, Sound Strength, Lateral Fraction, and Interaural Cross-Correlation Coeffecient. It was found that up to 500 Hz, the influence of the source's directivity is fairly low, while above 1 kHz, all of the tested parameters except Reverberation Time showed deviances greater than the just noticeable difference. Thus, source orientation and directionality have a significant influence on acoustic parameters at high frequencies above 1 kHz, even when the source is a dodecahedron loudspeaker. This is due to the lobe shape of the source directivity and where the receiver is positioned with respect to the minimum and maximum directions of the source (Martín et al. 2007).

Chiang and Lin performed computer simulations using a basic room form

with a volume of approximately 4000 cubic meters and an audience area of 430 square meters (2008). Using this room model, elements such as surface treatments, length-to-width proportion, seating arrangement, and platform location were evaluated along with various directivities to determine optimal room conditions relative to source directivity. Acoustical parameters dealing with acoustic support for the performers were disregarded in this study. In addition to the first room model, three additional room forms were used in the simulations. Simulations of each room were done using CATT acoustics V8.0 software packages with three sources including an omni-directional source, a baritone singer, and a violin. Experiments involving variables of room proportion and existence of side box seating were combined with aiming a baritone source at both 0 and 45 degree azimuth angles. The length-to-width ratio of the hall had little effect on early sound strength (G_E) for the 0 degree angle but caused a drop of $G_E = 1.2$ dB for the 45 degree angled source. The length-to-width ratio became less important for a turned source when platform walls and terraced seating were placed in specific arrangements. The inclusion of side audience boxes increased G_E by 0.4 dB for the 45 degree angled source. Results of Chiang and Lin's study concluded that source directivity becomes more of a concern when the overall proportion of seats close to the platform is large, thus is more important in the design of smaller recital halls (2008).

2.3.2 Directivity and Stage Position

Directivity can be an important factor in deciding seating arrangement of instruments in a hall. This is thought to be particularly important for wind

players (Meyer 2009). Although Meyer (1993) does not directly discuss the effect of stage setup on directivity, he does emphasize the effect that stage position can have on dynamics. Meyer states that the specific level at which an individual plays is dependent on the perceived level of the orchestra for that player. In other words, an instrumentalist's dynamic playing level is dependent on the levels heard at that player's position from the other instruments in the orchestra. Because directivity patterns of an instrument can cause level differences with position, instrument directivities may ultimately affect the overall sound power level of the orchestra (Meyer 1993). It is generally accepted that acoustical properties of a room largely affect the dynamic range of an orchestra, but is important to realize that this is not the only variable in the sound level of an ensemble. Various methods of placement of string sections in particular within an orchestra are discussed further in Meyer's earlier work (1972).

2.3.3 Time Varying Frequency Spectra

Beauchamp acknowledges the importance of time variance when he states, "while many persons hear musical-instrument tones simply in terms of fixed pitch, loudness, and tone color, closer listening indicates that they are, in fact, constantly changing in their physical attributes throughout their duration" (Beauchamp 1974). In his University of Illinois study beginning in 1966, Fourier spectrum data were analyzed for a violin. The violinist played 57 tones in an acoustically dead room varying in pitch and dynamics. Each tone was analyzed using a computer Fourier analysis program to derive parameters

of fundamental frequency, harmonic amplitudes, and harmonic phases for the tone over time. In observing these parameters over time, the effect of vibrato on spectra over time was better analyzed. It is known that vibrato affects the spectra by making the partials sharper compared to the partials of a flat tone. The results showed additional time-varying spectra content of vibrato tones found in the form of phase and amplitude modulations. For some tones, frequency modulation between harmonics varied as little as 0.7% while variation in percent frequency modulation was much larger between harmonics of other tones analyzed. Attack and decay rates were calculated by analyzing the level differences of tones over time. These rates were measured in dB/s and range from 270 dB/s and 2300 dB/s for the tones analyzed. Attack and decay rates were found to vary depending on the harmonic and overall dynamic. These effects are noticeable for some harmonics and tones more than others (Beauchamp 1974).

Current knowledge of directivity acknowledges that radiation patterns of instruments behave differently depending on both frequency and dynamics. Radiation patterns have been quantified for held notes across a wide frequency bands, and it is understood that variables such as pitch and dynamics affect directivity patterns at a static levels. Observing the nature of spectra changes for vibrato tones of the violin can be beneficial in recognizing vibrato tones as another variable affecting the time variance of directivity.

2.4 Computer Room Simulation and Perception

Just as source directivity may affect measured acoustical parameters in a space, source directivities used in computer room simulations can affect the results of calculated acoustic parameters and the accuracy of models. Source directivity is an important aspect of room acoustic computer modeling in architectural acoustics. Simplifications of sources are often used, as source directivity is complex. This section looks at studies involving the importance of source directivity and how computer simulations, auralizations, and realism are affected by the source radiation patterns used.

2.4.1 Perceptibility of Directivity

Caussé et al. (1992, 1994, 1995) studied the link between auditory perception and musical source directivity and radiation patterns. The experiment involved controlling the Directivity Index using a synthesized source consisting of twelve loudspeakers mounted to a dodecahedron to reproduce the pressure field. Directivity index was controlled for by the synthesized source with a programmable DI range of 0 - 10 dB for each loudspeaker, and perceptual differences were compared to a real trombone and clarinet. Results from the experiment showed that people are sensitive to differences in directivity indices, and the value of the Directivity Index is strongly linked to the perceptual characteristics of a source.

Otondo and Rindel examined room simulation accuracy by comparing the results from using measured source directivity versus directivity averaged over octave bands by instrument that is typically used in computer simulations (2004). In doing this, Otondo and Rindel examined the level of accuracy of simulations using averaged directivities as well as the degree to which radiation patterns may affect acoustical parameters in a room. They point out that most of the musical instrument directivity data used in room acoustic simulations and auralizations are octave band averaged directivites for each instrument from research done in Jürgen Meyer's studies (1972, 1993). In Otondo and Rindel's paper, musical instrument performance directivity was measured and compared to typical averaged room simulation directivities. A Bb clarinet, a Bb trumpet, and a French horn were recorded using 13 flat response electret mircrophones in 45 degree intervals spaced 1 m from the source in an anechoic chamber. A 24-bit quantization and 44.1 kHz sampling rate were used. Short isolated tones of about 700 ms were recorded, and the recordings from the 13 microphones were post-processed and filtered into octave bands 125 - 8000 Hz in order to recreate directivities. From here, octave band averaged directivity and the measured directivity of individual tones were compared by generating two separate room simulations for a listening test. A qualitative forced choice comparison for loudness, perceived reverberance, clarity, sound localization, and timbre difference was done using eleven test subjects. A McNemar test was used to analyze the statistical significance of results. Otondo and Rindel found that while some of the acoustic parameters turned out to be similar in the different room simulations,

others were not. In the listening tests, all of the subjects were able to perceive a difference in the loudness parameter. The results for reverberance perceptibility were significant for two-thirds of the instruments tested while the perception of clarity differences was significant only for the simulations involving the French horn. While some of the acoustical parameters showed little differences, Otondo and Rindel's results point out that instrument directionality as it varies through time indeed has some effect on the accuracy of acoustical parameters and room simulations.

Building on Otondo and Rindel's work, Vigaent et al. (2008) studied improving auralizations by incorporating source directivities in ODEON computer models using a multi-channel approach. The sources used included multi-channel anechoic recordings of short musical excerpts for a piano, violin, and singing voice as well as an omnidirectional source and a 1/16 sphere slice highly directional source. The five source types were combined with three source and three receiver positions for a total of 45 simulation scenarios. Auralizations created in an ODEON model were used in a subjective pair-wise comparison test with 28 subjects. Perceptability in realism, reverberation, and clarity were found to be statistically significant for only the omnidirectional and 1/16 directional sphere sources. Realistic instrument and omnidirectional source directivities showed only slight differences, but omnidirectional radiation was used for octave bands that did not have data, and static directivities were used. Static directivities are used as approximations for instruments. Incorporating a time aspect may provide increased realism.

Additional research on reproduction of source directivity in computer auralizations has been conducted by Schmidt (2011) and Feistel & Ahnert (2005). Schmidt used a system involving directivity data every 10 degrees around a musical instrument for simulating directivity in the program, CATT-Format SD1. Challenges associated with directivity simulation such as choosing a reference direction are discussed. Schmidt also highlights the importance of considering the musician's effect on the radiated sound when implementing directivities in room simulations (2011). Feistel and Ahnert evaluated the error associated with different methods of loudspeaker measurement. It was found that using phase data reduces the amount of measurement error (2005). Considering the large interest in computer simulation and improved accuracy of the radiation patterns of sources, quantification of time-varying directivity has promising applications.

2.4.2 Multi-Channel Auralization

Otondo and Rindel proposed a new way to create auralizations of sources with time-varying directional characteristics in a performance setting within a room (2005). They acknowledge the complexity of the directivity of musical instruments, and admit that even fixed directivity patterns per octave are a poor representation of the true time-varying properties of the directivity of musical sources. The proposed technique includes a 4-track recording system where each source corresponds to a quarter of a sphere. Using this method, the source used in the auralization is a new source consisting of four virtual sources, each radiating in a way distinguishable to that particular direction as

recorded with one of the four microphones. The expectation with the introduction of this recording concept is that incorporating a multi-channel auralization approach may increase the realism and reliability of acoustic simulations (Otondo & Rindel 2005).

In another study by Vigeant et al. (2011), subjective tests were carried out using the multi-channel auralization technique to analyze how this method affects the realism of a musical source. The three modeled sources included an omnidirectional source as well as an omnidirectional sources divided into four and thirteen parts. Thirteen channel recordings of a violin, flute, and bass trombone used the 1, 4, and 13 source models to create auralizations in ODEON. Thirty subjects analyzed both realism and the perceived source size on a seven point scale for each combination of instrument and source configuration, and analysis of variance (ANOVA) was used to analyze the significance of the results. It was found that as the number of channels used increased from 1 to 4 to 13 channels, realism also increased, especially for more directional instruments. Additionally, a higher number of channels resulted in subjects being better able to distinguish between source orientations. Although realism increased for multi-channel auralizations of a single source, it was found that multi-channel auralizations had no significant benefit over single-channel auralizations for the case of multi-source simulations. Thus, a multi-channel auralization approach appears more promising for a single player than for an entire orchestra (Vigeant et al. 2011). Although a multi-channel recording and auralization technique was

used to incorporate time-varying directivity, analysis of the change in spatial characteristics over time was not studied.

A more complex multi-channel high spatial resolution acoustic directivity acquisition system (ADAS) has been developed by the Brigham Young University Acoustics Research Group (Eyring 2013). This method involves the rotation of a musical instrument in sequential steps under a fixed array of microphones positioned along a semicircular arc. Data acquisition using this method allows for highly detailed multi-channel directivity measurements. Using this ADAS, animations of flute and tenor trombone directivities have been simulated and analyzed (Eyring et al. 2014a, 2014b). Acoustic directivity acquisition systems such as this may be a useful tool in provided recordings for further development of time-varying directivity quantification methods. This method has provided the ability to create animations to visualize directivity patterns of musical instruments over time. However, these directivity patterns have not been quantified over time. Quantification methods may provide a better understanding for how instruments compare in the level of variance in their directivity patterns over time.

Aspock and Vorländer (2015) developed a virtual reality real-time simulation model that accounts for room acoustics and source directivity to create a realistic use experience. Image source modeling and ray tracing were used to generate a binaural room impulse response to be used with an anechoic sound file such as a musical instrument recording. The generated room acoustic field

is combined with a visual 3D SketchUp model, and provides the ability to vary source position and directivity within a room model. The combined visual and audio model allows for a user to experience a realistic simulation of the effects of changing source location and directivity. The time-varying aspects of directivity are relied on for increased realism in the simulation, but the simulation model lacks a way to quantitatively compare real-time instrument directivities. The source directivities used for immersive environment simulations at the Institute of Technical Acoustics at RWTH Aachen University are multi-channel recordings created using a 32 channel pentakis dodecahedron setup (Reuter 2008). These recordings provide another example of the acquisition of detailed time-varying directivity recordings, but not specifically quantified for their time-varying qualities.

2.5 Time Varying Directivity Quantification

In previous research at the University of Nebraska - Lincoln, quantification methods of the time-varying properties of musical instrument directivity were investigated using twenty-second long anechoic recording excerpts of a violin, flute, and bass trombone recorded with 13 microphones (Buck 2013). For each 1 s time window, the directivity for each microphone was averaged over the 1 s time frame. The DI for the maximum of the 13 microphones was plotted at that second, and the time window was shifted by 0.5 s such that the windows were overlapped. The microphone at which the maximum was located was also noted. The method of analysis provided data at each 1 s of the excerpt. Using this data, quantification methods proposed by Buck include Average

Maximum Directivity Index (DI) and a count of how often the maximum channel changes over the excerpt. Additionally, Buck analyzed the standard deviation, range, and the average change in DI over the 20 s excerpt. Using the count of change in channel of maximum DI, the number of adjacent microphone changes and nonadjacent microphone changes were quantified separately in order to better separate more extreme changes in the location of maximum DI. Average Change in DI calculated by octave band for the entire excerpt was found to be the preferred metric for quantification of time-varying directivity with the 1 second windowing method used for the 20 second musical excerpts, as it was thought to best represent time variance (Buck 2013). Thus, the Average Maximum DI and Average Change in DI metrics are included in further development of quantification methods within this thesis. Limitations of Buck's research include a lack of a versatile quantification method of spatial changes. Additionally, Buck's research did not include an analysis of the effect of temporal windowing length on the quantifiers studied. These topics will be addressed in this thesis.

2.5.1 Summary

This chapter has covered background regarding fundamentals of directivity, previous research on the static behavior of instrumental directivity, and effects of directivity in a musical context. Information regarding factors influencing time variance, measurement approaches, and quantification systems were provided. Starting with the preliminary methods established by Buck, this thesis seeks to define metrics for quantifying time-varying directional

characteristics that are more easily interchangeable for recordings varying in number of channels. The use of much smaller timing windows is evaluated. With the increased detail, additional emphasis is placed on quantifying spatial directional changes in addition to changes in magnitude of the maximum Directivity Index. The proposed metrics are then applied to orchestral excerpts to observe how an established set of metrics can assist in the comparison of time-varying directivity between instruments and excerpts.

Chapter 3

Time Window Length Comparison

3.1 Window Technique

In order to analyze directivity of a musical instrument as it varies through time, a time windowing technique is applied (Buck 2013). Maximum Directivity Index and the direction associated with that Maximum Directivity Index are evaluated over a time window of specific length, based on data recorded from an array of microphones placed around an instrumentalist ideally in an anechoic chamber. After the directivity is analyzed for the first time window, the window of defined length (L) is then shifted by some set amount (typically some fraction of L) in order to evaluate the directivity at the next window of interest. Figure 3.1 shows the L = 1s window length and L/2 = 0.5s overlap used by Buck (2013) for the first three windows. This technique allows for evaluation of Maximum Directivity Index at small

intervals as the excerpt progresses through time with a data point for every L/2 seconds. The overlap of the windows improves the accuracy of the windowing technique, as any variation near the edges of a particular window are less likely to be missed. Spatial direction is quantified by identifying the specific recording channel that the Maximum Directivity Index is associated with for each window.

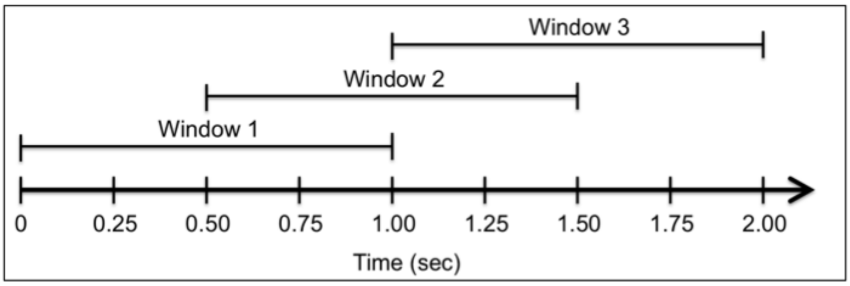

Figure 3.1: Windowing technique (Source: Buck 2013)

Time varying directivity quantification results can be influenced by the specific window length used in analysis. In general, a shorter window length gives more detail about intricate patterns or brief events related to the instrument's directivity. By selecting a standard window length to be used in future evaluation of time-varying directivity, variables in the analyzed recordings such as instrument and excerpt are more easily evaluated and compared. This chapter presents a preliminary evaluation of the time-varying directivity metrics proposed by Buck (2013) of Average Maximum Directivity Index and channel of maximum Directivity Index, using various time windowing lengths to determine the extent of the effect of window length on the results.

3.2 Musical Instrument Anechoic Recordings

3.2.1 Solo Excerpts - 13 Channels

Anechoically recorded excerpts of solo musical instrument were used in the initial window length study. The 13 channel recordings were previously carried out in an anechoic chamber by Otondo and Rindel (2004) with an approximate volume of 1,000 m^3 at the Technical University of Denmark and used by Vigeant et al. (2011). The microphone channel arrangement is shown in Figure 3.2. The recordings were made using flat response electret microphones at 45 degree angles in the horizontal and vertical planes. The microphones were spaced 1.5 m from the sound source. A 44.1 kHz sampling rate and 24-bit quantization were used. The particular microphone locations were chosen in a way that allows radiation changes in both the horizontal and vertical directions to be observed. The expectation was to obtain a sample of the radiation in each direction rather than a radiation pattern that provides complete detail, as the original intention of the recordings was for use in room simulation software. The particular instruments analyzed by Buck (2013) included solo excerpts for violin, bass trombone, and flute. These three instruments were chosen to represent the three major groups of instruments, with the violin for the string group, flute for the woodwinds, and the bass trombone for the brass. Although each instrument has its own unique directional tendencies, examining one instrument from each group can give a general idea of directivity trends for each instrument group as well as a general idea of the dispersion of values. For the window length study in

particular, the main concern with the results is differences due to changes in window length rather than the differences seen between the specific instruments themselves. The 13 channel recordings for these same three instruments, violin, flute, and bass trombone, are used in this chapter's investigation and throughout this thesis.

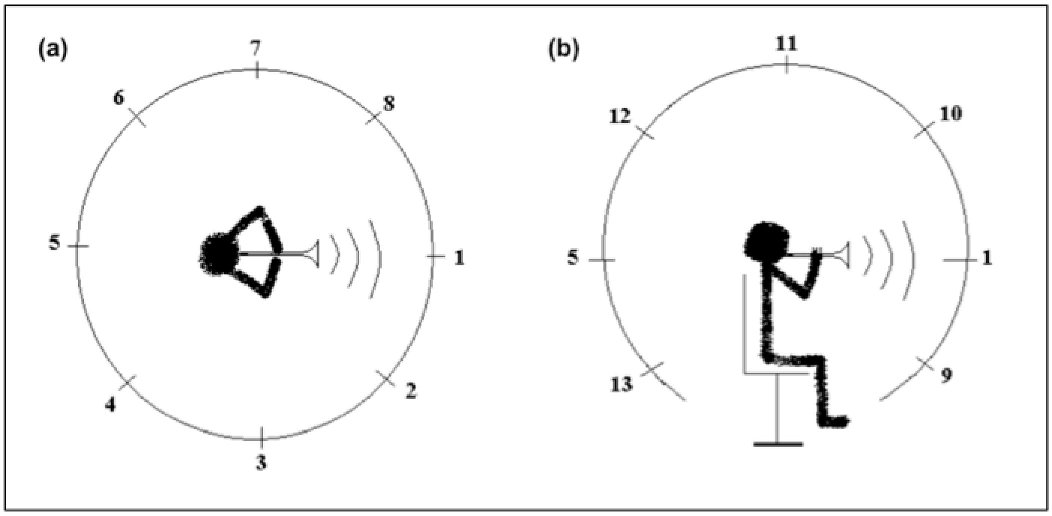

Figure 3.2: Microphone positions for thirteen channel anechoic recordings (Source: Otondo and Rindel 2004)

3.2.2 Individual Instrument Parts in Orchestral Excerpts - 5 Channels

Five channel recordings were also previously obtained in the same anechoic chamber at the Technical University of Denmark as shown in Figure 3.3 and used by Vigeant & Wang (2008). The five channel data involved recording each orchestral instrument playing that instrument's individual part from a symphonic piece. The symphonies recorded were Mozart's Symphony No. 40 in G minor, K.550: Mvmt. 1 and Brahms' Symphony No. 4 in E minor, Op.

98: Mvmt. 3. The sheet music for the first 82 bars of the Mozart and the first 107 bars of the Brahms are shown in Appendix A.1. The instrumentalists were members of the Tivoli Symphony Orchestra in Copenhagen, Denmark. To assist with timing between instrumentalists, each musician played their part while listening to the full orchestra parts over headphones and watching a video recording of a conductor. All of the instruments were recorded with five microphones with the exception of the double bass. Due to the height of the double bass, the overhead microphone location was excluded, so only four channels were acquired for this instrument.

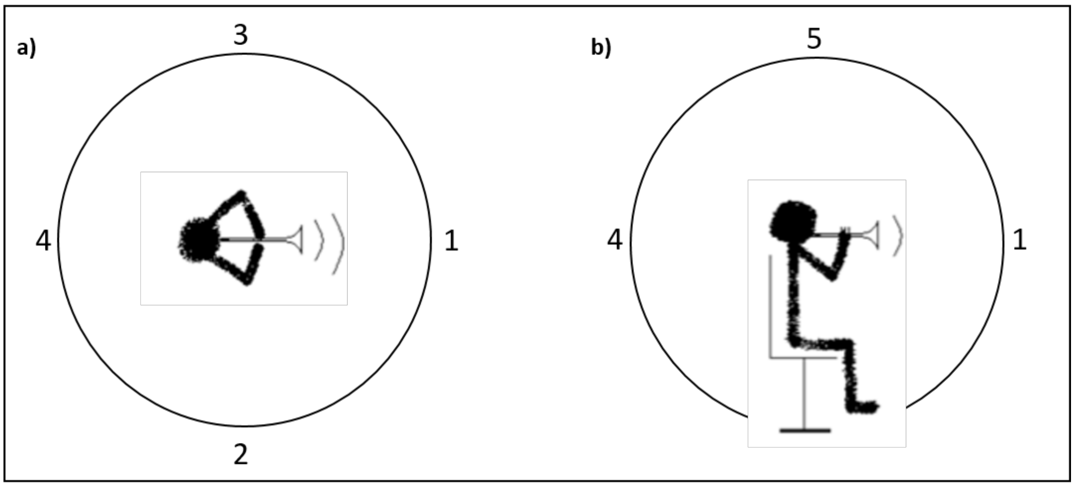

Figure 3.3: Microphone positions for five channel anechoic recordings (Source: Author, adapted from Otondo & Rindel 2004)

3.3 Time Window Length Comparison

3.3.1 Initial Comparison

An investigation of the effect of time window length on metrics of time-varying properties of directivity was conducted to determine a window

length to be used in continued research. The metrics proposed by Buck (2013) chosen for analysis were Average Maximum Directivity Index (Avg Max DI) and the number of of times its location changes. These two metrics involve both spatial direction and magnitude of Directivity Index. The comparison of window lengths was investigated using the thirteen channel anechoic recordings of solo excerpts for violin, flute, and bass trombone. Analysis was done without editing the wave files, so silent periods within the recording were left in. Due to the nature of solo musical pieces, the particular solo excerpts were generally void of silent periods of extensive length. Directional changes were quantified simply by summing the number of channel changes of the Avg Max DI found over the excerpt. Buck (2013) had utilized only 1 second window lengths. The window comparison herein examines window lengths of 1 s, 0.5 s, and 0.2 s. The Average Maximum Directivity Index results from this comparison are shown in Figure 3.4 for each octave band and the unfiltered full spectrum. Shortening the window length does not cause significant differences in Average Maximum Directivity Index values for the particular window lengths analyzed. For the violin, the Average Maximum DI varies most in the 500 Hz and 1000 Hz octave bands across window lengths. For the flute, the most variation occurs in the 250 Hz octave band and in the full spectrum results. For the bass trombone, little variation is seen aside from the 125 Hz octave band. It is worth noting that lower frequency content may not be played throughout the entire excerpt depending on the instrument and the particular musical passage. Due to this, the results in lower octave bands may be less reliable.

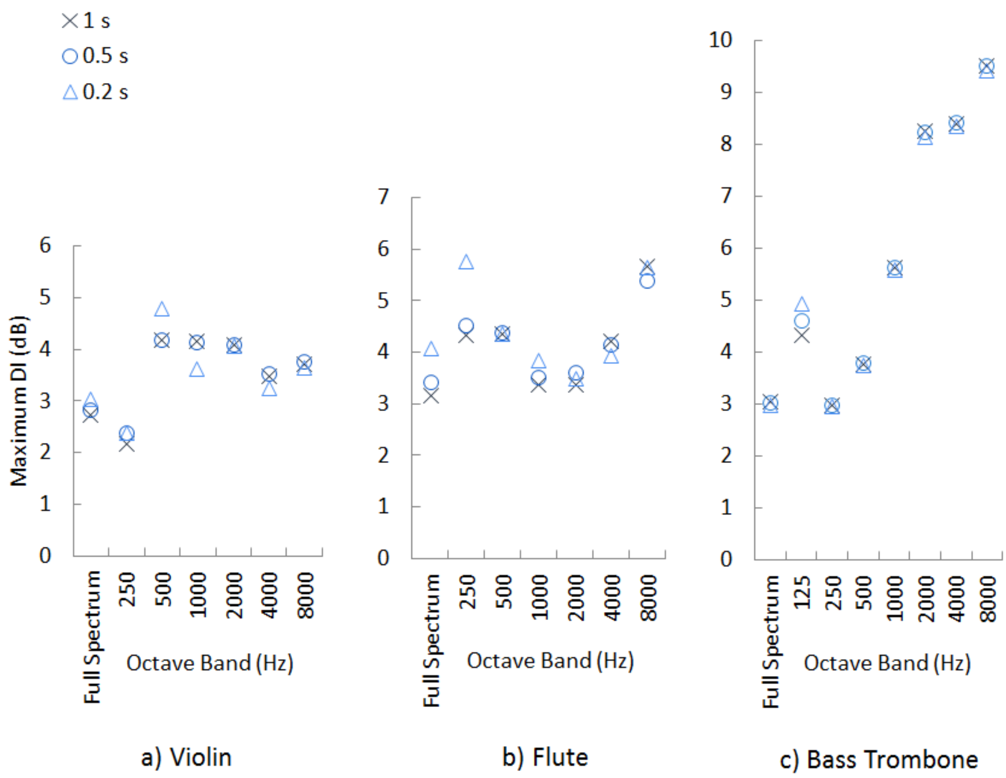

Figure 3.4: Window comparison of Average Maximum Directivity Index for three instruments (Source: Author)

The number of times that the channel of maximum DI changes is designated by the value of maximum channel location changes (MCLC). There was much more variation in MCLC due to window length. Intuitively, by increasing the number of windows, the MCLC is expected to increase, even when discounting the effect of increased resolution on the amount of detail obtained. This is simply due to an increased amount of data points. The channel change comparison deals with the 13 channel solo excerpt data. In this case, instances where the channel with maximum DI changes to an adjacent channel in successive windows may signify a directivity that is hardly changing, whereas channel changes between nonadjacent channels are related to a more obvious change in directivity. Thus, MCLC is evaluated in terms of

the channel of Maximum Directivity Index for adjacent and nonadjacent microphone locations separately, as shown in Figures 3.5 and 3.6.

For the adjacent location changes, the bass trombone shows relatively consistent trends between different window lengths. The violin and flute have generally higher MCLC with decreased window length and show somewhat similar patterns at each frequency, but the results are still somewhat unpredictable.

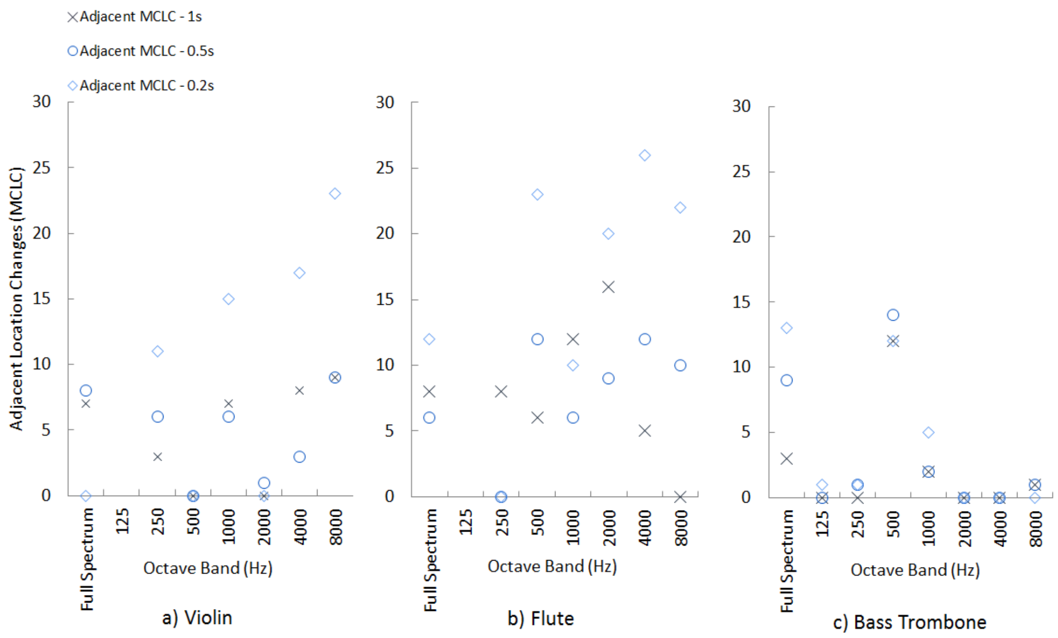

Figure 3.5: Time window length comparison of adjacent MCLC for three instruments (Source: Author)

The nonadjacent MCLC also exhibits a general increase with decreasing window length, as one would expect (Figure 3.6). Although the nonadjacent results seem to be somewhat more predictable than the adjacent results, there is not a clear observation that can be made regarding how the number of channel changes shifts with a changing window length.

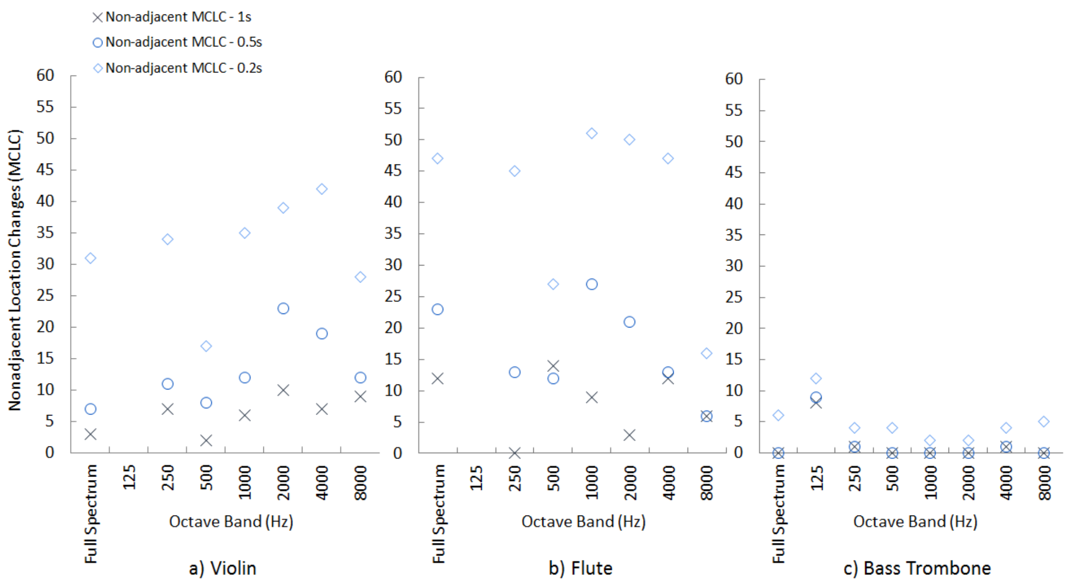

Figure 3.6: Time window length comparison of non-adjacent MCLC for three instruments (Source: Author)

3.3.2 Using Temporal Threshold as Time Window Length for Editing Silences

A second time window length analysis was done using the 5 channel anechoic data from violin, flute, and trombone in the Mozart symphony. A much smaller window length was additionally examined in order to get a better idea of how window length impacts the time-varying directivity metrics of interest. This short window length was chosen as it is close to the auditory temporal resolution of a normal hearing adult (Lister et al. 2000, Moore et al. 1988, Moore 2012). There has been extensive psychoacoustics research done regarding the human temporal threshold of hearing. Temporal threshold is somewhat difficult to measure, as it is hard to isolate time as a factor in measuring human response to auditory stimulation. As Moore explains, "a

major difficulty in measuring the temporal resolution of the auditory system is that changes in the time pattern of a sound are generally associated with changes in its magnitude spectrum" (Moore 2012). Many studies regarding gap detection have suggested that temporal gap detection is as low as 2 to 3 ms at high enough decibel levels (Moore 2012). Lister, Koehnke, and Besing found that gap-duration discrimination thresholds were anywhere between 10 - 40 ms depending on the frequency disparity between the two signals (Lister et al. 2000). A study of the shape of the ear's temporal window carried out by Moore et al. explains the window as a means of modeling the auditory temporal resolution similar to an auditory frequency filter, but in the time domain. In this particular study, the equivalent rectangular duration (ERD) of the window was found to be around 8 ms (1988). In this thesis, a 10 ms window with a 5 ms overlap between windows was selected as the shortest window length to be studied, as many temporal resolution studies have suggested temporal threshold values close to this value.

Unlike the solo excerpts used earlier in this chapter, individual instrumental parts taken from a full symphony more commonly include rests or silences throughout the part. These silent parts affect the overall directivity data over time. Since the silent parts are irrelevant to quantifying the overall traits of a specific instrument, silences in the excerpt were removed and disregarded in analysis. To accomplish this, Audacity was used to edit WAV files by detecting silences falling below a -40 dB level relative to the peak amplitude and lasting longer than 0.01 s in duration and removing these silent sections

from the WAV files completely. Silent sections were found using channel 1. Equal length rest removals were then applied to the other channels. A duration of 0.01 s was chosen for the same reason as the 10 millisecond time window with reference to the human temporal threshold of hearing. Figures 3.7 to 3.10 show the resulting Maximum DI over time using four different time window lengths for the violin 1 Mozart recordings at 2000 Hz. The y-axis shows the maximum DI in blue with the scale on the left and the channel number of maximum DI in orange dots with the scale on the right.

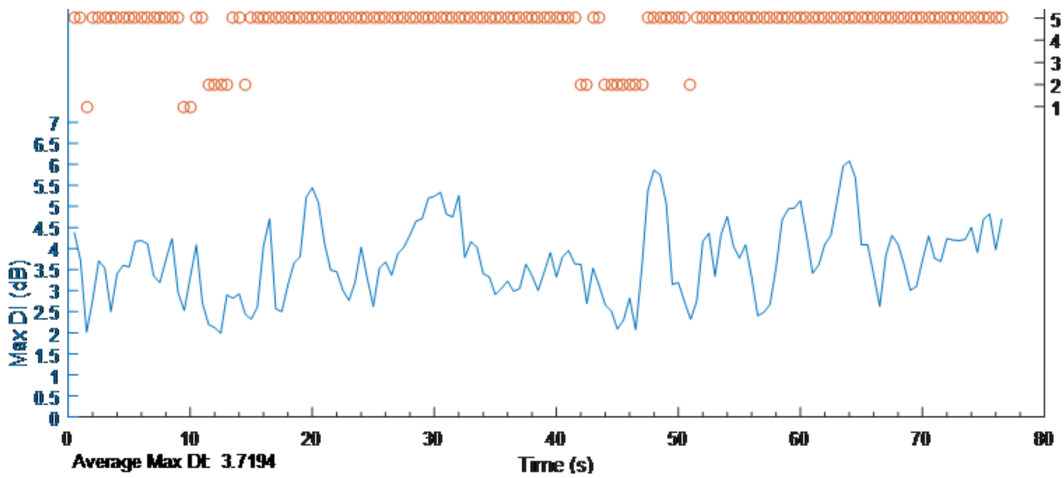

Figure 3.7: Average Maximum DI (blue) and Location of Maximum DI (orange) for a violin Mozart excerpt with 1 second windowing (Source: Author)

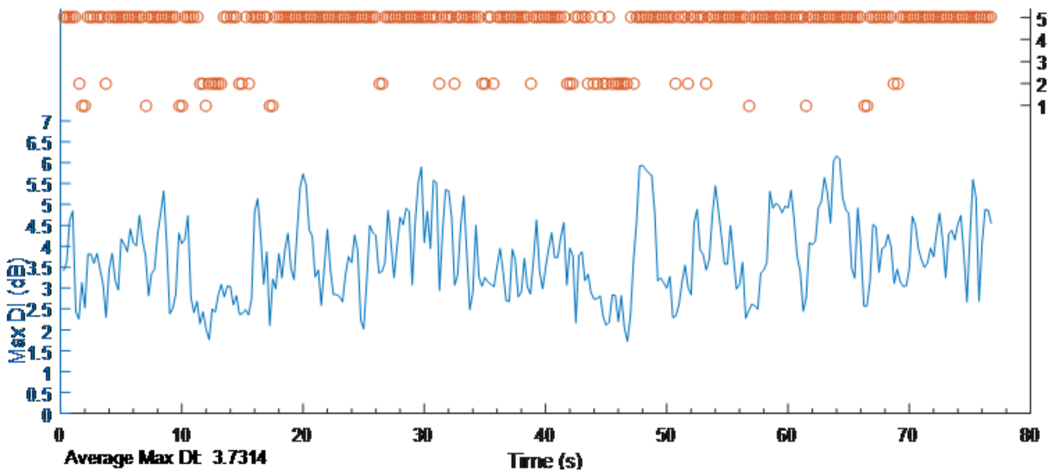

Figure 3.8: Average Maximum DI (blue) and Location of Maximum DI (orange) for a violin Mozart excerpt with 500 ms windowing (Source: Author)

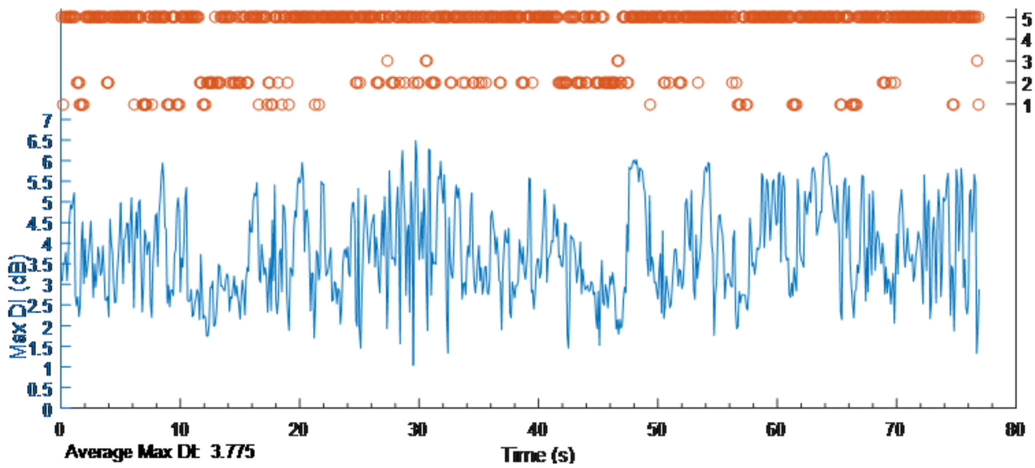

Figure 3.9: Average Maximum DI (blue) and Location of Maximum DI (orange) for a violin Mozart excerpt with 200 ms windowing (Source: Author)

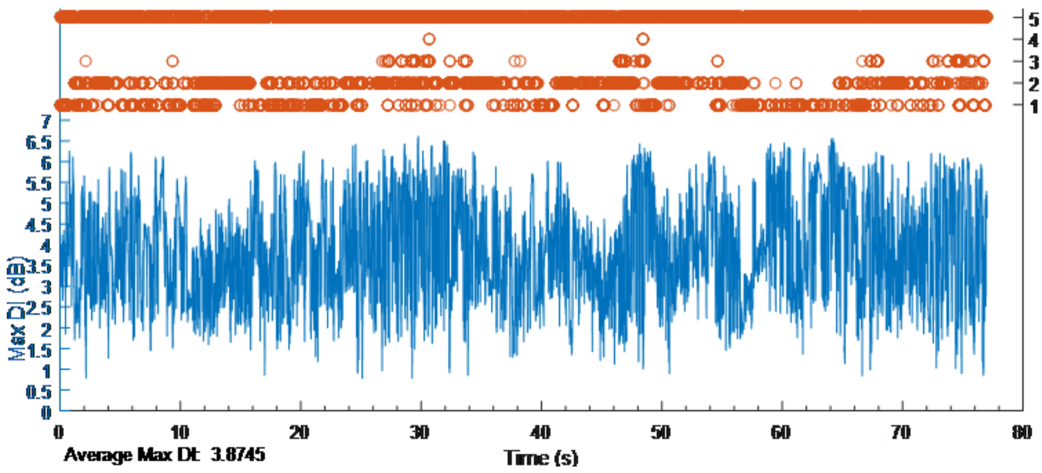

Figure 3.10: Average Maximum DI (blue) and Location of Maximum DI (orange) for a violin Mozart excerpt with 10 ms windowing (Source: Author)

Although the Maximum DI plots have similar shapes across all four window lengths, there is a definite increase in resolution of detail as the time window length decreases. In addition, it is clear that there are rapid changes regarding location of maximum DI that are only accounted for in higher resolutions. This is particularly apparent in the later part of the excerpt shown. For the one second window, the main channel of energy propagation is consistent after around 52 seconds into the excerpt. However, as the window length decreases, there are rapid directional changes that are only detectable with a higher resolution.

Time-varying metrics were examined across three instruments, one from each major orchestral instrument group as before. Since the bass trombone was not an instrument used in the 5 channel Mozart symphonic recordings, the French horn in G was used as a representation of the brass family. Window length seems to have a small effect on the results obtained from excerpts of

approximately 80 s in length with silences removed. Figures 3.11, 3.12, and 3.13 show these results by frequency band for each of the three instruments. For the violin (Figure 3.11), the values of Average Maximum DI increase slightly as window length is increased. Figure 3.12 shows that the Average Maximum DI values for the flute either increase or decrease with window length depending on the frequency band of interest, but remain within a close range at all frequency bands. Figure 3.13 for French horn in G shows opposite trends to the violin. Average Maximum DI generally decreases as the window length shortens.

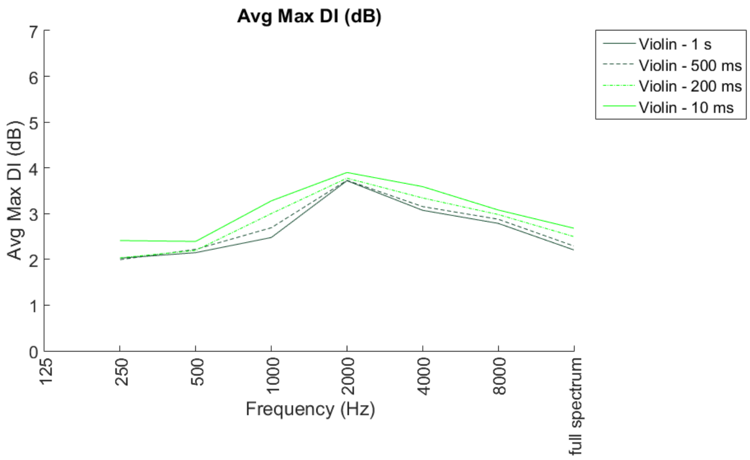

Figure 3.11: Window length effect on Average Maximum DI for the Mozart violin excerpt (Source: Author)

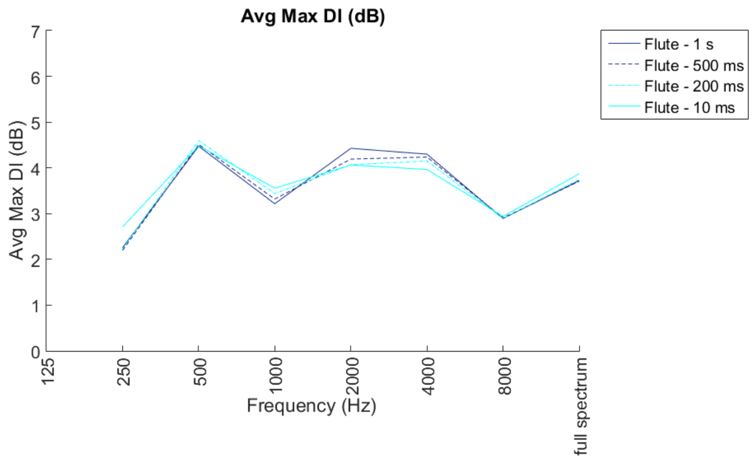

Figure 3.12: Window length effect on Average Maximum DI for the Mozart flute excerpt (Source: Author)

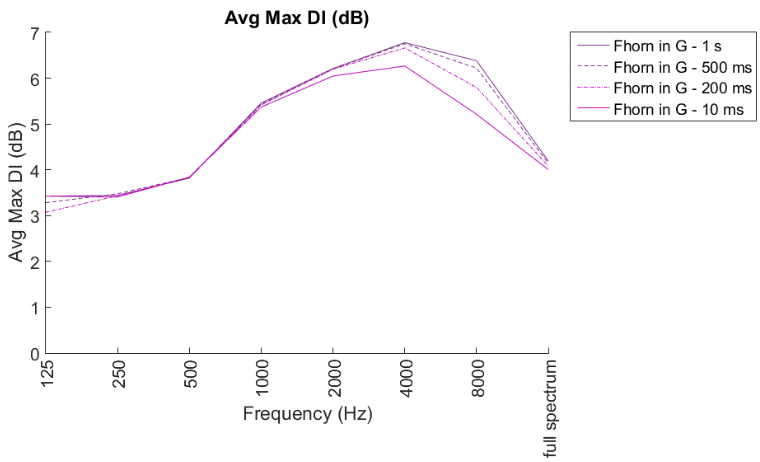

Figure 3.13: Window length effect on Average Maximum DI for the Mozart French horn excerpt (Source: Author)

Overall, time window length seems to have a small effect on Average Maximum Directivity Index results.

The number of times that the channel of max DI changes (MCLC) was previously used as a quantifier to account for the spatial changes in directivity. This metric was reformulated for further analysis to a ratio

described as the Location Change Ratio. The Location Change Ratio is a ratio of the MCLC to the total number of windows used in the excerpt analysis. Further details on Location Change Ratio will be presented in Section 4.1. Additionally, adjacent versus non-adjacent location changes were not accounted for in analyses of the 5 channel data due to low channel resolution. Overall, Location Change Ratios have much more variation based on the window length used than the Average Maximum DI results showed, although patterns are not predictable.

As seen in Figures 3.14, 3.15, and 3.16, the 10 millisecond window gives results that are quite different from the other time windows. This suggests that the 10 millisecond window provides greater detail, and windows of longer length do not necessarily provide a sufficient representation of the spatial changes over time. The large differences in results with window length for the Location Change Ratio suggest that this small window is necessary to detect rapid variance in directional characteristics over time.

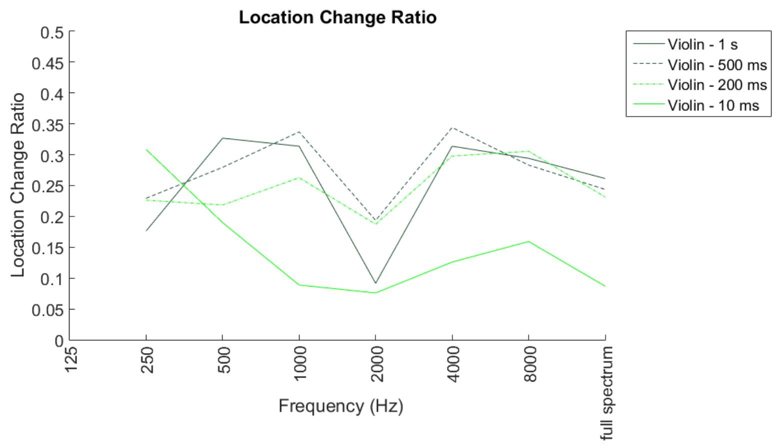

Figure 3.14: Window length effect on Location Change Ratio for the Mozart violin excerpt (Source: Author)

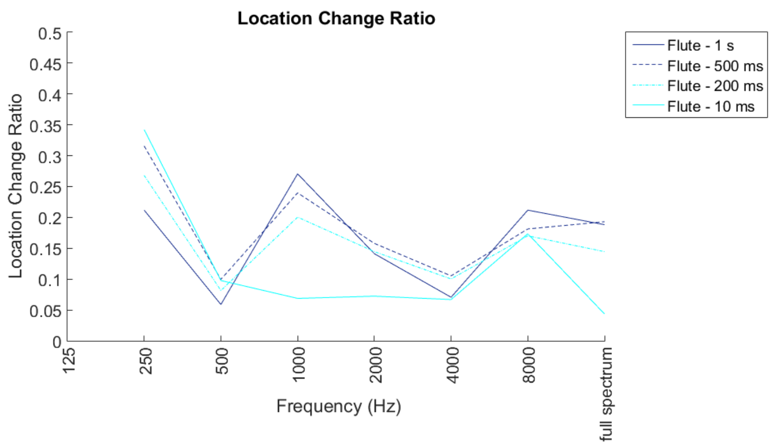

Figure 3.15: Window length effect on Location Change Ratio for the Mozart flute excerpt (Source: Author)

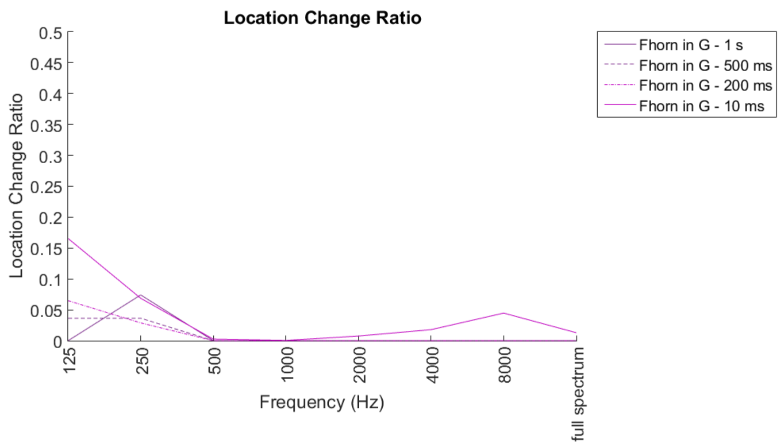

Figure 3.16: Window length effect on Location Change Ratio for the Mozart French horn excerpt (Source: Author)

3.3.3 Summary

In examining the effect of time window length, it was found that Average Maximum Directivity Index values stayed somewhat consistent as the window length changed. However, there was enough change between the specific window lengths that a standardized window length was deemed necessary for further analysis. In the plots of maximum Directivity Index, the shorter

window lengths showed more detail of how the maximum Directivity Index was changing, as would be expected with a finer resolution. The number of location changes showed some similar patterns with changing window length, but as one would expect, increasing the overall number of windows analyzed increases number of location changes. Although some trends existed, the effect of changing the window length on the number of location changes showed even less predictable results than what was seen with Average Maximum DI. To retain higher resolution, a window length of 10 ms was selected for further use in this thesis. This value was chosen based on the human temporal threshold of hearing, which is on the order of 10 milliseconds.

The temporal threshold length of 10 milliseconds was also used as the tolerance for length of silences. Anechoic recordings were edited such that detected silences from the front channel (1) with a level of -40 dB relative to the peak amplitude and a duration of 0.01 seconds or above were removed. This method of silence removal is applied to all subsequent excerpts analyzed in this thesis such that only played sections relevant to time variance behavior of an instrument are accounted for.

Chapter 4

Methodology and Results

4.1 Metrics

To better compare time-varying directivities of different instruments as well as from different excerpts, a method of quantification is established. Proposed metrics in this thesis are primarily concerned with quantifying the changes in the magnitude and direction of the maximum Directivity Index as an instrument plays over a period of time. The five metrics devised and defined in this section are the Average Maximum Directivity Index, Average Change in Maximum Directivity Index, Location Change Ratio, Dominance Ratio, and Dominating Location. The application of these metrics is introduced using the five channel anechoic WAV files for the first violin part from the Mozart symphony excerpt. The WAV files used in this section were edited using the method described in Section 3.3.3. Quantifiers are calculated from WAV files in MATLAB (Appendix B).

4.1.1 Average Maximum Directivity Index

As previously mentioned, Directivity Index is calculated using Equation 2.3. The Average Maximum Directivity Index is calculated for the entire excerpt by averaging the maximum Directivity Indices across the set of windows. The blue line in Figure 4.1 shows the maximum Directivity Index in dB plotted at each 10 ms window for the Mozart violin excerpt. The black dotted line represents the time-average of the maximum Directivity Indices, and the value of this Average Maximum Directivity Index quantifier is highlighted in yellow on the plot. In this example, 2.6815 dB represents an average of the violin's maximum DI over this specific excerpt's time frame. In general, the Average Maximum DI quantifier reduces the time-varying maximum DI information for a particular instrument and excerpt to a single value.

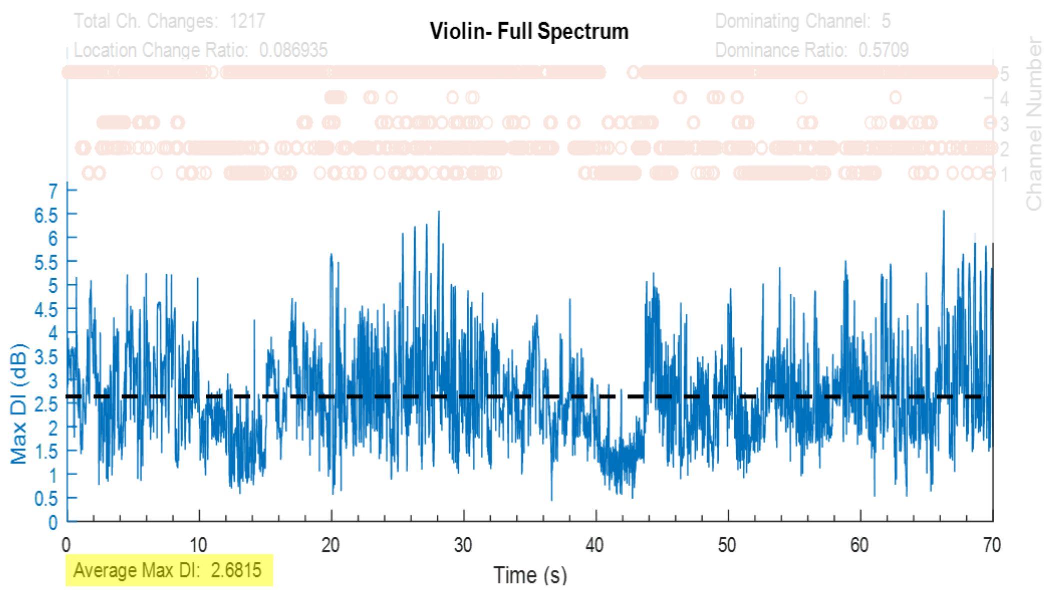

Figure 4.1: Typical presentation of maximum Directivity Index over time, with average marked by black dashed line and value given at bottom of plot as highlighted (Source: Author)

4.1.2 Average Change in Maximum DI

The Average Change in Maximum DI is similar to the Average Maximum DI in that it is a quantifier of how the magnitude of maximum radiation changes over time. Instead of averaging the Maximum DI over all of the windows of the excerpt, the Average Change metric takes the difference between the Maximum DI between two consecutive 10 ms time window steps, and averages these differences.

$$Average\Delta_{DI_{\mathrm{max}}} = (1/W)\sum_{w=1}^{W}(DI_{\mathrm{max,w+1}} - DI_{\mathrm{max,w}}) \tag{4.1}$$

where

W is the total number of windows in the excerpt

w is the index corresponding to a particular window

$DI_{\mathrm{max,w}}$, $DI_{\mathrm{max,w+1}}$ are the maximum Directivity Indices for the corresponding window index

Average Change in Maximum DI can be interpreted as a quantification of how quickly changing the magnitude of DI for an instrument is. A higher Average Change in Maximum DI is associated with an instrument with a very flashy and quickly changing Maximum DI while a lower value is associated with a more consistent maximum DI.

4.1.3 Location Change Ratio

The Location Change Ratio is a metric that is similar to the count of MCLC over an excerpt used by Buck (2013), but it converts this integer number into a ratio in order to normalize across excerpts varying in length. Qualitatively,

the Location Change Ratio signifies how often the direction of maximum sound energy propagation changes direction (or location) for the source in question. Quantitatively, the Location Change Ratio is equivalent to Equation 4.2:

$$L = N_{\delta}/N_{\text{total}} \tag{4.2}$$

where

L is the Location Change Ratio

N_{δ} is the number of times the maximum Directivity Index changes channels over an excerpt

N_{total} is the total number of windows for the particular excerpt

This gives L a value between zero and one. A Location Change Ratio close to zero corresponds to a source that strongly radiates towards a certain channel in its directivity pattern. A higher Location Change Ratio is associated with a source that has more variance in the channel of maximum Directivity Index, thus having more variation in direction of energy propagation. The location of maximum radiation for the five channel measurement data is plotted for each window and labeled on the right y-axis, as shown in Figure 4.2. Each red circle marks the channel of maximum DI for the corresponding 10 millisecond time window, as labeled on the x axis. As the excerpt progresses through time, the number of times the maximum DI changes channels is summed and divided by the total number of windows. This ratio is then taken as the

Location Change Ratio, which is highlighted in Figure 4.2.

In the example shown in Figure 4.2, the maximum DI of the violin changes 1,217 times over the 13,999 windows in the 70 second excerpt. Thus, $1,217/13,999$ gives L a value of 0.086935. The Location Change Ratio of 0.086935 gives insight to how much spatial variance there is in energy propagation over time for the violin as it plays the Mozart excerpt. This value becomes more meaningful when it is used in comparison with additional Location Change Ratio data involving other instruments or excerpts, as done in Sections 4.2 and 4.3.

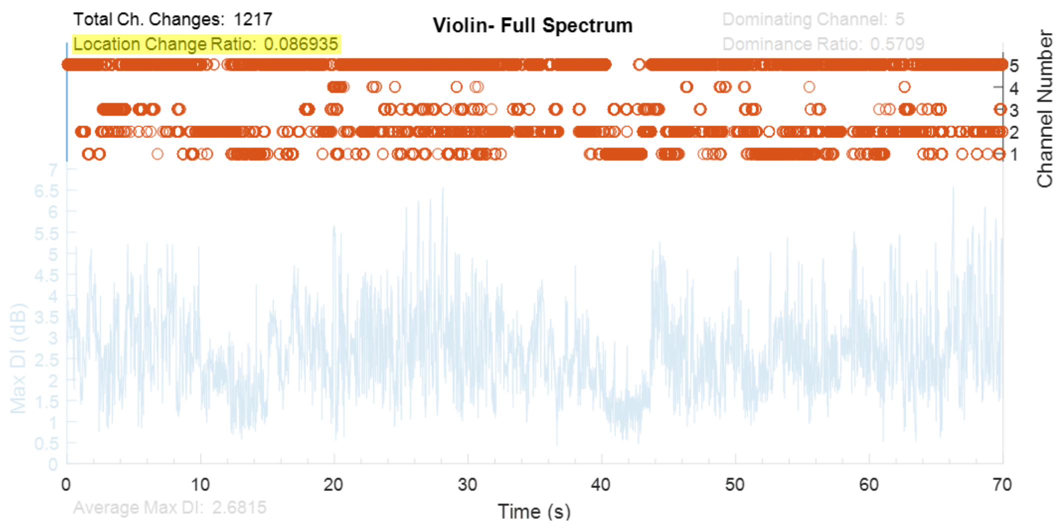

Figure 4.2: Typical presentation of maximum DI locations over time, with value of Location Change Ratio given at top of plot as highlighted (Source: Author)

4.1.4 Dominance Ratio

The Dominance Ratio metric is proposed as a quantifier of how much the most prominent max DI channel dominates over the other possible channels.

The Dominance Ratio corresponds to the channel that is most frequently associated with the maximum DI for the excerpt. Quantitatively, Dominance Ratio can be calculated using Equation 4.3.

$$D = N_{\mathrm{x}}/N_{\mathrm{total}} \tag{4.3}$$

where

D is the Dominance Ratio

x is the channel that most frequently demonstrates the maximum DI

N_x is the number of windows at which channel x demonstrates maximum DI

N_{total} is the total number of windows for the particular excerpt

Like the Location Change Ratio, the Dominance Ratio also yields values between zero and one. A lower Dominance Ratio value is associated with a source having a directivity pattern that is more spatially distributed or even. The lowest possible Dominance Ratio is one divided by the total number of channels used in the data. For example, for the five channel data, D = 1/5 or 0.2 would be associated with an instrument having the lowest possible level of directivity dominance, as even the most dominant channel only dominates one-fifth of the time. On the other hand, a Dominance Ratio close to 1 is associated with a very directional instrument through time. A Dominance Ratio of 1 corresponds to a case where one channel dominates the maximum Directivity Index throughout the entire excerpt. Figure 4.3 demonstrates how Dominance Ratio is discerned on plots throughout this thesis.

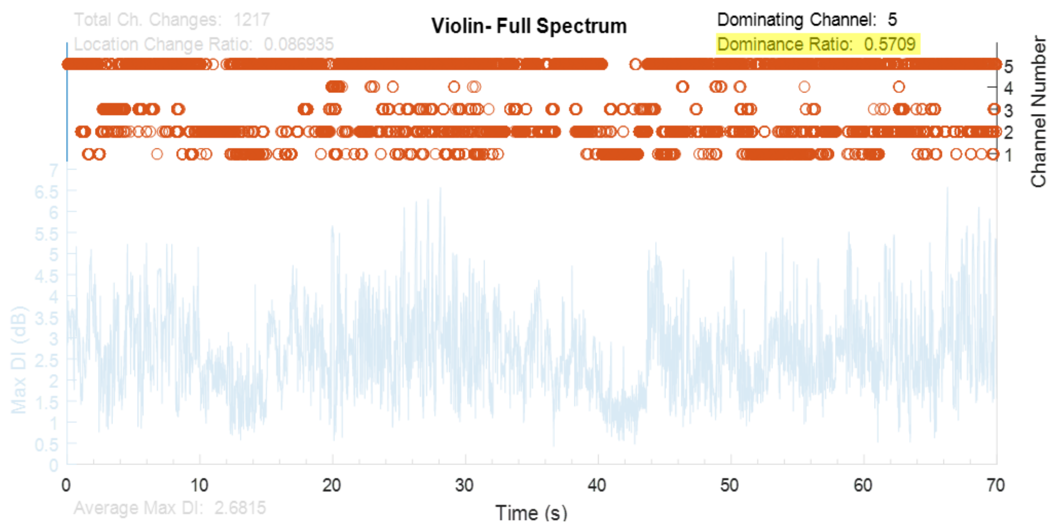

Figure 4.3: Typical presentation of maximum DI locations over time, with value of Dominance Ratio given at top of plot as highlighted (Source: Author)

In this particular example, there is a clearly dominant channel, as seen in the top y axis labeled "Channel Number". Channel 5, which corresponds to the overhead direction, is the dominating direction of radiation. Thus, the Dominance Ratio refers to the amount of dominance for channel 5. In this example, channel 5 is the dominant location for 7,992 of the 13,999 windows. Using Equation 4.3, $D = 7,992/13,999 = 0.5709$. The Dominance Ratio value of 0.5709 is somewhere between 0.2 and 1, so although there is a clearly dominant channel, other channels are also somewhat well-represented. Technically, the Dominance Ratio may be calculated for any direction, but the Dominance Ratio for the dominating channel will be of primary concern in the scope of this thesis.

4.2 Instrument Comparisons

In this first phase of analysis of the quantifiers described in Section 4.1, each symphonic work is analyzed individually. By looking at a single piece of music, trends for specific instruments as well as trends across instrumental groups are more easily examined. The orchestral recordings are short excerpts not exceeding two minutes starting from the beginning of the symphonic movement. In Figures 4.4, 4.12, and 4.16, all of the instruments for the Mozart symphony are shown together on a single plot for Average Maximum DI, Location Change Ratio, and Dominance Ratio, respectively. The summary plots with the quantifier results for the Brahms are shown in Figures 4.6, 4.14, and 4.18. The stringed instruments are shown in green, woodwinds in blue, and brass in purple. Instruments that have a relatively higher frequency range are plotted in lighter colors, while instruments typically playing in lower frequency ranges are shown in darker colors. Instrument types are separated by marker shape, and instruments with multiple parts are separated by line type. General comparisons and tendencies can be seen between and within instrument groups by examining the full orchestra instrumentation on one plot. Instruments are divided into smaller groups for each metric in Figures 4.5, 4.7, 4.13, 4.15, 4.17, and 4.19 in order to further examine details and possible discrepancies or trends within each group.

4.2.1 Expectations

By putting a quantifier to the time-varying directional characteristics of a wide range of instruments, Weinreich's description of the violin's "directional

tone color" and "flashing brilliance" can be put to test in a quantifiable way. Objectively, if Weinreich's description of the violin holds true, one would expect the violin to have a high Location Change Ratio and low Dominance Ratio, as these trends would generally be attributed to a more changing radiation pattern. Additionally, one might expect higher values of Average Maximum DI and Average Change in Maximum DI for the violin, as higher magnitudes of these quantifiers are attributed to more extreme changes.

The frequency dependence of static directivity patterns may be a predictor of how time-varying directivity quantifiers behave across different octave bands. For low frequency bands, the energy radiation is more omnidirectional. The value of maximum Directivity Index corresponding to an omnidirectional radiation pattern is expected to be relatively low. Because of this, low values of Average Maximum DI and Average Change in Max DI are expected for lower frequencies. Low frequencies tend to have a less definite primary direction of radiation. This may result in greater values of Location Change Ratio and lower values of Dominance Ratio. Opposite trends are expected for higher frequencies. Musical instruments tend to be more directional as frequency increases. Thus, the expectations associated with increased frequency include higher values for Average Maximum DI and Average Change in Max DI. Location Change Ratio is expected to be lower and Dominance Ratio is expected to be higher as energy becomes more concentrated in a particular direction, which is often associated with increasing frequency.

4.2.2 Average Maximum Directivity Index

In Figure 4.4, the Average Maximum DI is shown for the Mozart symphony by instrument. One prominent trend suggests that the French horns have a relatively high Average Maximum DI. The string and woodwind groups seem to be more similar in Average Maximum DI for the Mozart excerpt.

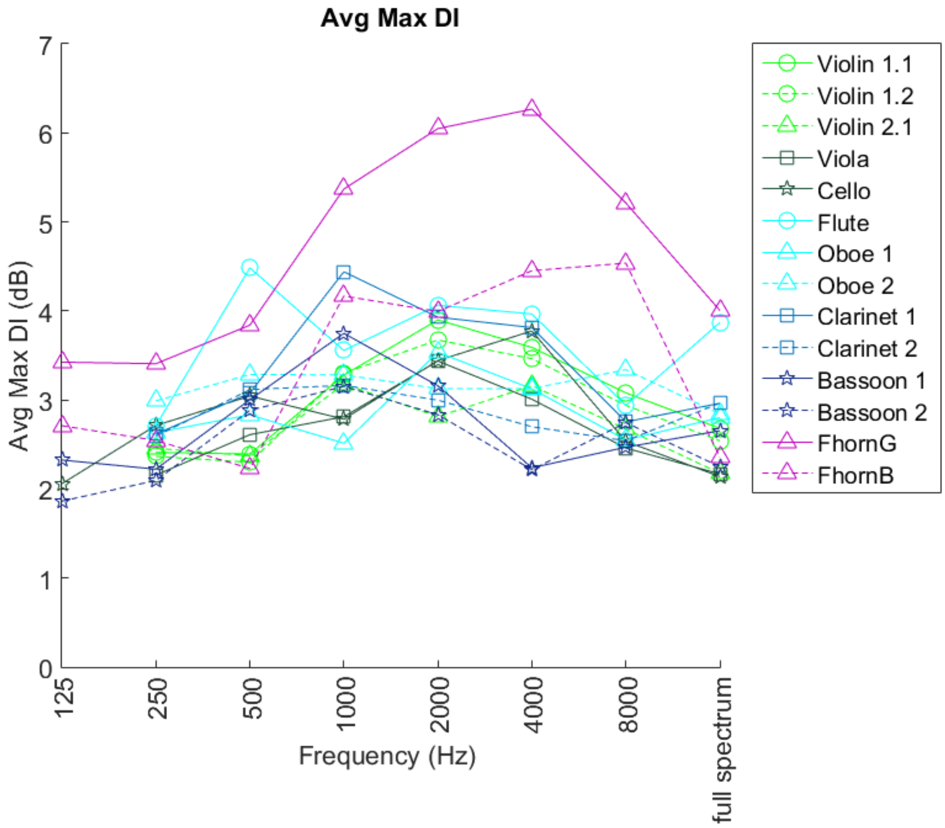

Figure 4.4: Average Maximum DI for the Mozart symphony (Source: Author)

Figure 4.5 shows the same values as Figure 4.4, but the instruments are split into four groups in order to more easily distinguish between specific instruments. The four groups displayed in Figure 4.5 are high woodwinds, low woodwinds, strings, and brass. This breakdown more clearly suggests that there are directional tendencies within each group. In Figure 4.5, many of the stringed instruments have a peak around 2000 to 4000 Hz while the low

woodwinds have a peaking pattern around the 1000 Hz octave band. Some of the instruments in the high woodwind group, namely the second oboe and second clarinet, have a relatively consistent Average Maximum DI magnitude across the entire frequency range.

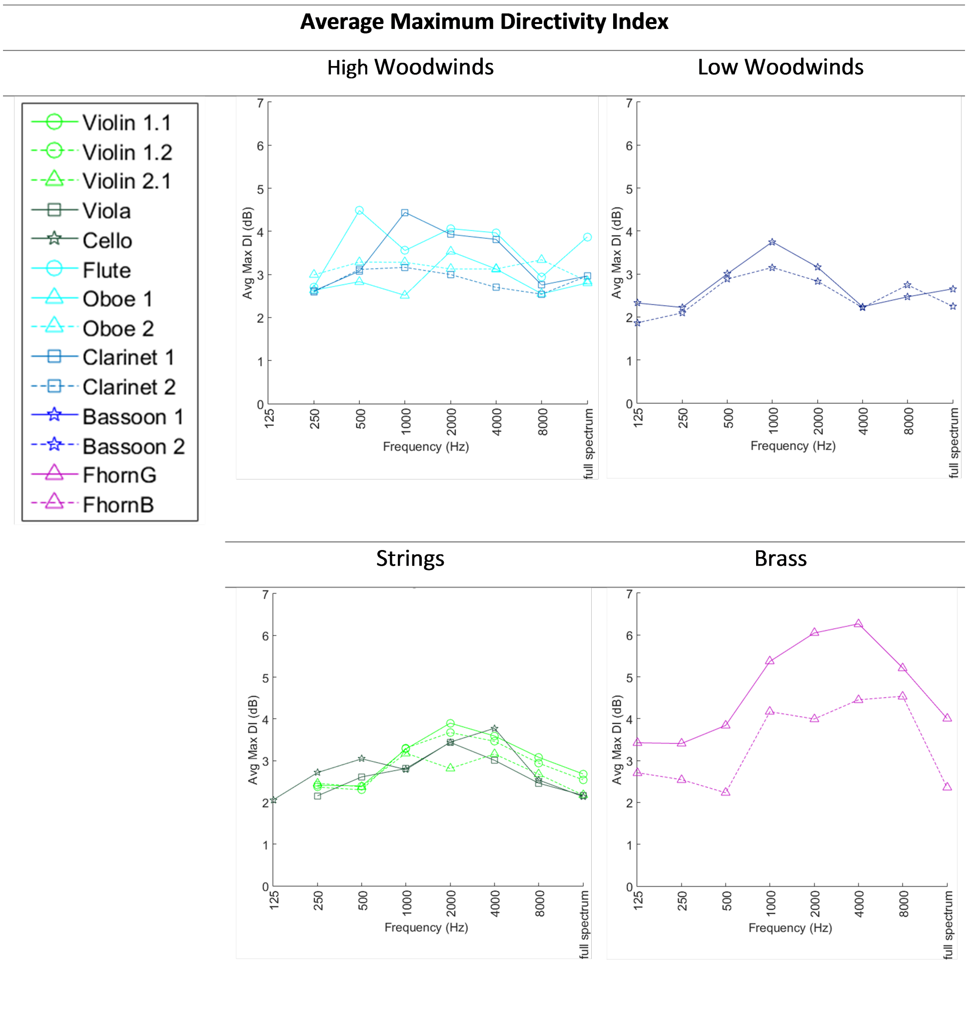

Figure 4.5: Average Maximum DI separated by instrument for the Mozart symphony (Source: Author)

Similar trends for Average Maximum Directivity Index are seen in the analysis of the Brahms instruments, as shown in Figures 4.6 and 4.7. The Brahms offers a broader data set, as the Brahms symphony is written with a

denser instrumentation than the Mozart symphony. Other instruments in the Brahms recordings include more individual parts for the violin and French horn as well as the addition of double bass, contrabassoon, piccolo, trumpet, and some percussion parts (timpani and triangle).

In Rossing's *The Science of Percussion Instruments* (2000), percussion is defined as those instruments that are "struck". One way to group percussion instruments is "by whether or not they convey a definite sense of pitch". Another way to group percussion is by categorizing instruments into one of four groups. These groups are idiophones (xylophone, marimba, cymbals), membranophones (drums), aerophones (whistles, sirens), and chordophones (piano, harpsichord) (Rossing 2000). Although the triangle is a idiophone and the tympani is a membranophone, they can both be classified as percussion instruments that have a sense of pitch (Rossing 2000). Because the timpani and triangle are percussion instruments with a sense of pitch, these may be some of the more practical percussion instruments to analyze by frequency band, as is done with the other musical instruments. The Mozart symphony recordings do not include percussion parts, so a comparison for percussion instruments by excerpt is lacking. However, the quantifier results for these percussion instruments are included in the analysis of the Brahms symphony, and the results from this group are designated with black lines. The percussion along with the other instrument groups in the Brahms are shown together in Figure 4.6.

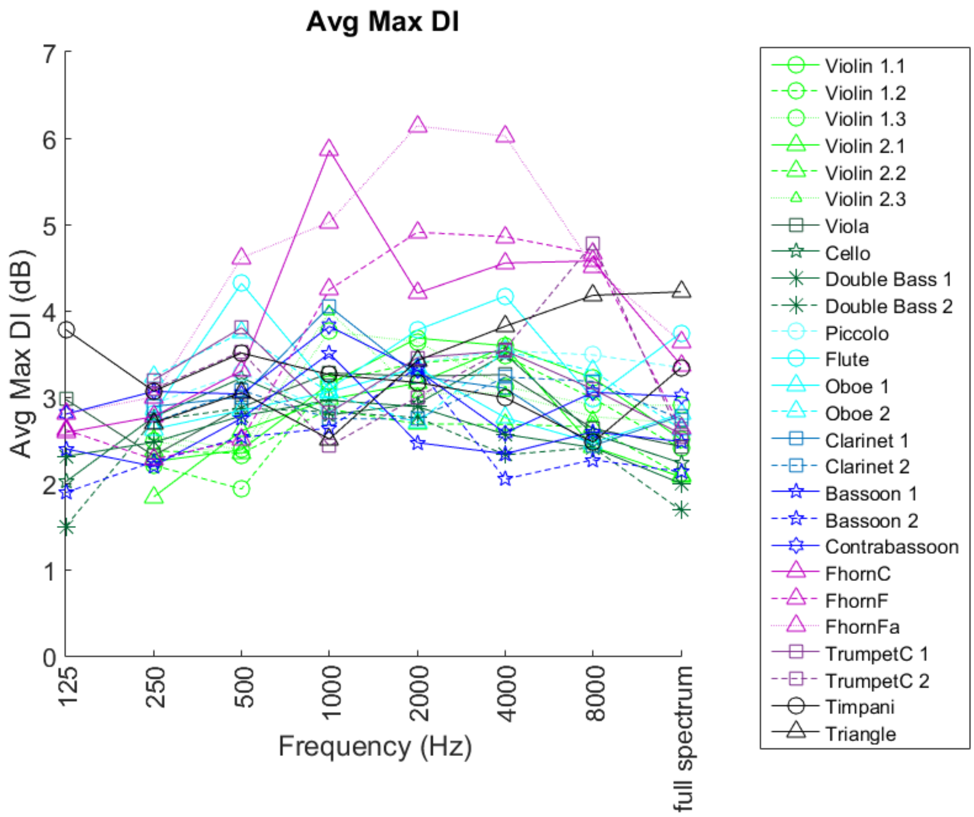

Figure 4.6: Average Maximum DI for the Brahms symphony (Source: Author)

Figure 4.7 gives a breakdown of Figure 4.6 by instrument group. The Brahms is divided into six groups instead of four due to the dense instrumentation of the symphony. The string group is divided into two plots for high and low strings, and an additional plot is added for the percussion instruments. One obvious trend in Figure 4.7 is that brass instruments have overall higher values of Average Maximum DI. The trumpet parts show this trend less prominently than the French horn parts. Within the stringed instruments, the magnitude of Average Maximum DI is not significantly different between high and low strings. Upper woodwinds have generally higher Average Maximum DI values than bassoons, though the contrabassoon has relatively high values of Average Maximum DI. All of the bassoon parts have a peak in the 1000 -

2000 Hz octave band range.

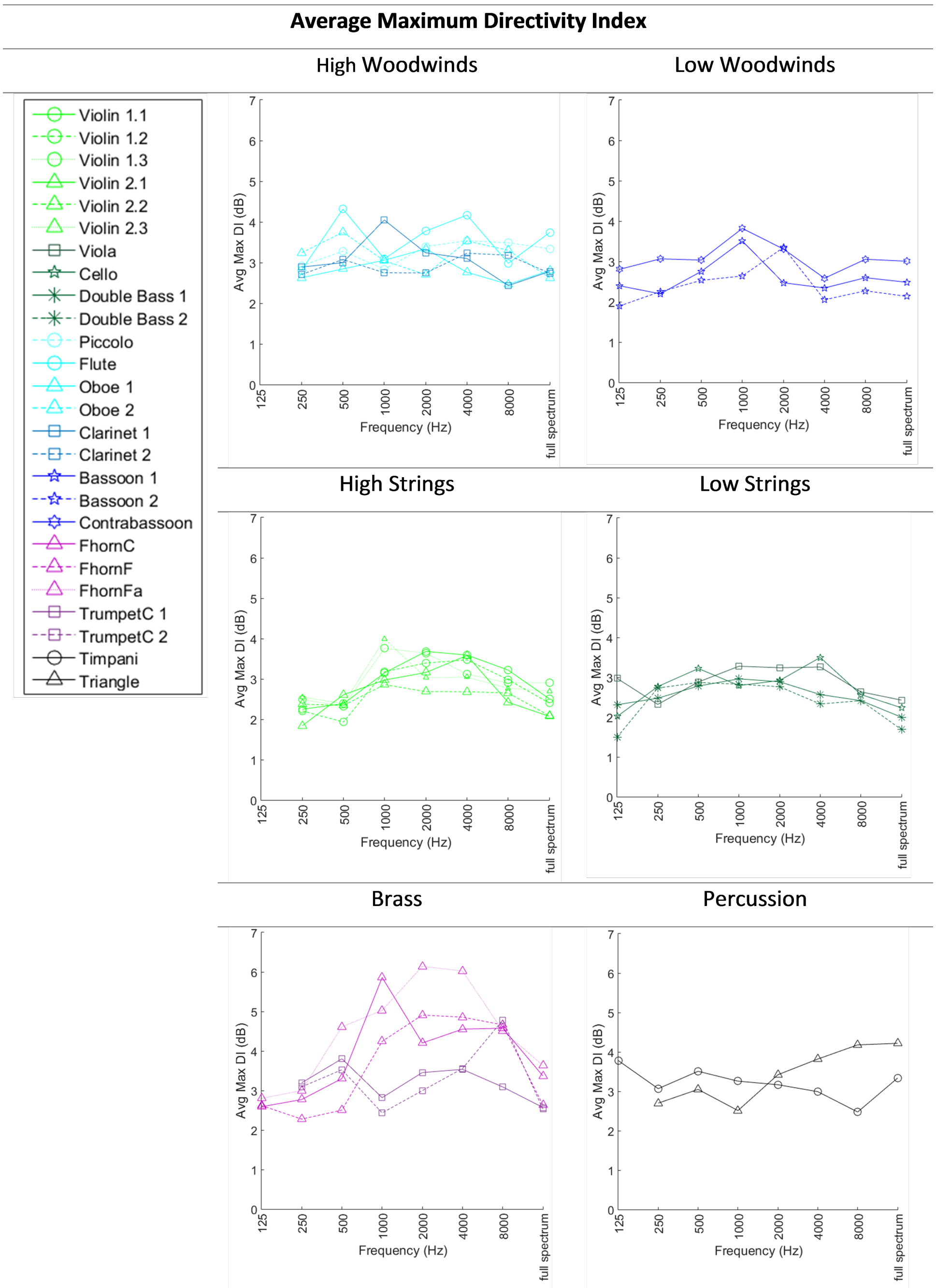

Figure 4.7: Average Maximum DI separated by instrument for the Brahms symphony (Source: Author)

4.2.3 Average Change in Maximum DI

Figure 4.8 shows the Average Change in Maximum DI for the Mozart symphony. The values for this metric are generally lowest for brass instruments and higher for stringed instruments, although this is not always the case, particularily for the bassoon.

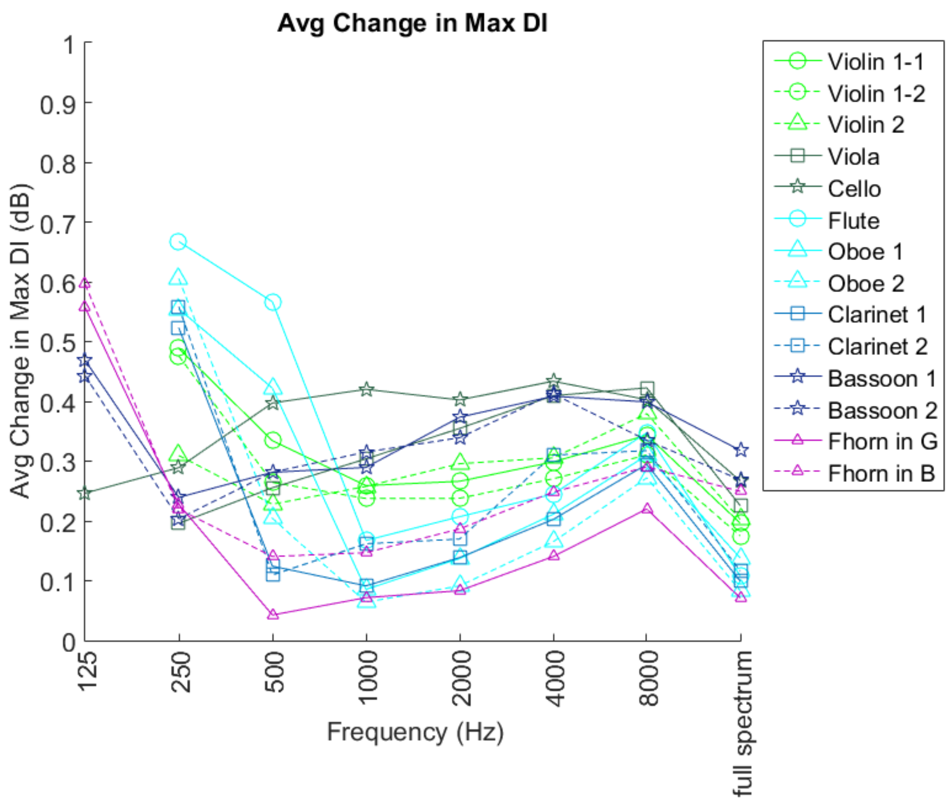

Figure 4.8: Average Change in Maximum Directivity for the Mozart symphony (Source: Author)

Figure 4.9 again separates the Mozart symphony into instrumental categories. As stated before, this particular quantifier could be associated with the "directional tone color" of the violin. Although the strings exhibit some of the highest values of Average Change in Maximum DI, the lower stringed instruments exhibit higher values than the violins.

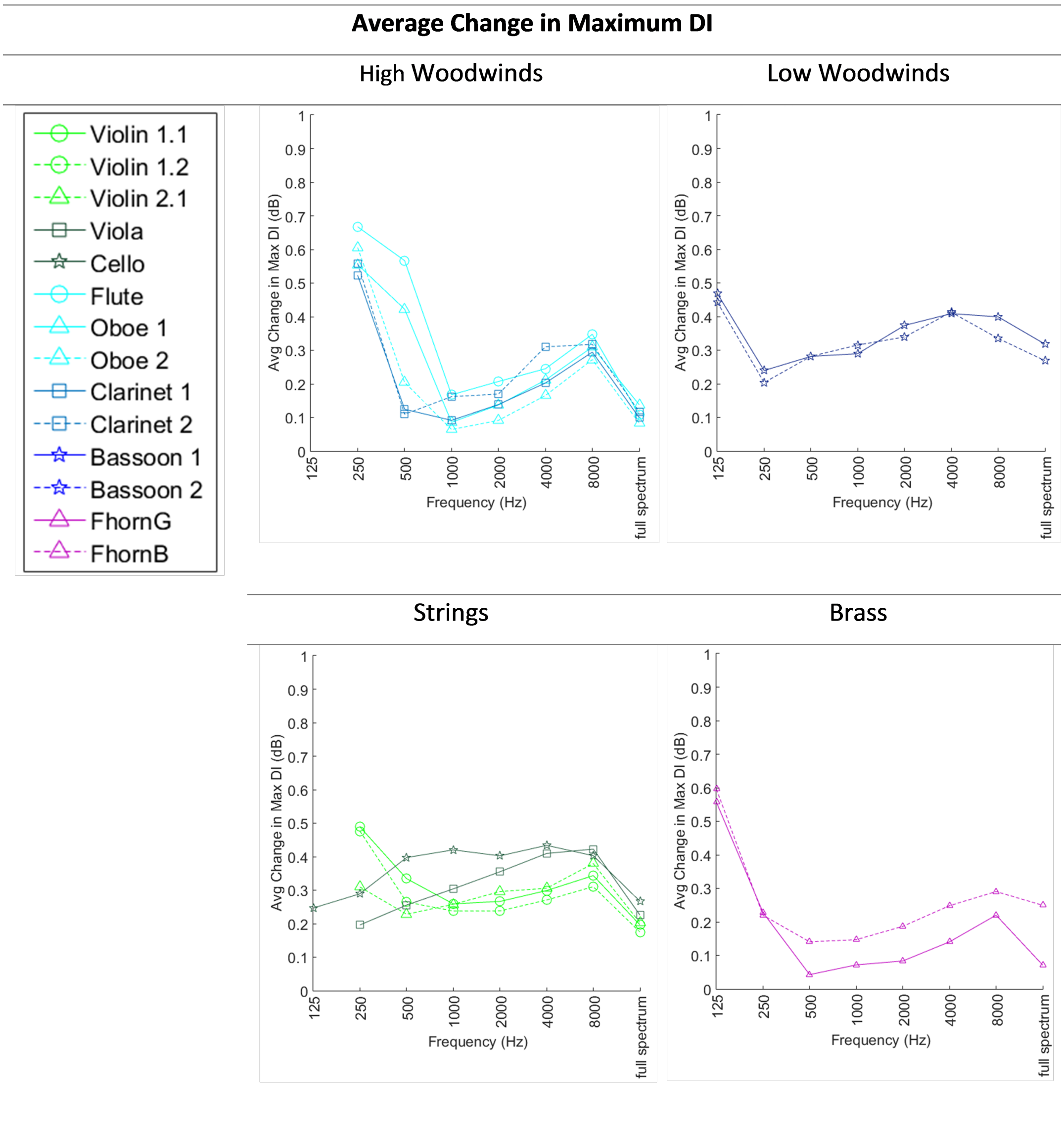

Figure 4.9: Average Change in Maximum DI separated by instrument for the Mozart symphony (Source: Author)

The Average Change in Maximum DI results for the Brahms instruments are shown in Figure 4.10. It is difficult to make clear comparisons with the dense instrumentation. However, the tympani stands out as exhibiting especially high values while the brass instruments have some of the lowest values.

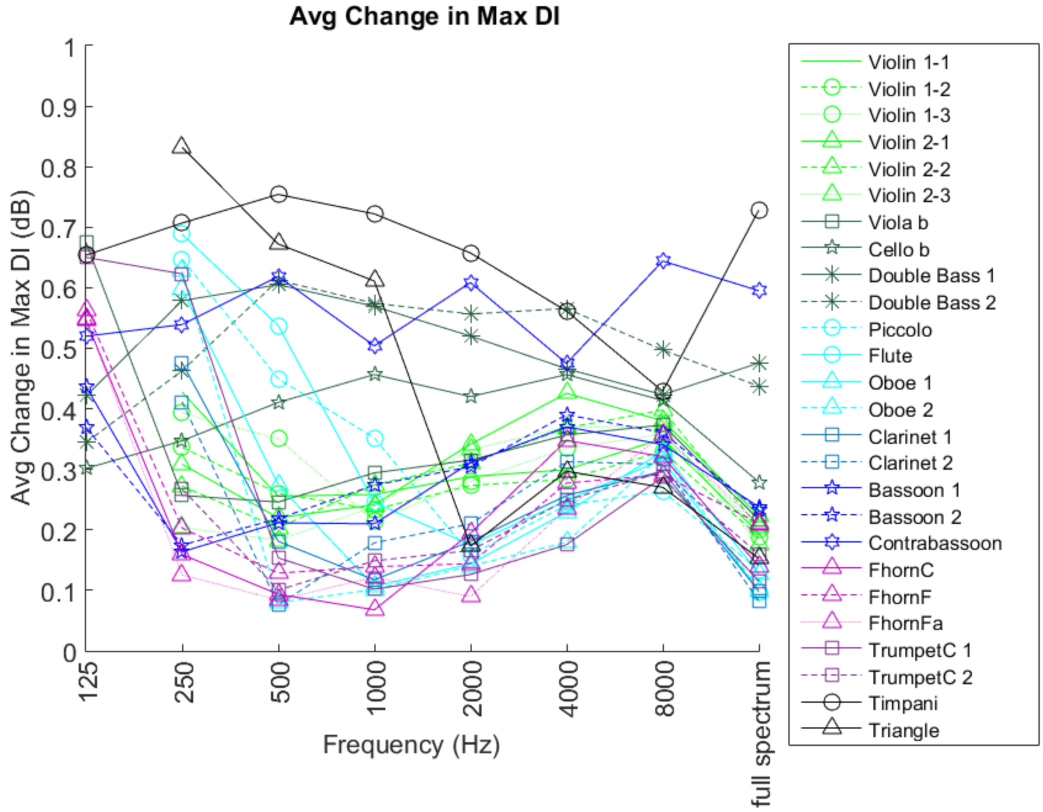

Figure 4.10: Average Change in Maximum DI for the Brahms symphony (Source: Author)

Similarities within each instrument group are more easily seen in the separation of instruments shown in Figure 4.11. Within the high woodwinds, high strings, and brass groups, the instruments all fall within a relatively close range, particularly in the upper frequency bands. There is a larger spread in values for the lower strings, but it is interesting to note that like the contrabassoon, the double bass also exhibits some of the highest values for Average Change in Maximum DI. This suggests a possible link between this metric and the played frequency range of an instrument.

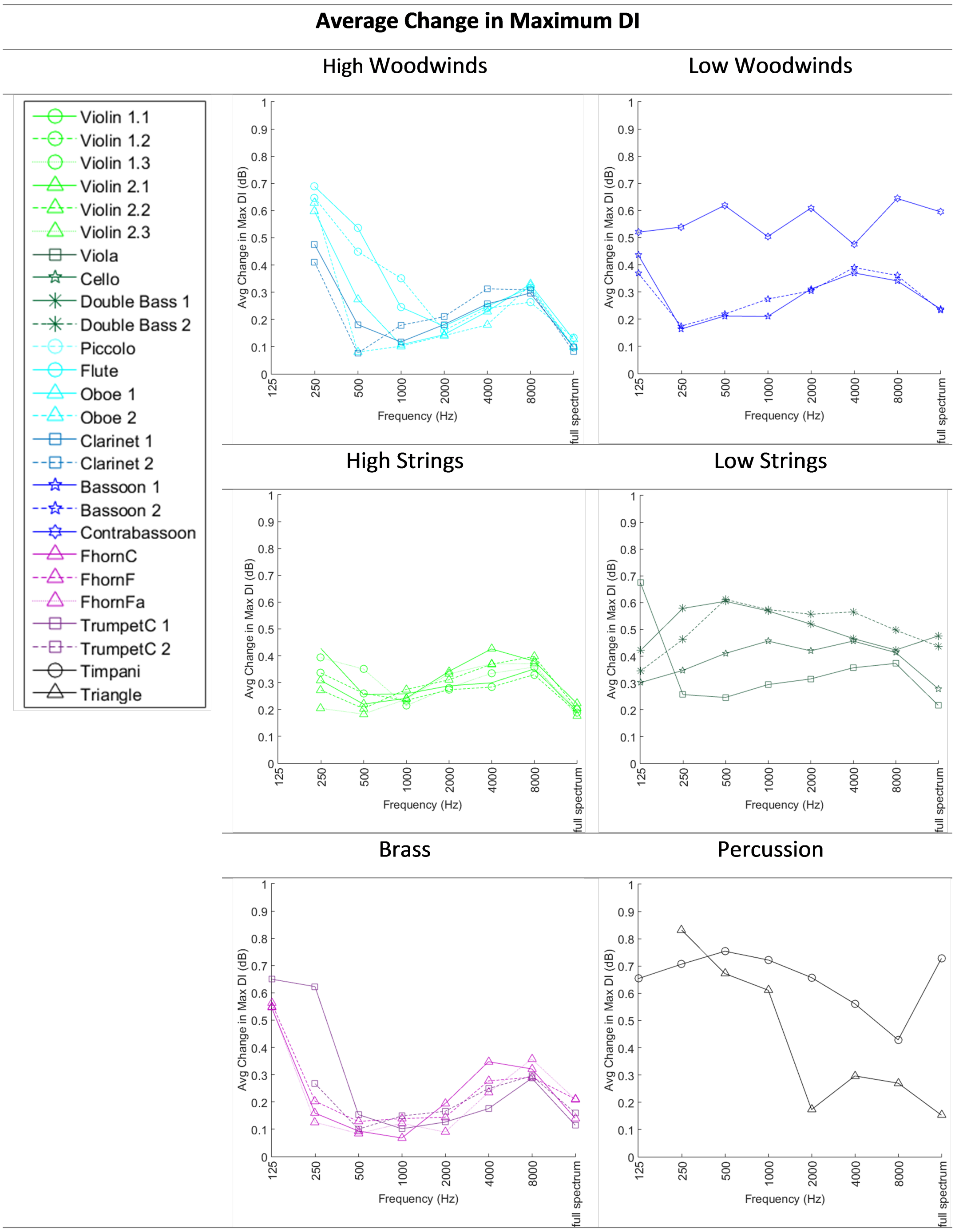

Figure 4.11: Average Change in Maximum DI separated by instrument for the Brahms symphony (Source: Author)

4.2.4 Location Change Ratio

The Location Change Ratios for the Mozart symphony are shown in Figure 4.12. This plot shows ratios close to zero for the brass instruments, especially in the mid to high frequencies. Though the string instruments have higher Location Change Ratios in general, the magnitude of the Location Change Ratio is largely dependent on individual instrument and frequency band, specifically within the woodwind group. For example, in the Mozart symphony excerpt, the first and second bassoon parts have the highest two Location Change Ratios for the full spectrum as shown in Figure 4.12. Additionally, instruments with the highest ratios at the 125 Hz, 250 Hz, and 4000 Hz octave bands are in the woodwind group, while stringed instruments exhibit the highest Location Change Ratios for the other four octave bands. The generally large Location Change Ratios for the stringed instruments may give some quantifiable support to Weinreich's description of the violin's "directional tone color".

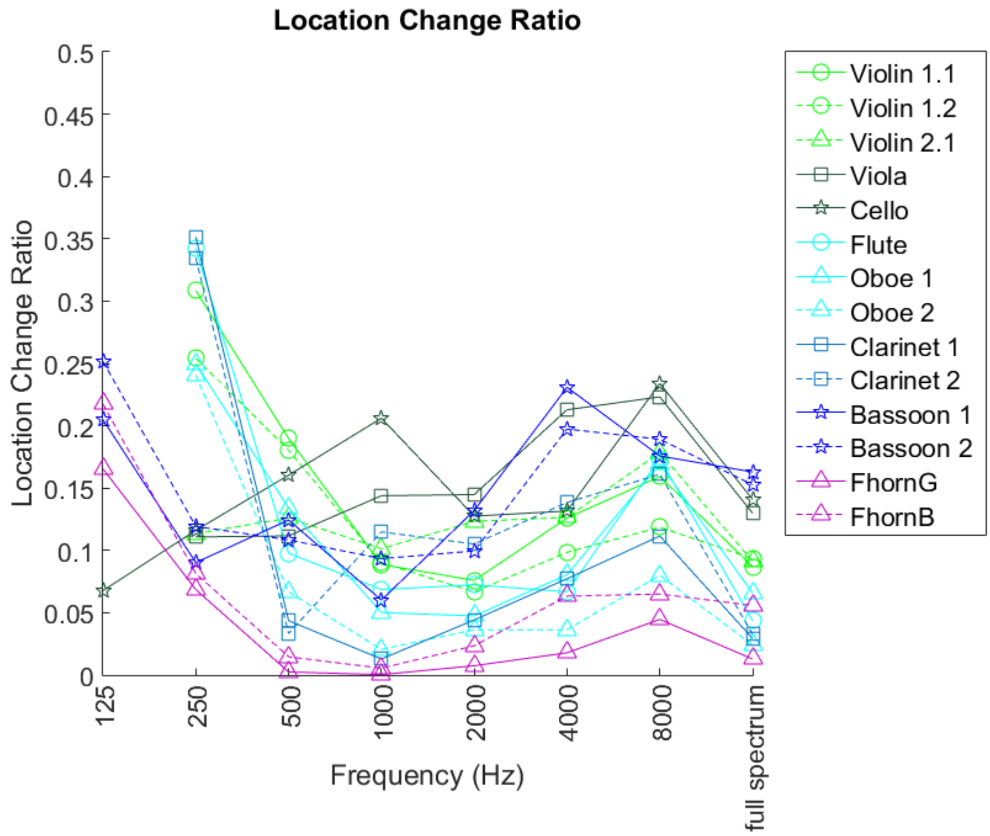

Figure 4.12: Location Change Ratios for the Mozart symphony (Source: Author)

In the breakdown of instrument groups shown in Figure 4.13, there is a somewhat consistent trend for all instruments of higher ratios at low frequencies with another peak in the upper frequency bands around 4000 Hz or 8000 Hz. It is again worth noting that the peaks in the low frequencies may be inaccurate depending on the specific instrument's playing range and potential lack of lower frequency content in the recording. This is not an issue in the upper frequency ranges due to harmonics that are present, even in lower playing ranges. Regardless, in the mid to upper frequencies, the strings and bassoons have generally higher Location Change Ratios in comparison to the high woodwinds and the brass.

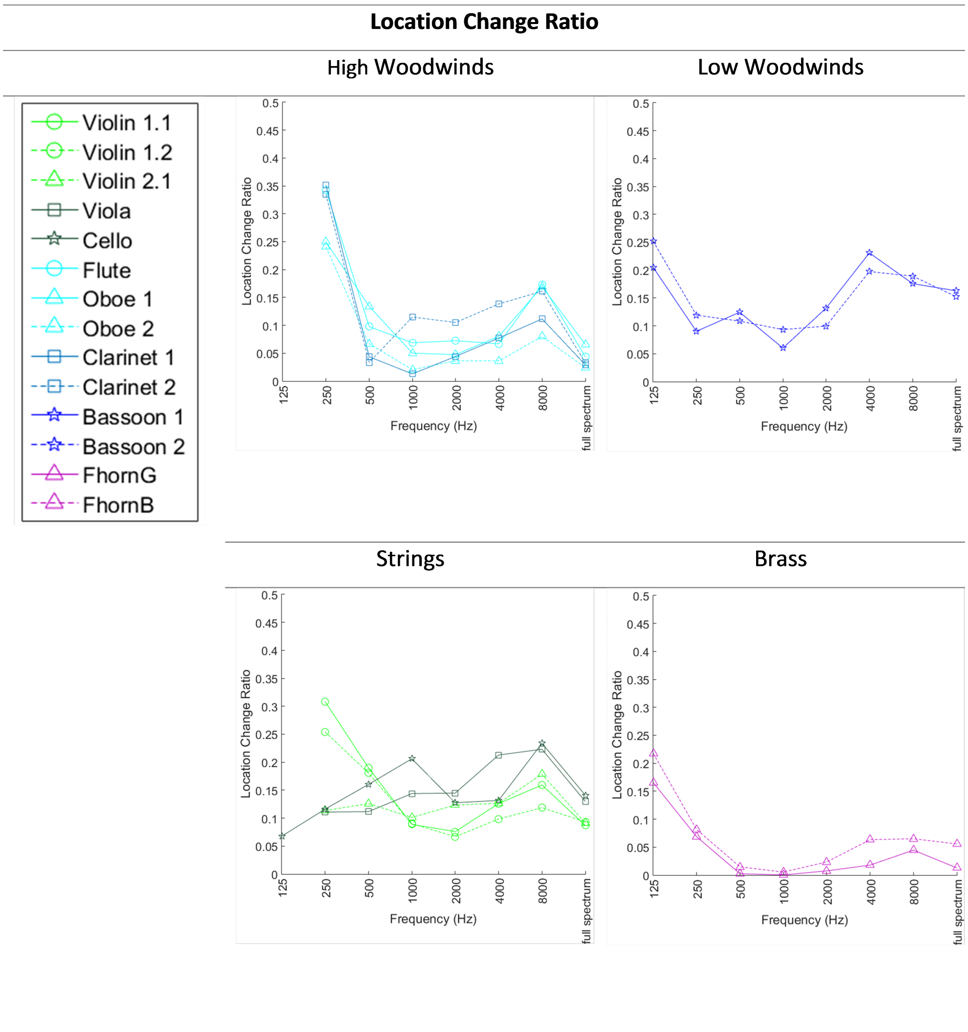

Figure 4.13: Location Change Ratio separated by instrument for the Mozart symphony (Source: Author)

In the Brahms symphony shown in Figure 4.14, stringed instruments again have consistently high Location Change Ratios, as seen with the Mozart excerpt. The contrabassoon in particular shows exceptionally high Location Change Ratio values for the 2000, 4000, and 8000 Hz octave bands. The percussion instruments show exceptionally high Location Change Ratio values for frequencies below 2000 Hz. It is possible that these high ratio values in the lower frequency regions for the percussion instruments may have some link to

the atonal properties that these instruments possess.

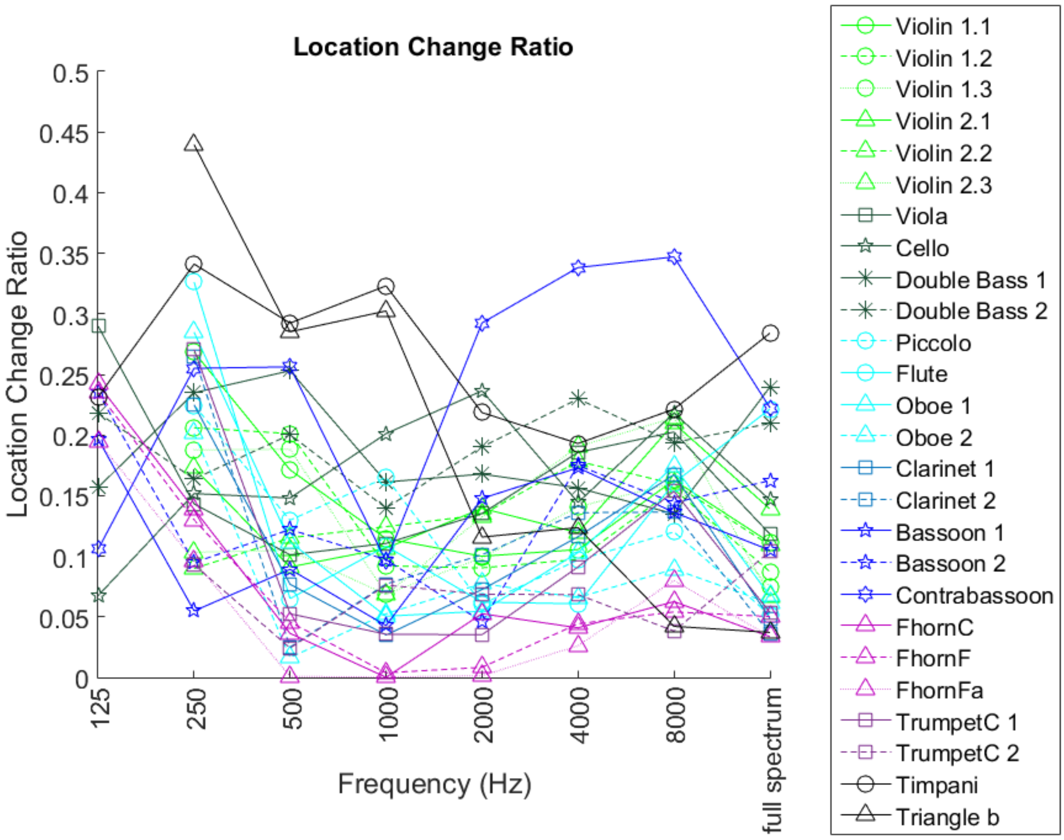

Figure 4.14: Location Change Ratios for the Brahms symphony (Source: Author)

In the instrumental group breakdown for the Brahms symphony in Figure 4.15, similar comparisons between the groups are seen from the Mozart symphony excerpt. Although there is some overlap between instrumental groups, strings have generally higher Location Change Ratios while the brass instruments have some of the lowest ratios. The contrabassoon behaves uniquely from the bassoon regarding its directional characteristics. The tympani does not have a clear primary direction of propagation mainly due to the shape of the instrument. Thus, the tympani has some of the highest Location Change Ratios.

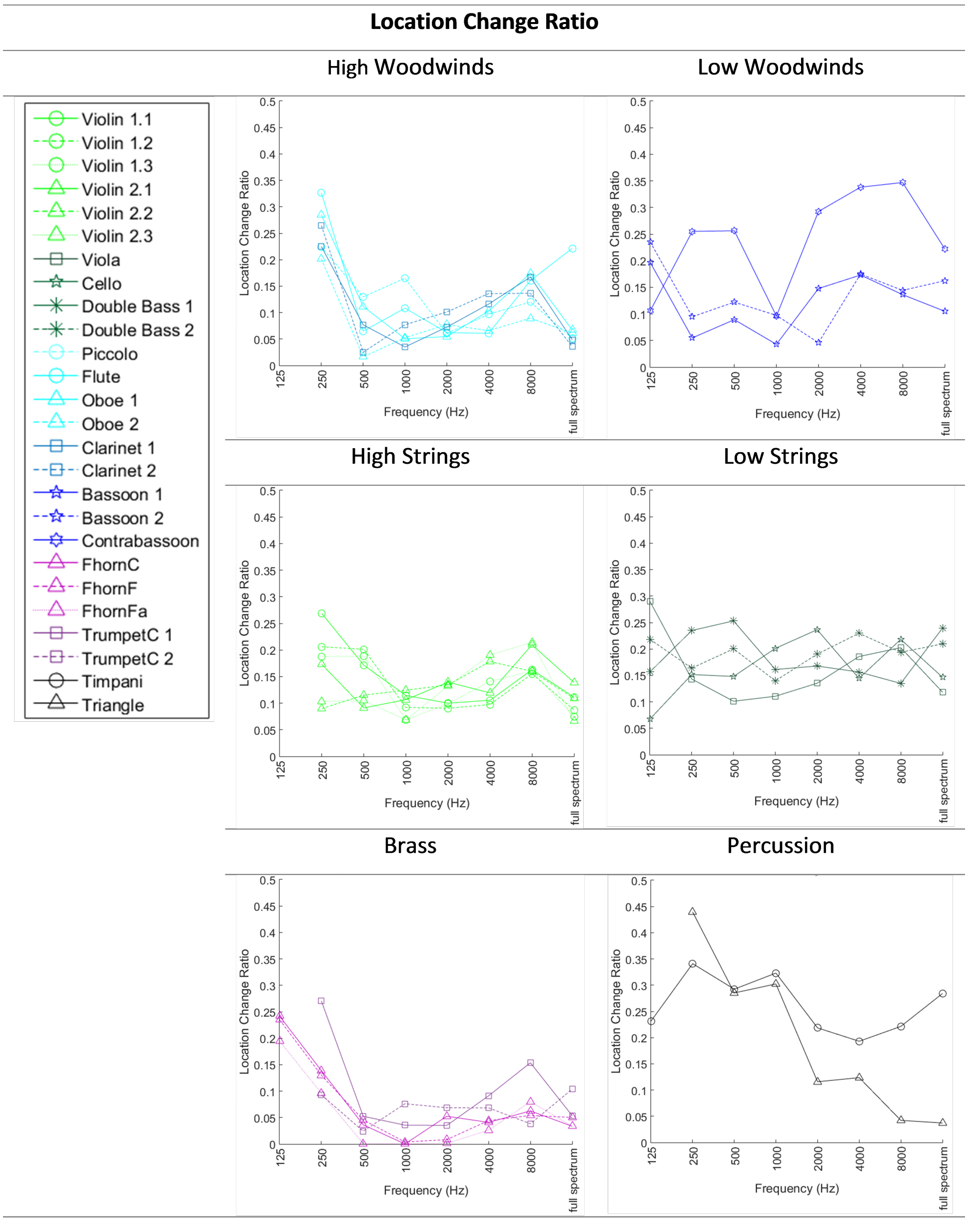

Figure 4.15: Location Change Ratio separated by instrument for the Brahms symphony (Source: Author)

4.2.5 Dominance Ratio

The Dominance Ratio results for the Mozart symphony are shown in Figure 4.16. In general, there is an inverse trend between the Location Change Ratio and Dominance Ratio. The brass instruments tend to have extremely high

Dominance Ratios and low Location Change Ratios. However, these metrics are not entirely inversely related, as the clarinet shows the lowest Dominance Ratio for the Mozart instruments at 4000 Hz, yet does not have the highest value for Location Change Ratio at this same frequency band.

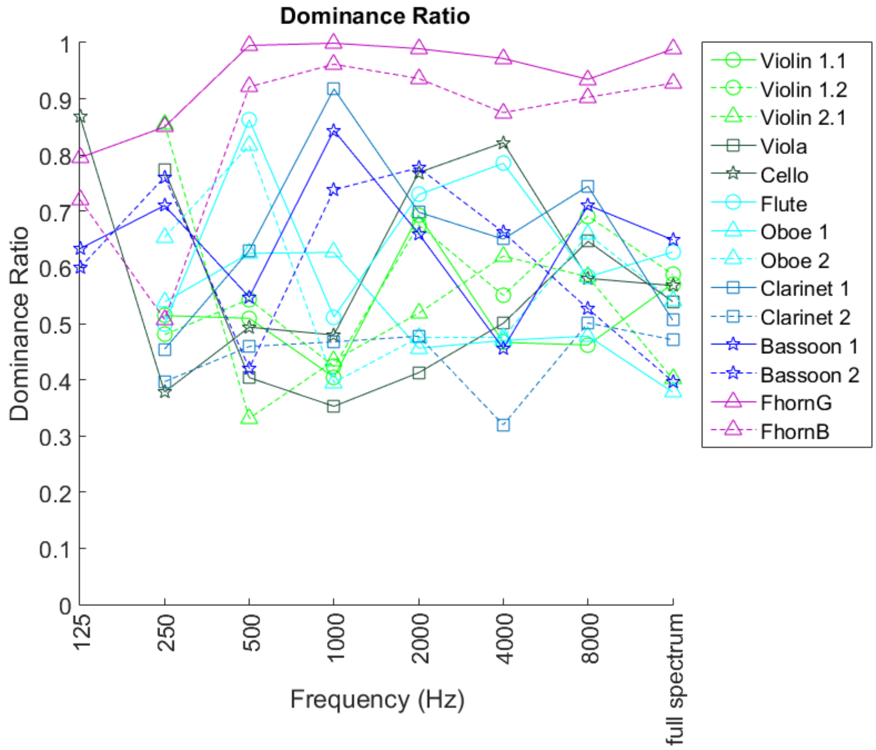

Figure 4.16: Dominance Ratios for the Mozart symphony (Source: Author)

Figure 4.17 shows quite a bit of variation for Dominance Ratio between instrument groups. The French horns show the highest Dominance Ratios, especially in the upper frequencies. This is consistent with brass instruments characteristically having strong directionality patterns at higher frequencies.

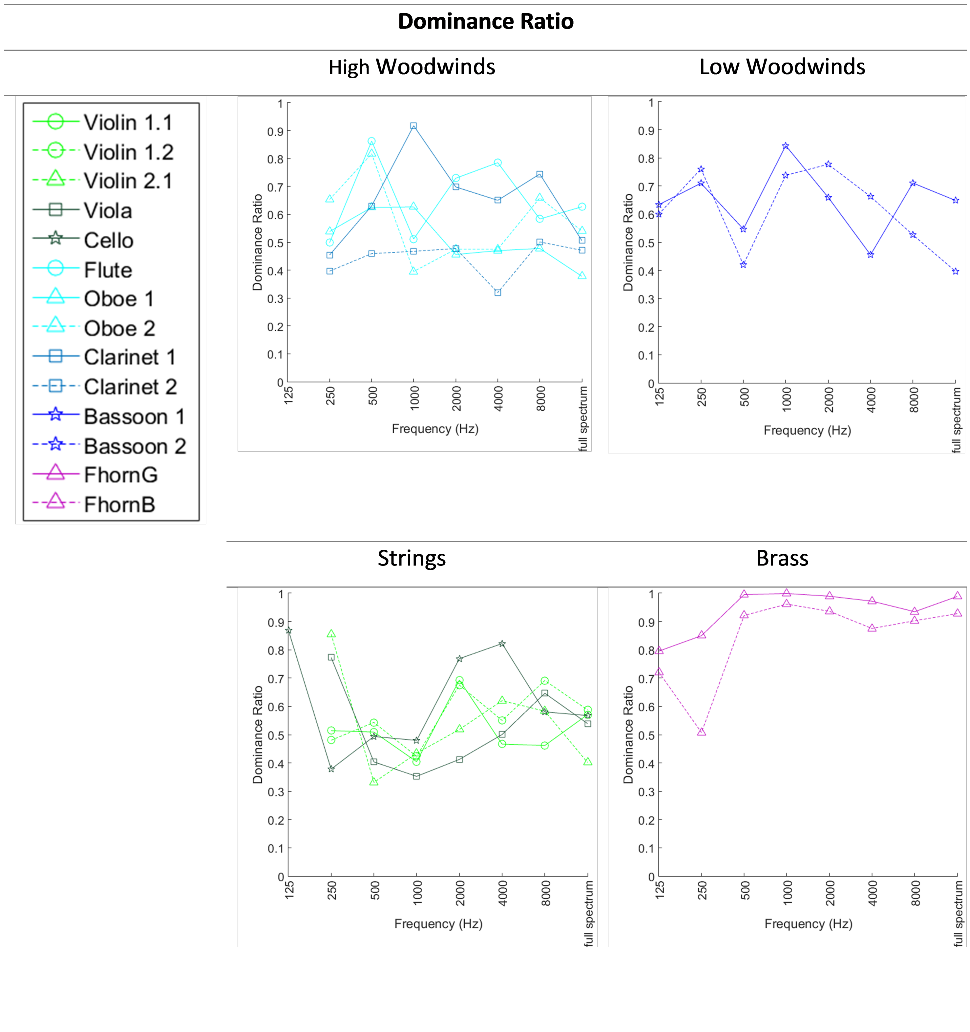

Figure 4.17: Dominance Ratio separated by instrument for the Mozart Symphony (Source: Author)

The corresponding Dominating Channel for each instrument is shown in Table 4.1 by frequency band. The integer numbers in the table correspond to which of the five microphone channels is associated with the Dominance Ratio for that particular instrument and octave band. Some instruments have more variance in the Dominating Channel over the frequency bands while other instruments have a single spatial direction that dominates for almost all of the frequency bands. With five channel anechoic recording data, there is not

much to be evaluated with the amount of variation in dominating channels for an instrument. Nearly all of the instruments have either two or three channels that are represented in the table of dominating channels. Data involving more microphones positions may be capable of giving more detail as to if and how instruments vary in corresponding Dominating Channels associated with the Dominance Ratio. General differences in primary direction of radiation are visible with five channel data. The French horn is unique in having a Dominating Channel of 4 due to the instrument's backward facing bell.

Table 4.1: Corresponding dominating channels for the Mozart symphony

	Frequency (Hz)							
Instrument	125	250	500	1000	2000	4000	8000	Full
Violin 1-1		1	5	5	5	2	5	5
Violin 1-2		1	2	5	5	5	5	5
Violin 2		2	3	3	5	2	2	5
Viola		1	2	1	5	2	5	1
Cello	1	5	2	1	5	5	1	1
Flute		5	5	1	1	1	2	1
Oboe 1		5	5	1	5	5	1	5
Oboe 2		5	5	5	5	5	1	5
Clarinet 1		2	1	5	5	2	1	1
Clarinet 2		1	5	2	2	5	2	5
Bassoon 1	1	1	5	5	5	5	1	5
Bassoon 2	1	1	5	2	2	2	1	5
Fhorn in G	1	4	4	4	4	4	4	4
Fhorn in B	1	1	4	4	4	4	4	4

Dominance Ratios for the Brahms instruments are shown in Figure 4.18. A low Dominance Ratio may be an indication of substantial "directional tone

color". However, many of the other stringed instruments as well as the upper woodwinds have equally low Dominance Ratios to that of the violin. The violin does not have exceptional Dominance Ratio magnitudes that set it apart from other instruments.

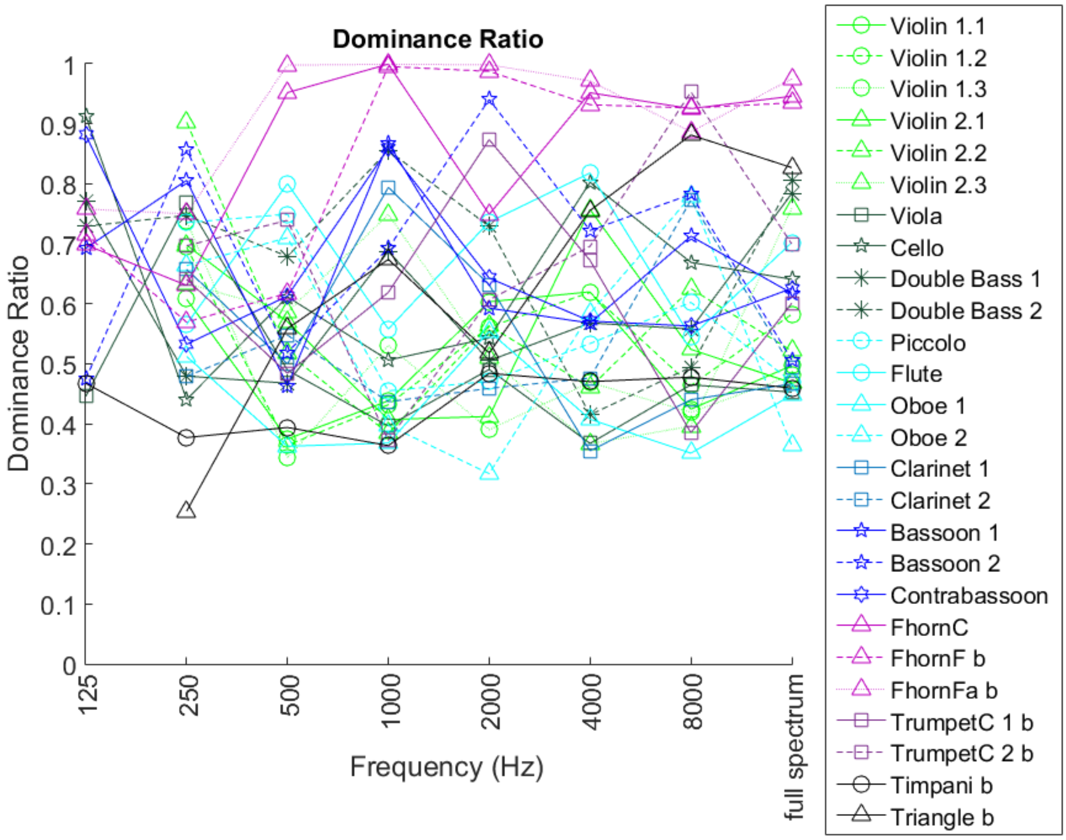

Figure 4.18: Dominance Ratio by instrument for the Brahms Symphony (Source: Author)

The Dominance Ratios for particular instrument groups are shown in Figure 4.19. Although the French horns have the highest Dominance Ratios, the Dominance Ratio values of the trumpet parts are less extreme. This suggests that while high Dominance Ratios may be characteristic of French horns, this may not be a safe assumption to make for all brass instruments.

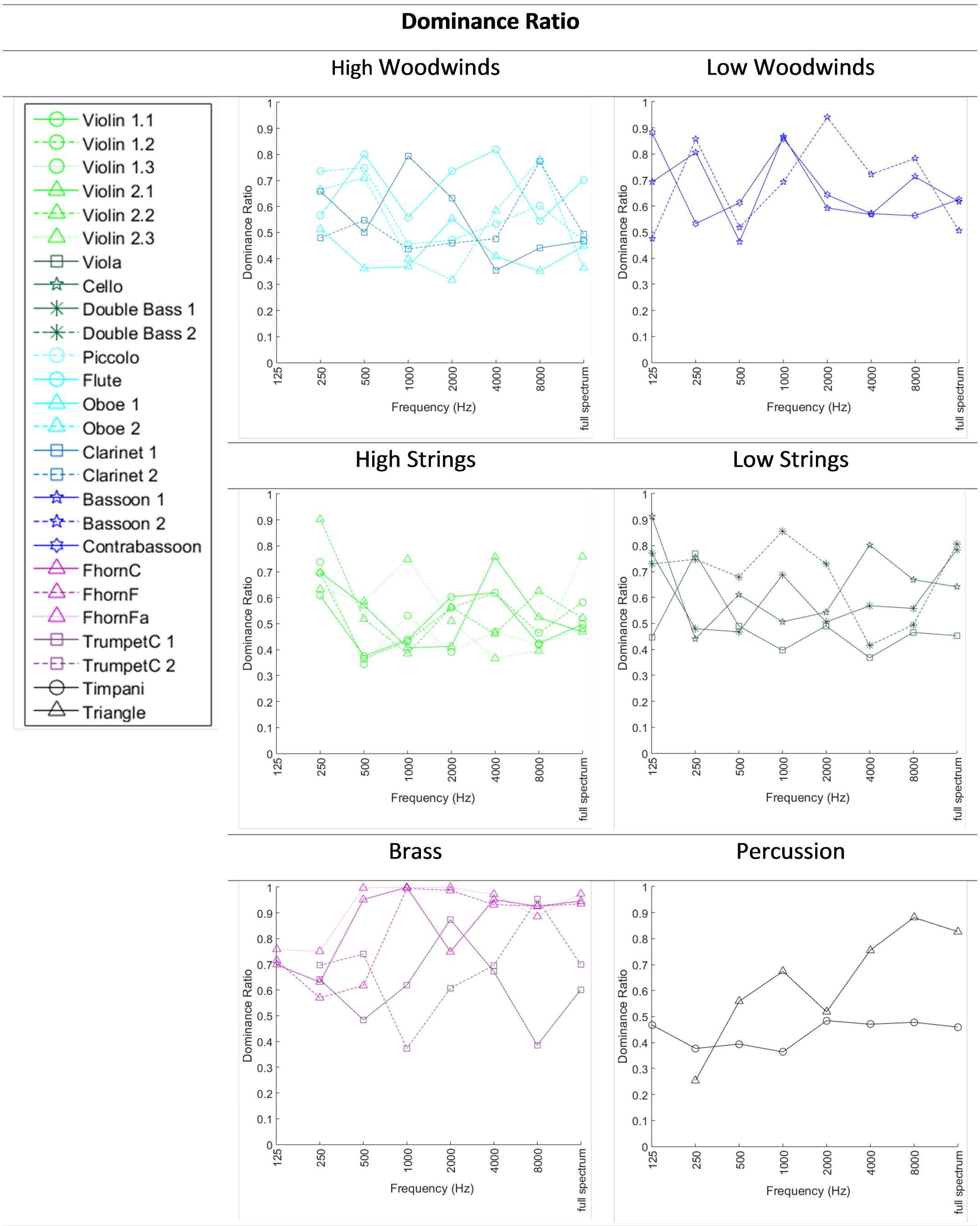

Figure 4.19: Dominance Ratio separated by instrument for the Brahms Symphony (Source: Author)

Further examining the corresponding channels associated with the Dominance Ratios gives more insight as to how instruments change spatial propagation between frequency bands. Table 4.2 shows the dominating channels for each

octave band for the instruments in the Brahms recordings. As with the Mozart symphony, the Brahms instrumental parts are also dominated by either two or three channels. As mentioned before, with limited microphones used in data collection, the amount of detail obtained in spread of spatial directionality dominance is limited using the five channel data.

Table 4.2: Corresponding dominating channels for the Brahms symphony

Frequency (Hz)

Instrument	125	250	500	1000	2000	4000	8000	Full
Violin 1-1		1	2	5	5	2	5	5
Violin 1-2		1	5	5	5	5	5	5
Violin 1-3		1	5	1	1	1	2	1
Violin 2-1		2	3	3	2	2	2	3
Violin 2-2		2	2	5	5	5	2	2
Violin 2-3		5	1	1	1	2	1	1
Viola	1	1	5	5	2	5	1	5
Cello	1	5	1	1	5	5	1	1
Double Bass 1	2	2	2	2	2	3	3	2
Double Bass 2	2	2	2	2	2	3	3	2
Piccolo		5	5	5	5	1	2	5
Flute		5	5	1	1	1	1	1
Oboe 1		5	5	1	3	1	1	3
Oboe 2		5	5	2	5	1	1	5
Clarinet 1		2	1	5	2	1	1	5
Clarinet 2		1	1	2	2	1	2	1
Bassoon 1	1	1	5	5	5	5	1	5
Bassoon 2	1	1	5	2	2	2	1	5
Contrabassoon	2	2	2	2	2	3	2	2
Fhorn C	1	4	4	4	1	4	4	4
Fhorn F	1	4	4	4	4	4	4	4
Fhorn Fa	1	4	4	4	4	4	4	4
TrumpetC 1		2	1	2	1	2	1	1
TrumpetC 2		1	2	2	2	2	2	2
Timpani	1	1	1	1	2	2	1	1
Triangle		4	1	1	1	1	2	2

4.3 Excerpt Comparisons

The time-varying quantifiers were compared and contrasted for each symphonic excerpt separately in Section 4.2 in order to assess the tendencies within and between instrument groups. In Section 4.3, the quantifier results for the two symphonies are compared by instrument in order to examine the influence of musical excerpt on the quantifiers. The Figures in Section 4.3 show four plots of time-varying directionality quantifiers with magenta and navy lines representing the Mozart and Brahms parts, respectively.

4.3.1 Strings

Figure 4.20 shows four quantifiers for the first violin parts. The Average Maximum Directivity Index and Average Change in Maximum DI results for the first violin are relatively consistent regardless of the musical excerpt. The Location Ratio shows similar results. However, the Dominance Ratio results show more variance. The results at some frequency bands suggest that Dominance Ratio may be more excerpt dependent, while other frequency bands disagree with this hypothesis. Whether the large amount of variance in Dominance Ratio patterns are due to the part, player, or instrument is a question for further investigation. For the first violin comparison, the first two players of the first violin part are very closely matched in Dominance Ratio values while the third player differs more prominently, namely in the 2000 Hz and 4000 Hz octave bands. The first violin parts for the Mozart symphony are closely related at most frequencies, but more variation arises in the 4000 Hz and 8000 Hz octave bands.

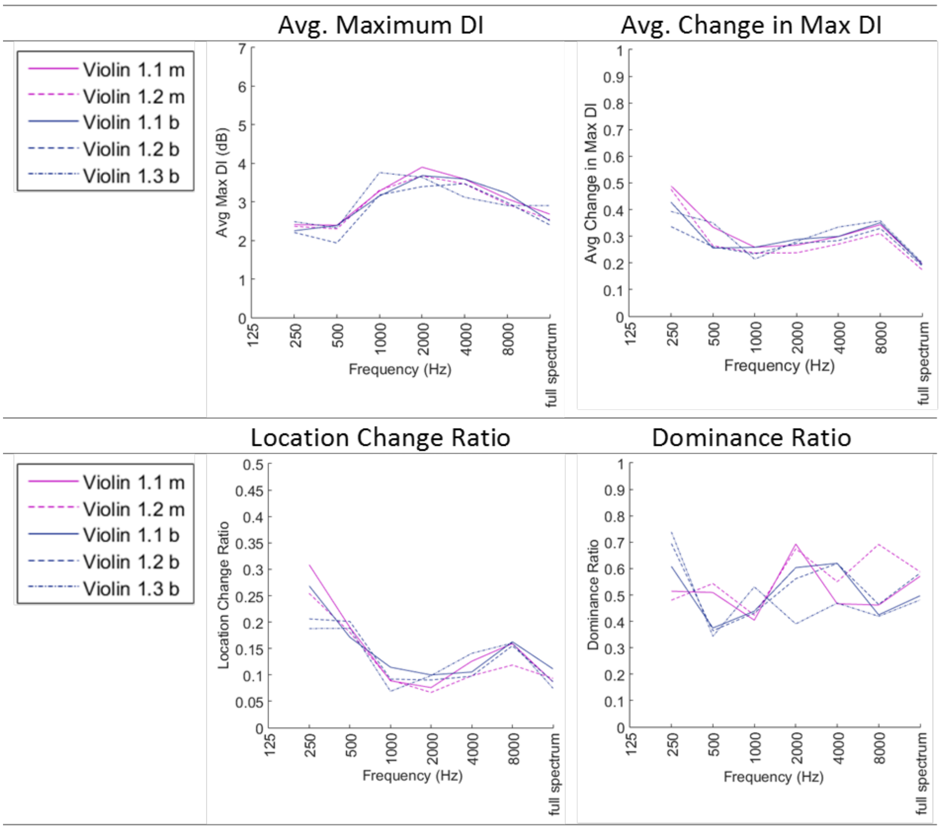

Figure 4.20: Excerpt comparisons of quantifiers for first violin parts (Source: Author)

The second violin quantifiers shown in Figure 4.21 show results similar to those for the first violin part. The Average Maximum DI, Average Change in Maximum DI, and Location Change Ratio results are more predictable between excerpts while the Dominance Ratio results show a large amount of variation between the individual instruments. Although there is quite a bit of predictability for three of the quantifiers within a specific instrument part, the violin 1 and violin 2 parts show trends that are distinguishable from one another at some frequency bands. This suggests that physical qualities of the individual instrument or the player may have a significant effect on the

directionality properties observed.

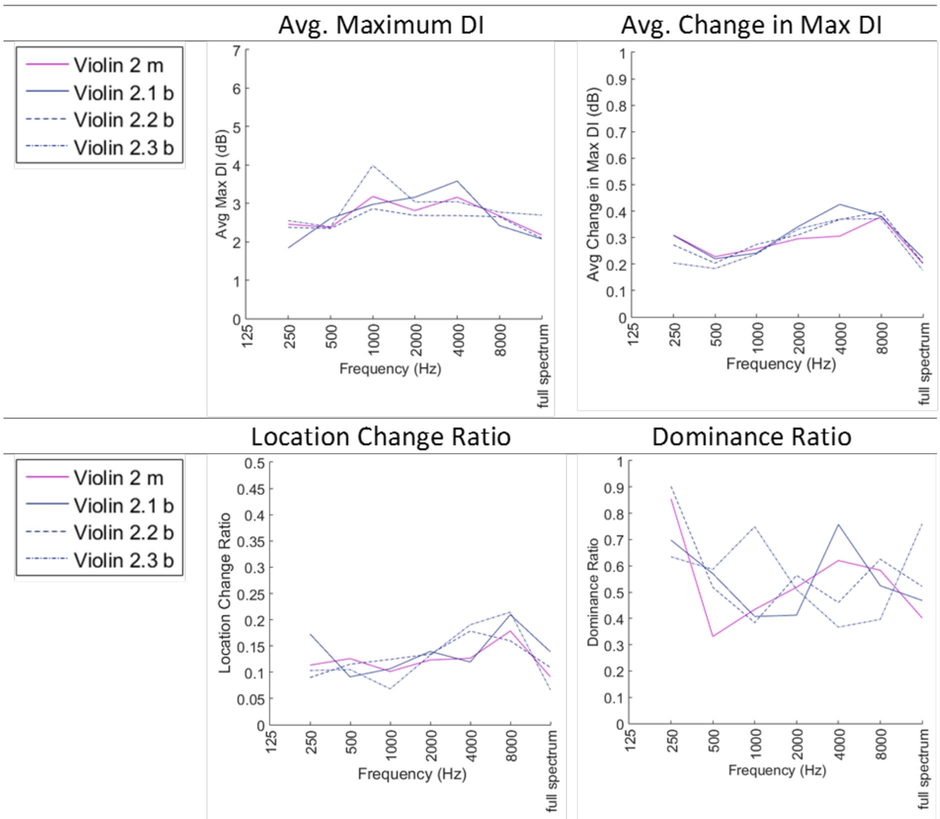

Figure 4.21: Excerpt comparisons of quantifiers for second violin parts (Source: Author)

Figures 4.22 and 4.23 show the quantifiers for Mozart vs. Brahms viola and cello parts. Some of the instrumental trends described in Section 4.2 are more easily seen in these figures. Unlike the violin parts, the Dominance Ratio values for the viola and cello parts are more closely related between the Mozart and Brahms.

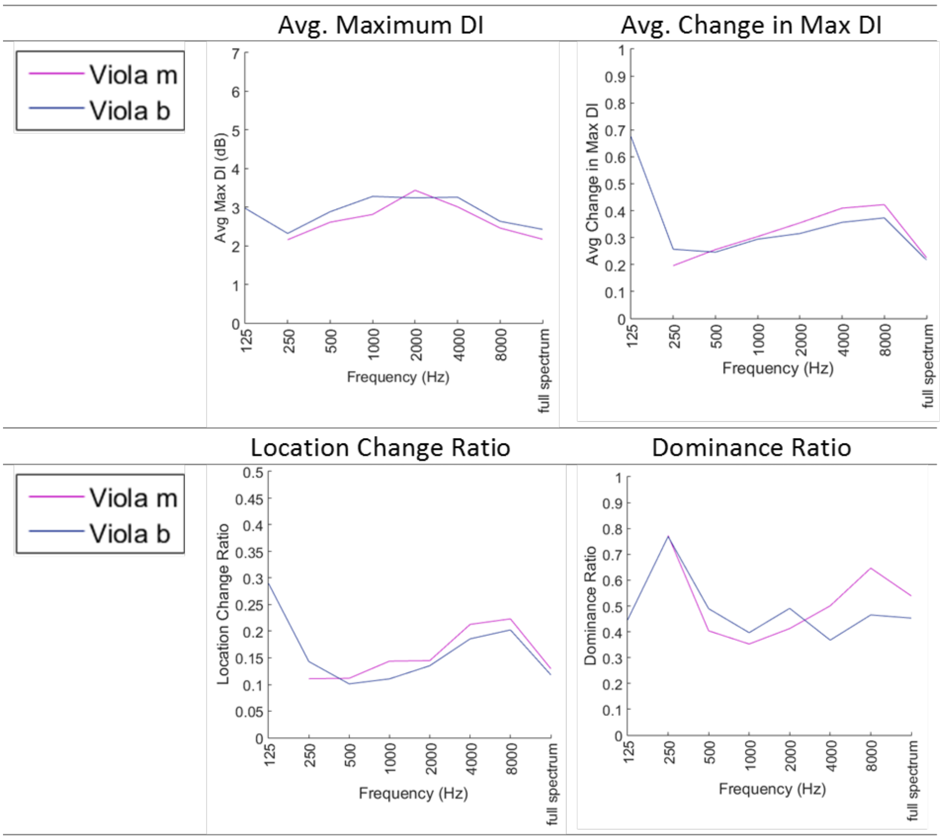

Figure 4.22: Excerpt comparisons of quantifiers for viola parts (Source: Author)

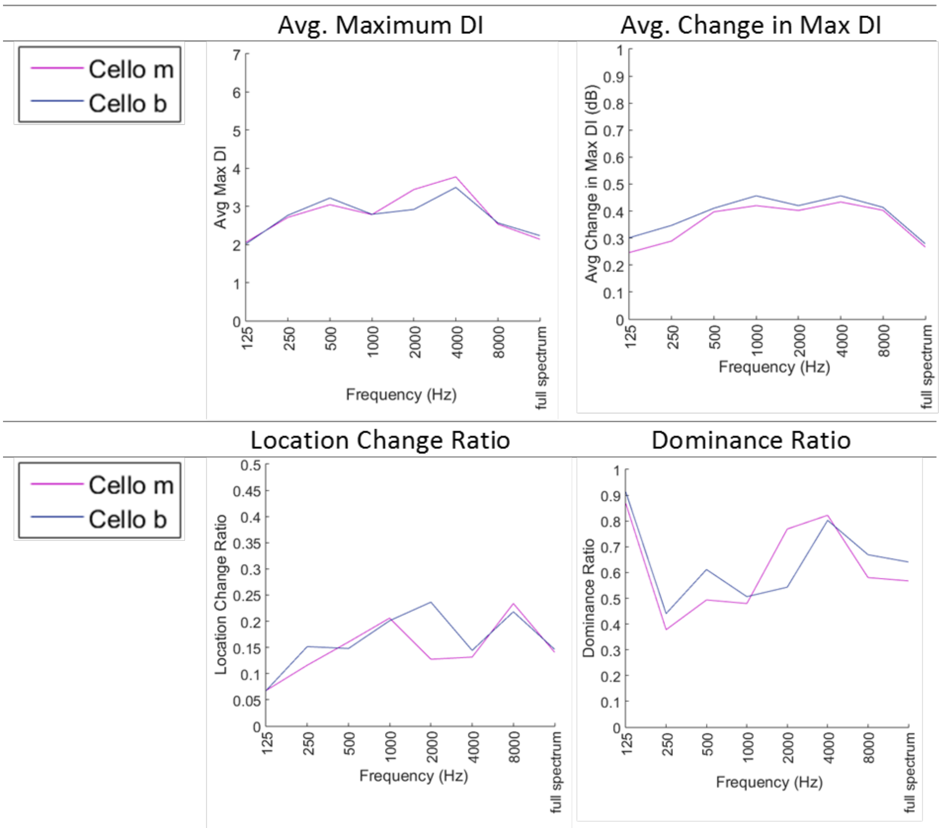

Figure 4.23: Excerpt comparisons of quantifiers for cello parts (Source: Author)

4.3.2 Woodwinds

Figures 4.24 and 4.25 show the time-varying directivity quantifiers for each of the symphonies for the woodwind group by instrument. Figure 4.24 also includes the piccolo in addition to the flute part. In looking at the results in Figure 4.24, the flute shows clear trends with all four of the directivity metrics. Within the Brahms symphony, the results for the flute and the piccolo differ much more than the flute parts from the separate symphonies. This supports that the specific instrument is more important than the excerpt regarding directional characteristics.

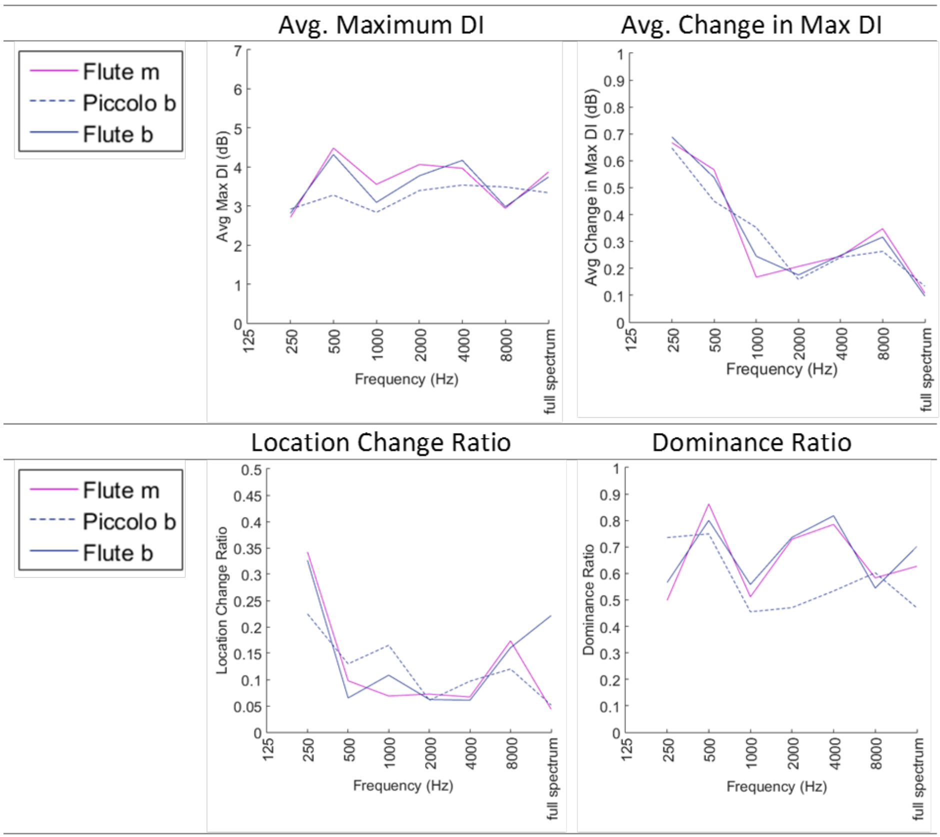

Figure 4.24: Excerpt comparisons of quantifiers for flute parts (Source: Author)

Figure 4.25 shows quantifier results for the oboe. The Dominance Ratio remains the most unpredictable quantifier. The four figures give evidence supporting distinguishable directivity differences among specific parts, whether this is due to different models of oboe instruments, reed types, or the musicians themselves.

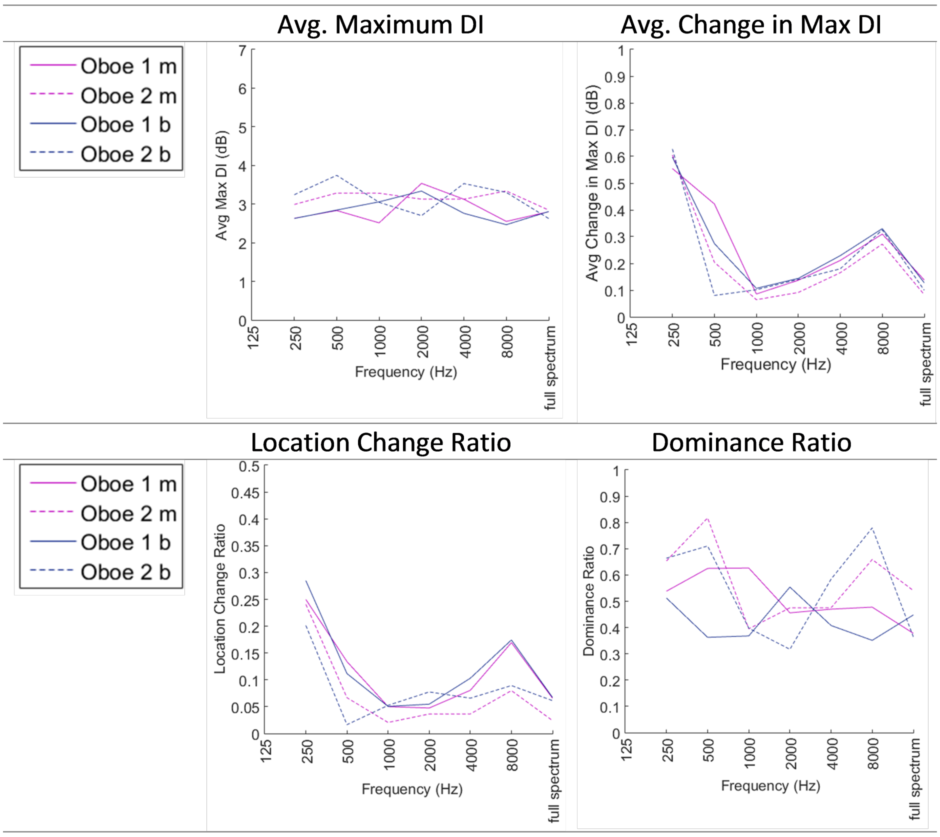

Figure 4.25: Excerpt comparisons of quantifiers for oboe parts (Source: Author)

The quantifiers for the clarinet parts are shown in Figure 4.26. In general, the clarinets seem to be more closely related by instrument than excerpt for the four quantifiers shown, although there are no consistent patterns with the Dominance Ratio across the frequency range.

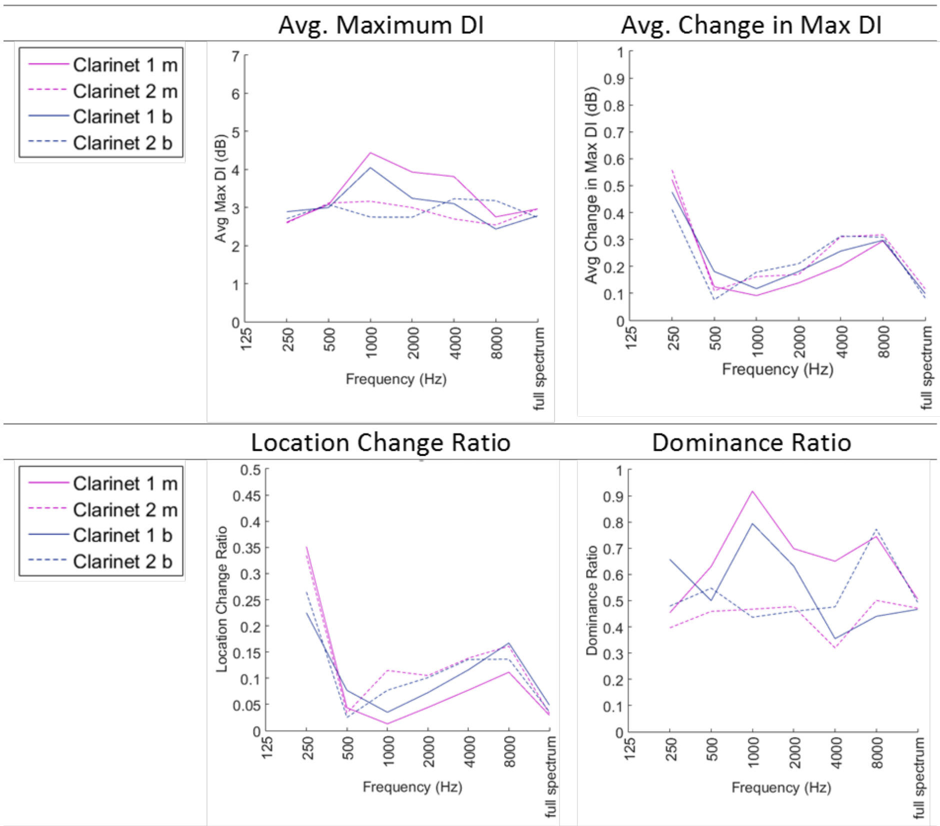

Figure 4.26: Excerpt comparisons of quantifiers for clarinet parts (Source: Author)

The set of quantifiers for the bassoon parts are shown in Figure 4.27. As with the other instruments, Average Maximum DI and Location Change Ratio are relatively consistent between the two symphonies. The Average Maximum DI for the contrabassoon is comparable to the values for the bassoon parts. However, the Location Change Ratio values for the contrabassoon are more unique for this particular instrument. Dominance Ratio values are once again less predictable, though the values for both bassoon parts and the contrabassoon part all fall within a common range.

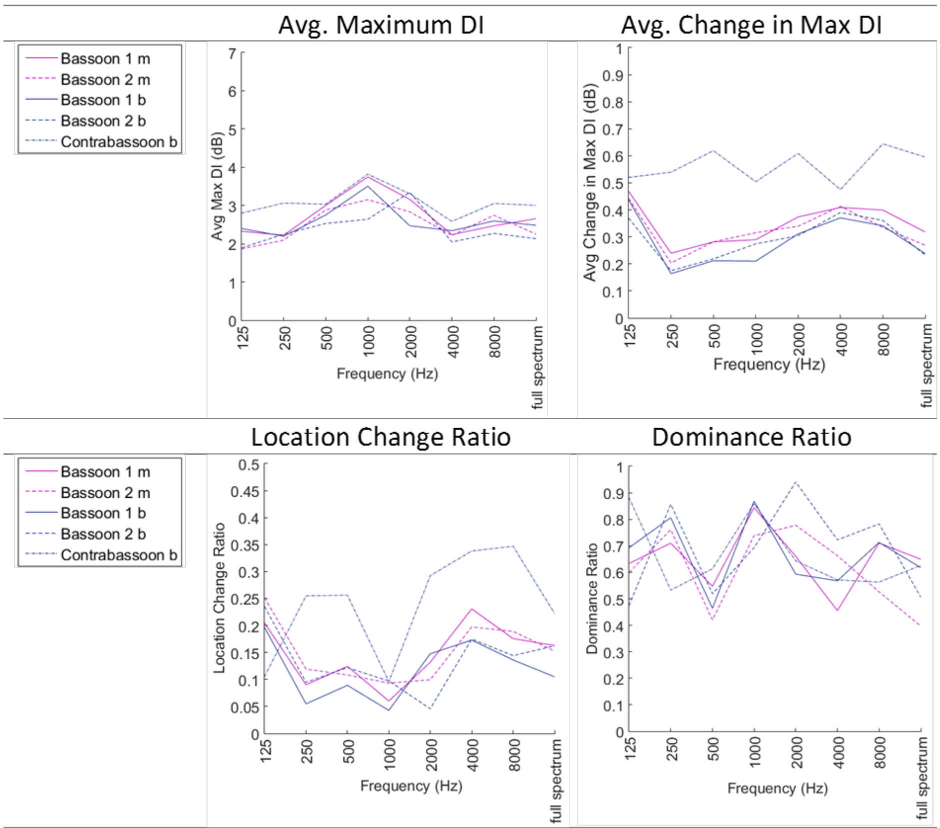

Figure 4.27: Excerpt comparisons of quantifiers for bassoon parts (Source: Author)

4.3.3 Brass

Time varying directivity metrics for the French horns for both the Mozart and Brahms symphonies are shown in Figure 4.28. The French horn is the only brass instrument used in excerpt comparison, since this was the only brass instrument common to both of the symphonic excerpts. Given the unique nature of the French horn, excerpt-related conclusions involving the brass section as a whole are not possible. Even with the French horn, the instrument recordings used involved horns in different keys, adding another

level of variation to the data. Still, there are commonalities seen in all of the metrics for the French horn. The Dominance Ratio shows more consistency for the French horn than the other instruments analyzed. The reason for this may be due to the general extremity of Dominance Ratio values that brass instruments tend to have, as discussed in Section 4.2.

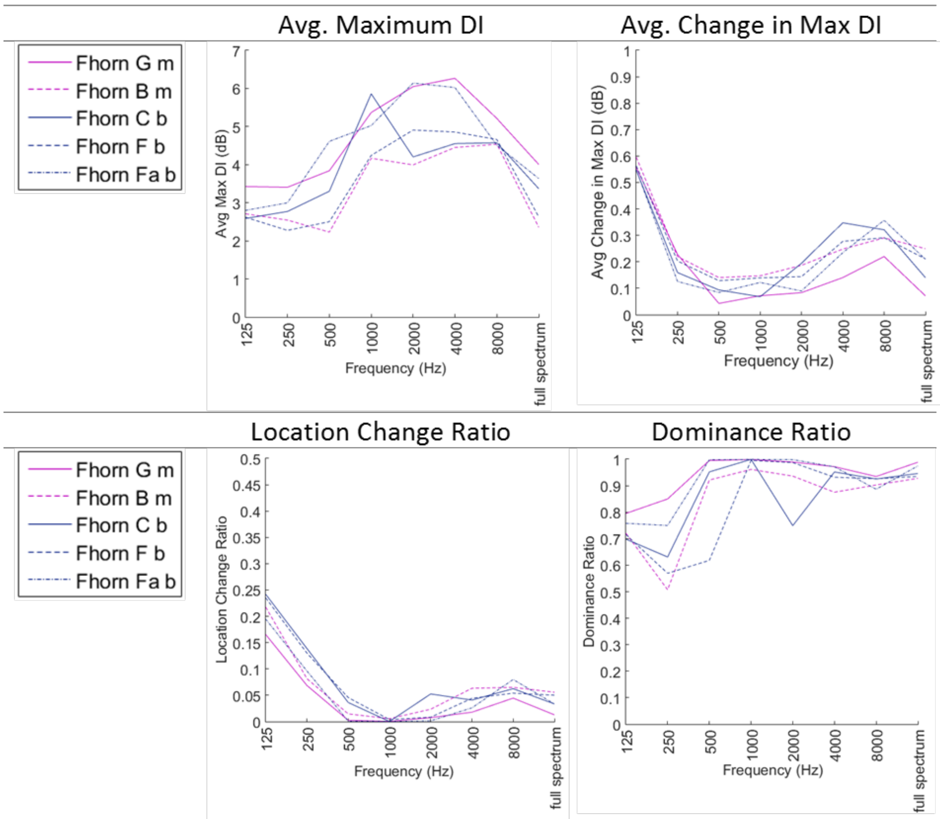

Figure 4.28: Excerpt comparisons of quantifiers for French horn parts (Source: Author)

4.4 Shortcomings

4.4.1 Recording Setup

One of the major shortcomings is the setup used for the anechoic recordings. Five channels provide very limited insight to the true directivity patterns of musical sources. Additional channels may result in increased resolution. Additionally, the number of channels affects the values of the metrics obtained, specifically with the ratio metrics. Ratio metrics including Location Change Ratio and Dominance Ratio rely heavily on the amount of channels, so this may affect the ability to draw conclusions of time-varying directivity properties in future research without the consideration of channel count. Another shortcoming related to the recording setup is the nature of the instrumentalist. Unique tendencies of a player can be hard to control and account for and may cause small amounts of variation in data for spatially sensitive directivity metrics.

4.4.2 Physical Instrument Characteristics

The physical musical instruments themselves may have directional qualities inherent to that instrument that are difficult to account for when attempting to compare so many other variables such as excerpt and instrument family. Two violin recordings of the same excerpt played by the same player on two separate violins may result in significantly different directivity quantification results due to variables such as the materials and construction of the instrument. Thus, it may be difficult to differentiate in the analysis whether

certain trends are due to the written musical part, the instrumentalist, or the specific violin being played.

4.4.3 Excerpts and Instrumentation

A shortcoming in excerpt comparisons is the instrumentation used in the symphonies. The only brass instrument that is included in both the Mozart and the Brahms symphonies is the French horn, which tends to have unique directional characteristics compared to the brass family as a whole. Thus, it is difficult to grasp a full understanding of brass time-varying directionality characteristics as they relate to a symphonic excerpt with the limited instrumental data discussed.

With the use of only two different musical excerpts, it may be difficult to fully understand the importance of excerpt in relationship to these directivity quantifiers. Although Mozart and Brahms are stylistically different composers, comparing these symphonies may show less variation than when compared to something more different such as a Jazz or Latin musical excerpt. Many of the shortcomings described here may be overcome and better understood by continuing research in this area and analyzing additional data.

Chapter 5

Application of Quantifiers

One of the shortcomings mentioned in the study and quantification of time-varying directivity is the difference in amount of channels used in data acquisition. Each microphone essentially takes a sample of the radiation of the instrument at a specific point. Thus, more microphones provide a more detailed sample of the true radiation pattern of a source. In order to further examine the limitations of the number of microphones or channels used in the recording process, three sets of data are analyzed and compared. These data sets include the five channel and thirteen channel anechoic recordings as described in Section 3.2 as well as 32 channel data for a solo saxophone. Comparing different data sets provides insight to the usefulness and limitations of directivity quantifiers for future evaluation of time-varying directivity properties of a sound source. Additionally, this comparison gives an idea of the adaptability of the quantifiers for application to various types of data.

5.1 Channel Number Comparison

Figure 5.1 shows an arbitrary two-dimensional polar radiation plot of a source in the horizontal plane where the blue line corresponds to the static directivity of a source, and each consecutive circle from the center represents an increase in 1 dB of the value of Directivity Index. In a 5 channel setup, the red points signify the directivity values that are included in the 5 channel sample. In this case, the maximum DI is about 3.2 dB. However, there is a lobe in the lower left quadrant that would be completely missed using this setup. The yellow directivity points would also be included in a sample if using a 13 channel setup. The maximum DI would then be greater than 4 dB. Thus, a large enough number of microphones becomes more crucial to the accuracy of the maximum DI results when dealing with radiation patterns involving many lobes, which is typically more relevant at higher frequencies.

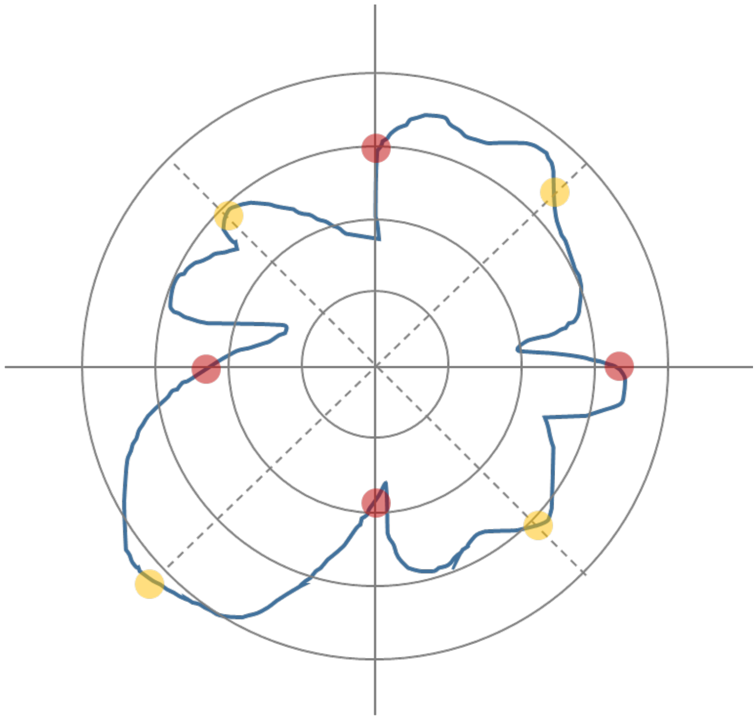

Figure 5.1: Polar plane microphone sampling for 5 and 13 channel setups (Source: Author)

Table 5.1 shows which microphones are spatially equivalent between the thirteen and five channel setups used for the anechoic recordings. The microphone setups are shown in Figures 3.2 and 3.3 in Section 3.2. Channel 1 for both setups corresponds to the forward direction. For the 13 channel setup, the microphone numbers increase clockwise around the instrumentalist for the microphones in the horizontal plane. The 13 channel setup includes additional microphones in the vertical plane at a 45 degree angle between the forward-above and backward-above microphones as well as microphones 45 degrees down from the front and back microphones. This numbering system results in the upward direction corresponding to channel 11 for the thirteen channel setup and channel 5 for the five channel setup. For the five channel setup, microphone 2 is to the right of the player while microphone 3 is to the

left of the player. Microphones 4 and 5 are behind and above the player, respectively. All equivalent channels are specified in Table 5.1.

Table 5.1: Equivalent microphones for 5 vs. 13 channel setups

	Channel Number												
Thirteen Microphone Data	1	2	3	4	5	6	7	8	9	10	11	12	13
Five Microphone Data	1		2		4		3				5		

Comparisons are made between recordings for the violin and flute using 5 channel Mozart recordings and the 13 channel solo excerpt recordings. The Mozart recordings were shortened to 20 seconds to match the length of the 13 channel solo excerpt recordings. Comparisons are made using the quantifiers defined in Section 4.1. Differences in the values obtained for the 5 and 13 channel data are expected given the nature of the metrics. Analyzing 5 and 13 channel data gives insight regarding how the metrics are related to channel number and whether they are related by some predictable factor.

Additional channels provide a larger sampling and increase the likelihood of the true maximum being represented. Given this, the Average Maximum DI and Average Change in Max DI are expected to be higher for the 13 channel data, particularly for higher frequencies which tend to have more lobed radiation patterns. A higher Location Change Ratio is also expected for the 13 channel data, as more channels allows more opportunities for the maximum radiation to change between microphones. Dominance Ratio is expected to be lower for the 13 channel data because more channels are available in the

recording process. For all the metrics, more discrepancies are expected to appear in the higher frequency bands where the radiation patterns are more directional.

5.2 Violin 5 vs. 13

Figures 5.2 and 5.3 give an example of side-by-side 5 channel versus 13 channel 20 second excerpt maximum Directivity Index plots. Although the excerpts are different musical pieces, similarities can be seen in the relative channel distributions. Additional plots for each frequency band can be found in C for both the violin and the flute.

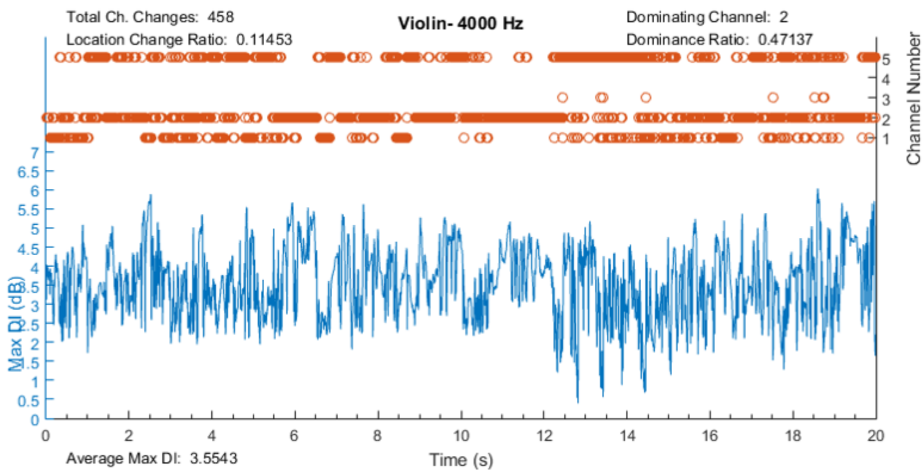

Figure 5.2: Violin- 5 Channel 4000 Hz

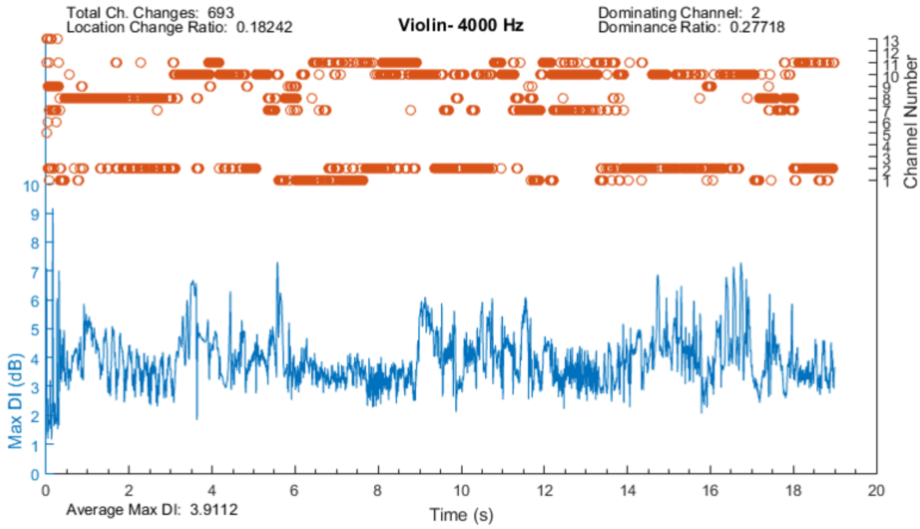

Figure 5.3: Violin- 13 Channel 4000 Hz

Figure 5.4 shows four of the time-varying directivity quantifiers comparing the 5 and 13 channel data. Some of the metrics show closer agreement between channel amounts than others. The Average Change in Maximum DI shows very close agreement between channel amounts, particularly above 500 Hz. Though lower agreement was expected for higher frequencies, this is not necessarily the case.

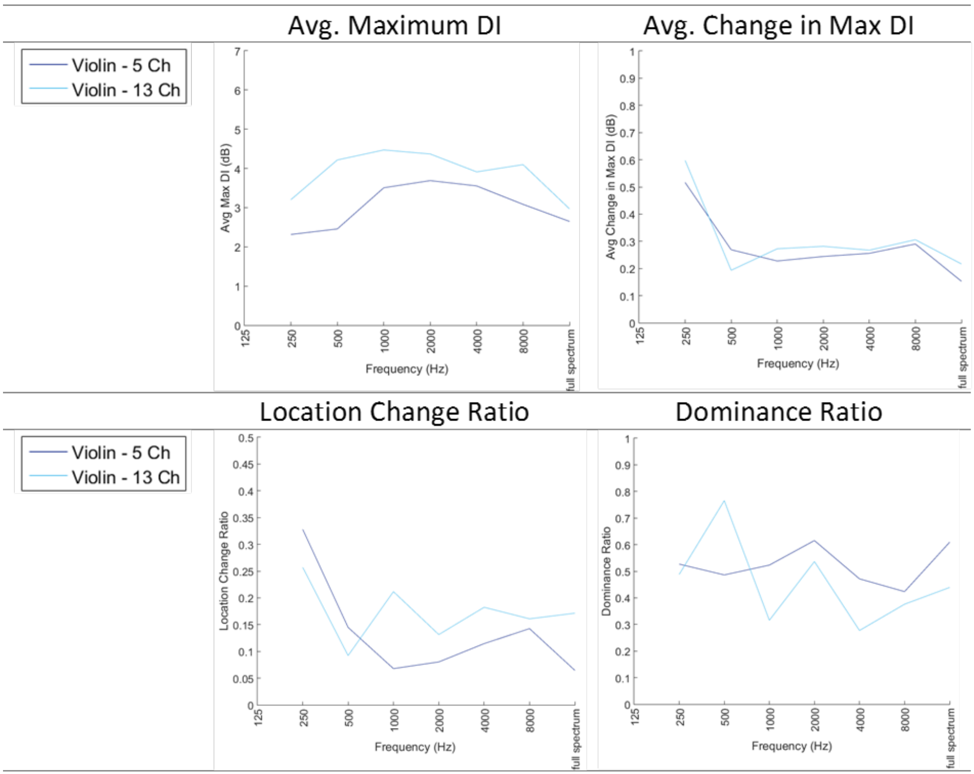

Figure 5.4: Violin quantifier comparisons for 5 vs. 13 channels (Source: Author)

Figure 5.5 shows the percent difference in four calculated metrics for the violin. The Average Change in Maximum DI has less than 18% difference for frequency bands above 500 Hz. However, the range of the violin is relatively high, so there may not necessarily be frequency content radiating from the instrument at the lower bands for the entirety of the excerpt. This leads to more questionability in the lower frequency bands for higher instruments. The Average Maximum DI is also somewhat comparable between channel amounts. The percent difference between Location Change Ratio and Dominance Ratio show trends that are somewhat unclear, although the relationship between the 5 and 13 channel data generally follows the expectations in terms of which is higher. The exception to this is in lower frequency bands, which as previously

mentioned may be the result of a lack of frequency content.

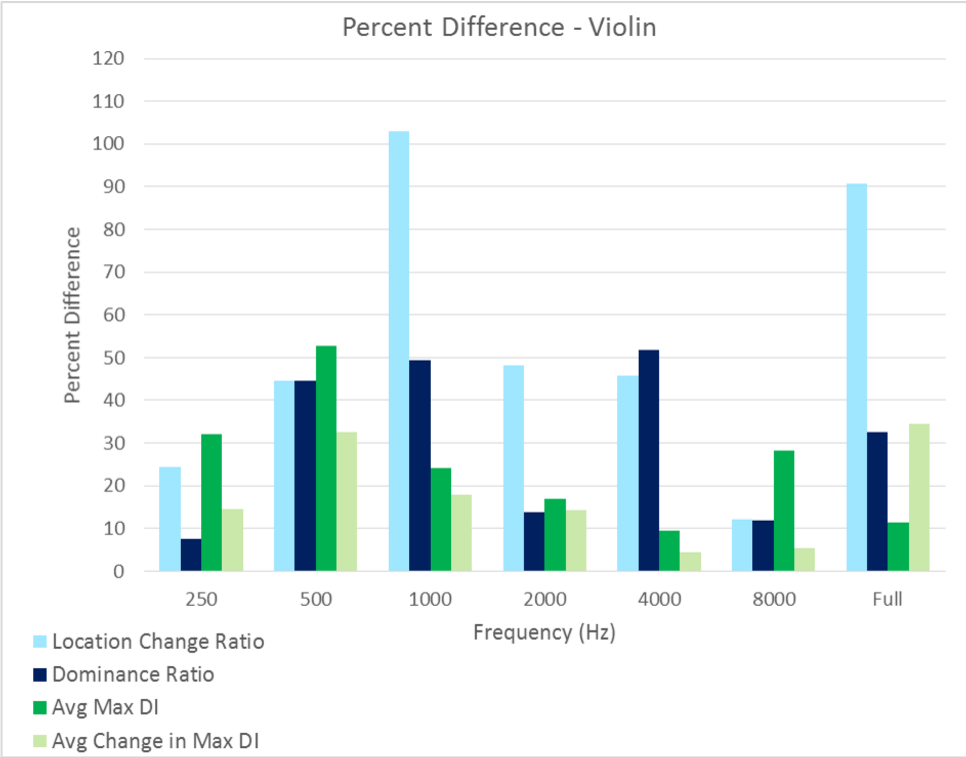

Figure 5.5: Percent difference for 5 vs. 13 channel violin recordings (Source: Author)

Although the dominating channels give little information regarding the time-varying aspect of directivity, it is useful to see where the maximums are generally located for the 5 versus 13 channel recordings, especially in the discussion of how directional lobes may ultimately affect time-varying quantifiers dependent on the Maximum DI results. Table 5.2 lists the channel of Maximum DI for each frequency band for both the 5 and 13 channel data.

Table 5.2: Dominating channels for 5 vs. 13 channel violin recordings

	Frequency (Hz)						
Channels	250	500	1000	2000	4000	8000	Full
5	1	5	5	5	2	5	5
13	8	9	9	8	2	8	9

Figures 5.6 through 5.12 visually depict the information shown in Table 5.2 by illustrating the main direction of radiation relative to the musical source, in this case, the violin. Each figure shows 5 and 13 channel data with two views for each. The left view is looking at the instrumentalist from above, and the right view is looking at the instrumentalist in section. In most cases, the primary direction of radiation is closely related for the 5 and 13 channel data. There are some differences that would not necessarily be expected. For example, Figure 5.8 shows the above direction as the primary direction of radiation for the 5 channel data while the 13 channel recording shows the front lower direction to be the main direction of radiation. The reason for this is not completely clear and could be due to a variety of factors including instrumentalist position.

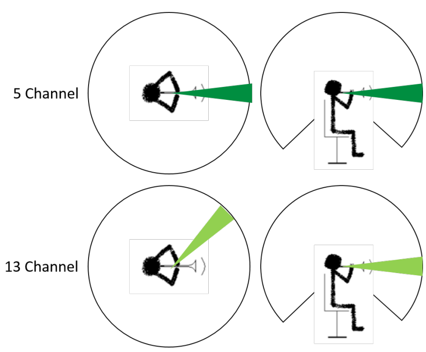

Figure 5.6: Violin- 250 Hz

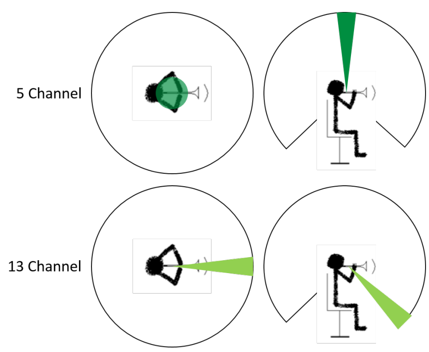

Figure 5.7: Violin- 500 Hz

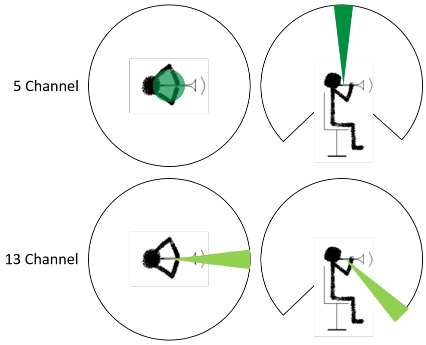

Figure 5.8: Violin- 1000 Hz

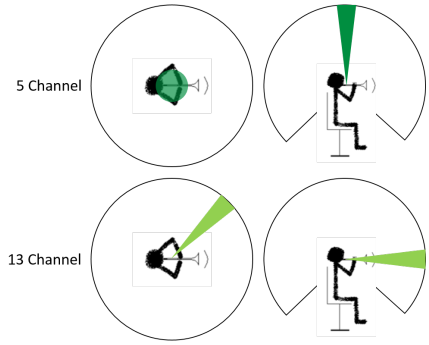

Figure 5.9: Violin– 2000 Hz

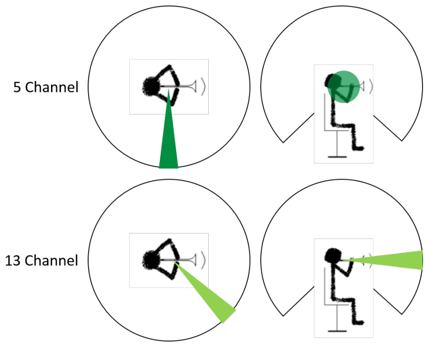

Figure 5.10: Violin- 4000 Hz

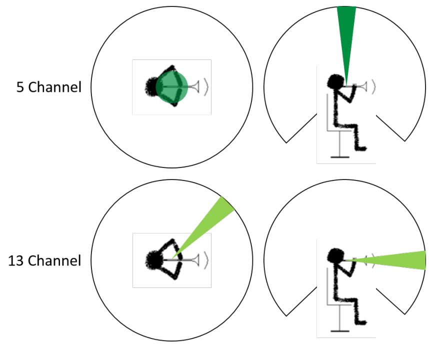

Figure 5.11: Violin- 8000 Hz

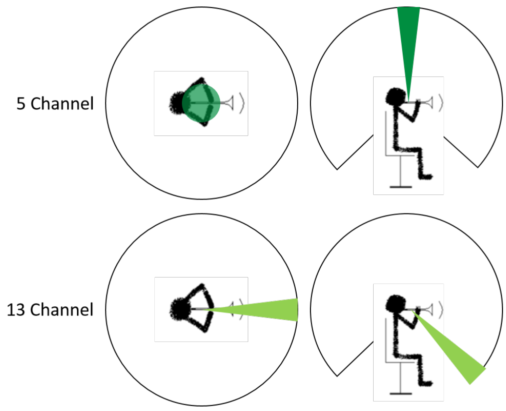

Figure 5.12: Violin- full spectrum

5.3 Flute 5 vs. 13

Like the violin, 5 and 13 channel comparisons were also explored for the flute. Figure 5.13 shows four time-varying directivity quantifiers of the flute for the

Mozart excerpt flute part (5 channel) as well as solo flute excerpt (13 channel). Excluding the 250 Hz frequency band, the Average Maximum DI shows close agreement for lower frequency bands and varies more with higher frequencies. This trend is what would be expected. Likewise, for both the Average Change in Maximum DI and the Location Change Ratio, the 5 and 13 channel data show a decrease in agreement through the 1000, 2000, and 4000 Hz octave bands. The Dominance Ratio is higher for the 5 channel data for the majority of the frequency spectrum, as expected. Beyond this generalization, the Dominance Ratio quantifier seems to have little transferability between 5 and 13 channel data.

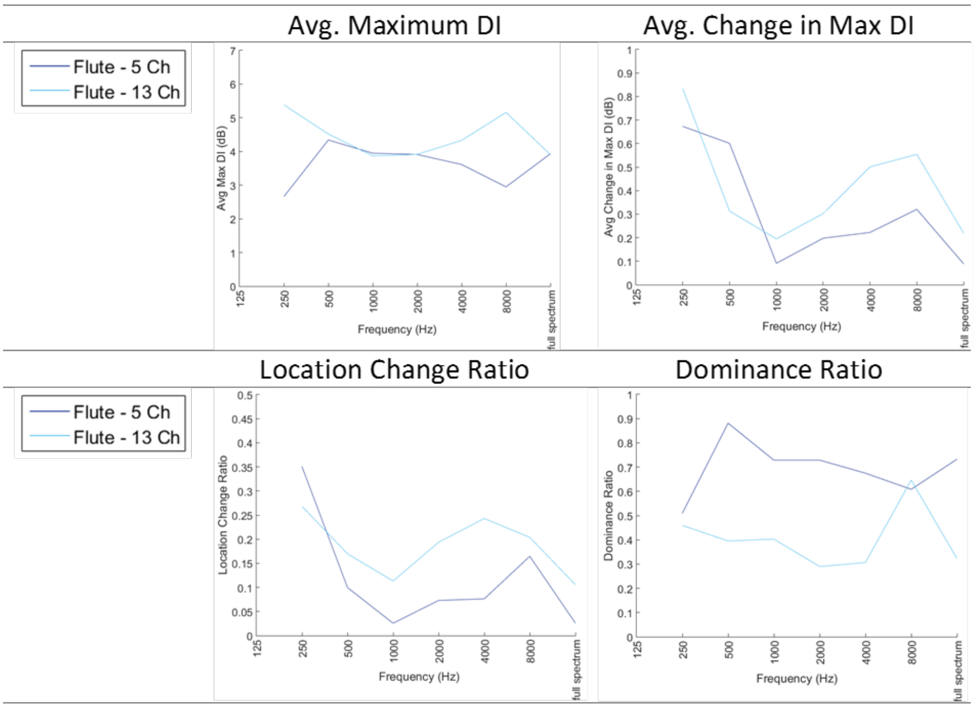

Figure 5.13: Flute quantifier comparisons for 5 vs. 13 channels (Source: Author)

Specific percent differences in quantifiers are shown in Figure 5.14. The Average Change in Maximum DI for the flute is much less comparable than the results obtained for the violin. This suggests that there is some aspect of chance involved in microphone position. If the microphones are set up such that the maximums of lobes are close to a microphone position, data using less microphones may still provide an acceptable representation of an instrument's directivity, which may have been the case for the violin. However, less channels generally increase the probability of misrepresenting the true nature of the directivity. The percent difference in values for the Average Maximum DI for the flute is quite low for octave bands 500 Hz, 1000 Hz, 2000 Hz, and full spectrum, while it is higher for 4000 Hz, 8000 Hz, and 250 Hz. The Average Maximum DI generally shows more agreement than the ratio metrics.

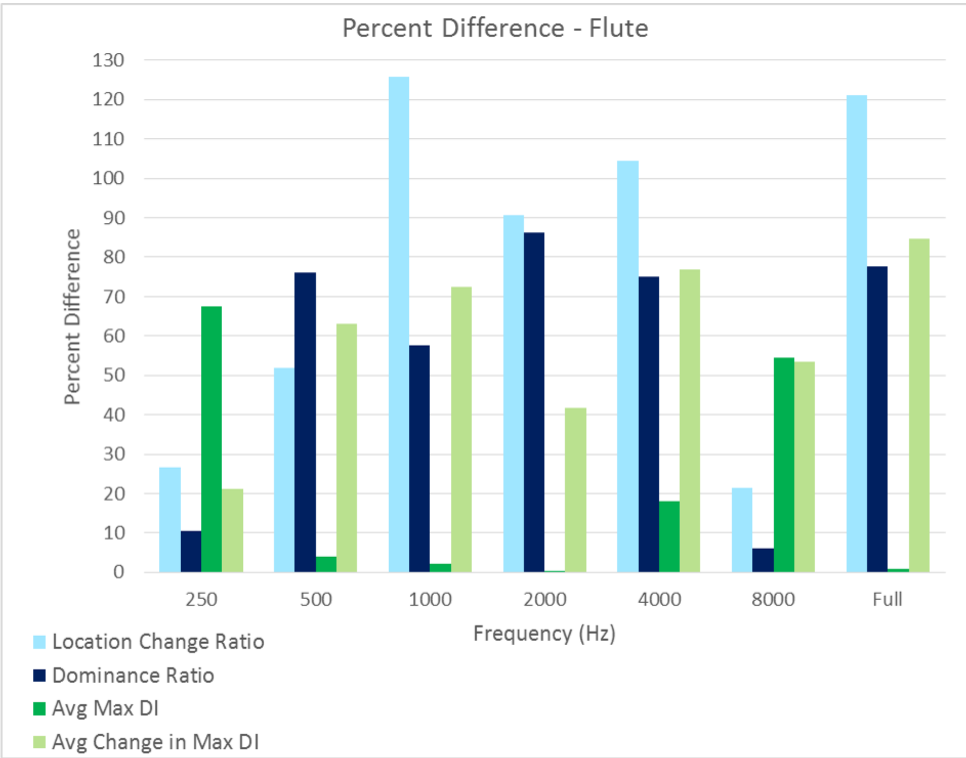

Figure 5.14: Percent difference for 5 vs. 13 channel flute recordings (Source: Author)

Primary direction of radiation by frequency band for the flute is given in Table 5.3 and is accompanied by visual representations in plan and section in Figures 5.15 through 5.21. Like the violin, the Dominating Channel data is quite comparable, although it follows more closely at some frequencies than others. For example, the 8000 Hz dominating direction is the exact same for the 5 and 13 channel data. However, at 2000 Hz, the 5 channel data shows a straight forward dominating direction while the 13 channel data shows a dominating direction to the right of the musician.

Table 5.3: Dominating channels for 5 vs. 13 channel flute recordings

	Frequency (Hz)						
Channels	250	500	1000	2000	4000	8000	Full
5	5	5	1	1	1	2	1
13	13	9	10	3	3	3	10

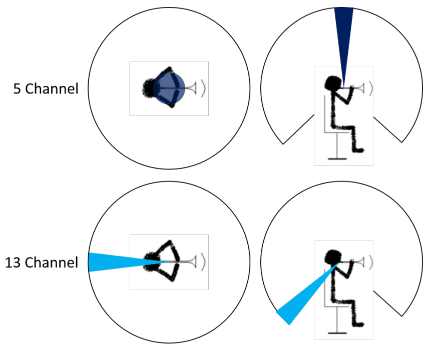

Figure 5.15: Flute- 250 Hz

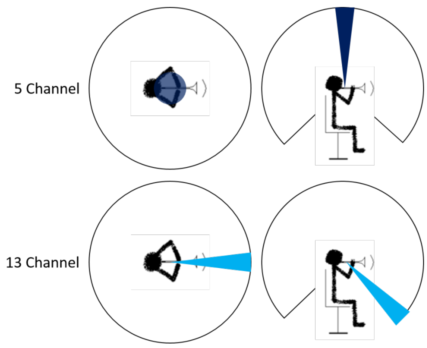

Figure 5.16: Flute- 500 Hz

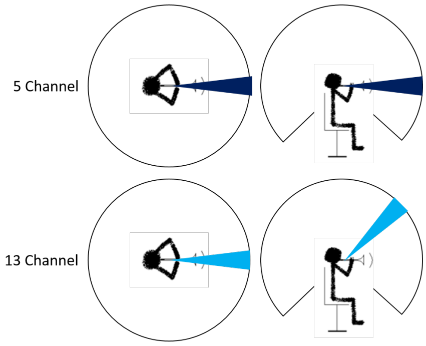

Figure 5.17: Flute- 1000 Hz

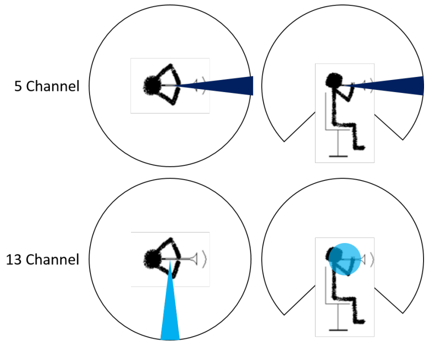

Figure 5.18: Flute- 2000 Hz

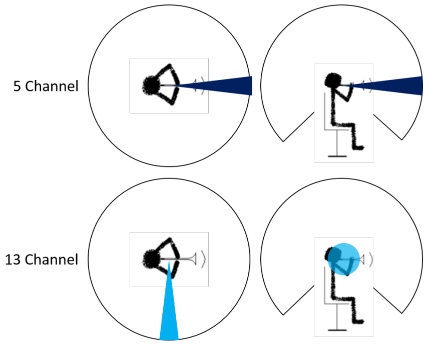

Figure 5.19: Flute- 4000 Hz

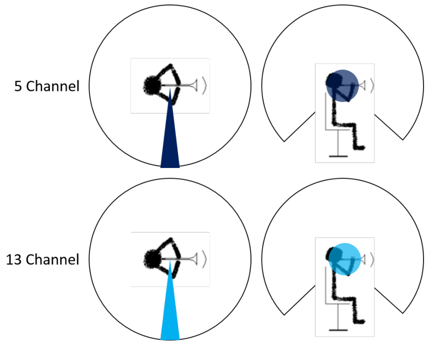

Figure 5.20: Flute- 8000 Hz

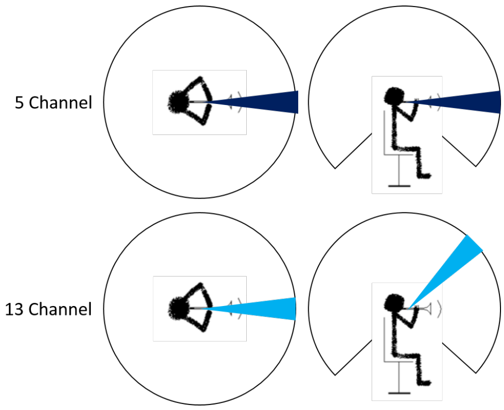

Figure 5.21: Flute- full spectrum

5.4 Application for 32 Channel Data

Ideally, the methods of quantifying time-varying directivity outlined in this thesis should have flexibility to be applied to data of any channel amount.

Five and thirteen channel data sets were the focus in the development and comparison of metrics since access to data sets with larger number of channels was limited. In addition to the five and thirteen channel data, a 32 channel data set was utilized to demonstrate the ability of the set of metrics to be used with a higher resolution recording involving an increased number of microphone channels.

5.4.1 32 Channel Data

The 32 channel data were recorded at the Institute of Technical Acoustics at RWTH Aachen University in Aachen, Germany. The recording was made as part of research on the aural components of virtual reality simulations. The set of data used in the following directivity quantification analysis is a solo musical excerpt of a saxophone recorded with 32 microphones in a pentakis dodecahedron setup. The microphone setup with the saxophone player is shown in Figure 5.22.

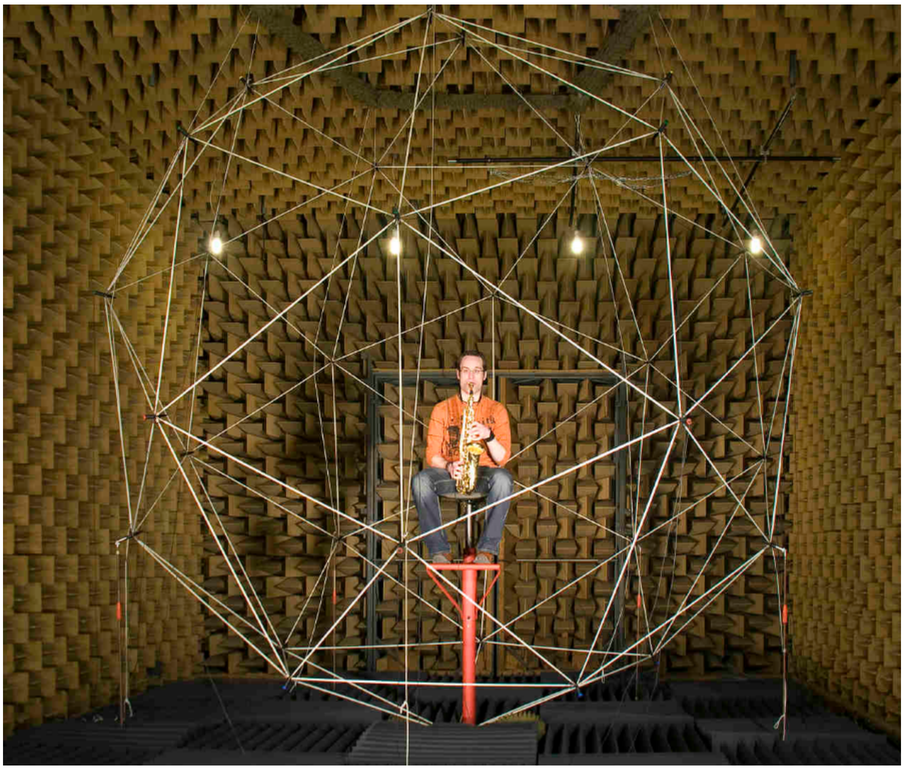

Figure 5.22: 32 channel recording setup (Source: Reuter 2008)

As outlined in Reuter (2008), a pentakis dodecahedron has the following characteristics.

- All of the vertices, or microphones, lie on a sphere.
- All vertex figures are regular polygons.
- All angles between two faces are equal.
- The solid angles of the pentakis dodecahedron are equivalent.
- All vertices, or microphone positions, are surrounded by the same number of faces.

The visible microphones are labeled on the vertices of Figure 5.23. Typically, consecutive microphones are grouped by five locations on a pentagon plane. For example, microphone 24, though not visible in Figure 5.23, is positioned in the back and lies in the same plane as microphones 22,

23, 25, and 26. The exception to the pentagon planar grouped microphones are microphones 21 and 32, which are positioned at the top and bottom of the pentakis dodecahedron.

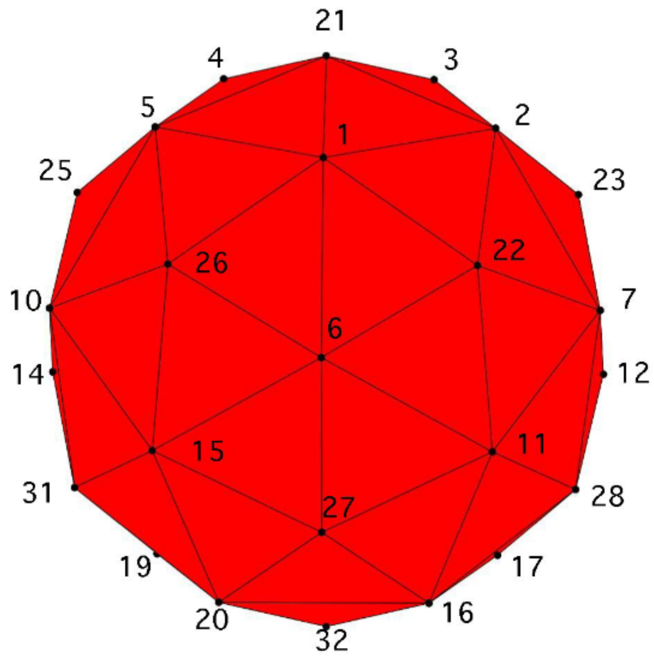

Figure 5.23: Dodecahedron microphone labels (Source: Reuter 2008)

Four quantifiers are shown for 13 and 32 channel saxophone solo excerpts in Figure 5.24. The Average Maximum DI and Average Change in Maximum DI values are generally higher for the 32 channel data, as was previously hypothesized with increased channel number from the comparisons between the 5 and 13 channel data. However, the predicted effect of increased channel amount on the Location Change Ratio and Dominance Ratio does not hold for the 13 versus 32 channel data in the same way that it did in the 5 versus 13 channel comparison. For the violin and flute comparisons, 13 channel data resulted in higher Location Change Ratios and lower Dominance Ratios in comparison to the 5 channel data. For the saxophone Location Change Ratio

values, there is not a clear trend of higher channel amounts resulting in higher Location Change Ratios. For the Dominance Ratio, the 32 channel data set gives a higher ratio value for 2000 Hz, 4000 Hz, and 8000 Hz octave bands. This suggests that while there may be predictable trends with increasing channel amounts, there may be some channel amount at which these patterns level off or become irrelevant. It is possible that the number of channels where this occurs is frequency dependent.

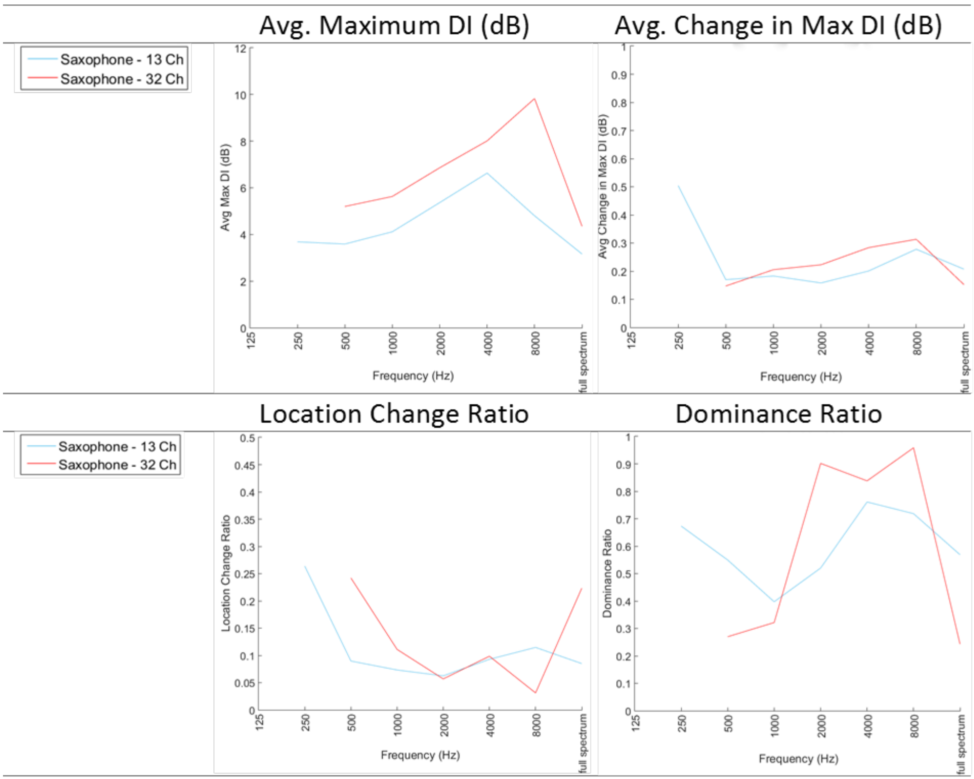

Figure 5.24: Saxophone quantifier comparisons for 13 vs. 32 channels (Source: Author)

Figure 5.25 shows the percent difference between the quantifiers for the 13 and 32 channel saxophone data. As with the violin and flute 5 and 13 channel comparison, the metrics directly associated with the value of Maximum DI

generally show less percent difference while the ratio metrics typically have higher percent differences. Overall, percent difference values are somewhat lower for the saxophone 13 vs. 32 channel analysis compared to the 5 vs. 13 channel analysis. This supports the idea that recordings involving more channels lead to increased detail and increased accuracy in time-varying directivity quantification.

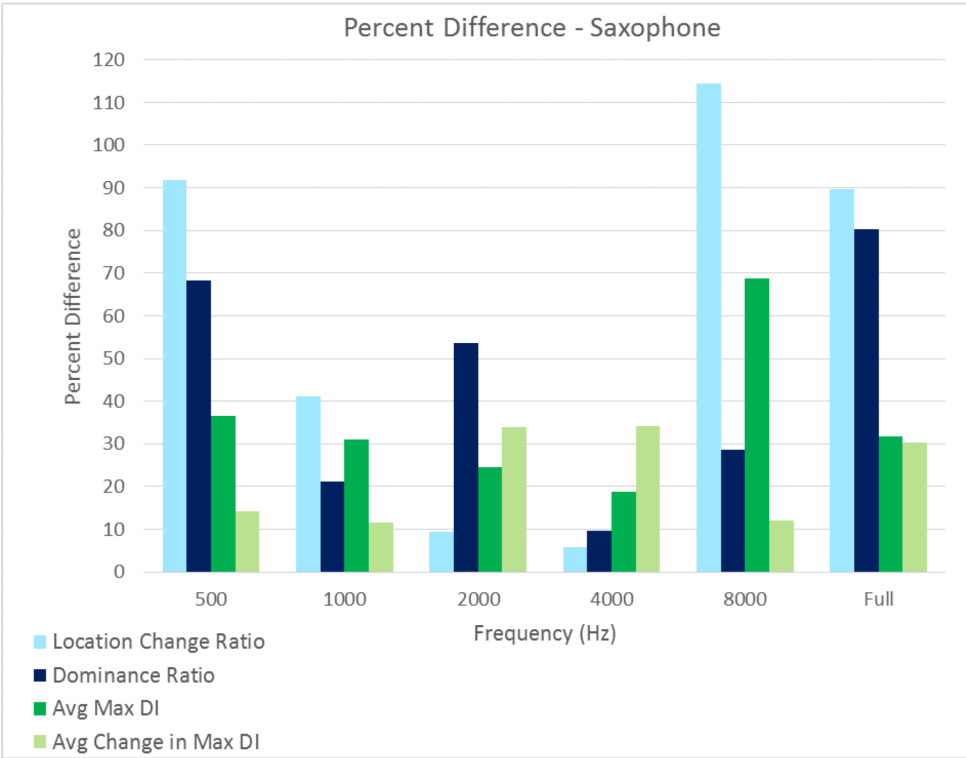

Figure 5.25: Percent difference for 13 vs. 32 channel saxophone recordings (Source: Author)

Spatial location of the main direction of radiation is shown by dominating channel for each frequency band for the 13 and 32 channel saxophone data in Table 5.4. Visual depictions of these are shown in Figures 5.26 through 5.31 where the diagrams represent the view looking at the saxophone player straight on. The dominating channels are generally agreeable for the

saxophone 13 to 32 channel comparison. The dominating location for the 13 channel plot is not visible for the 1000 Hz octave band (Figure 5.27), as channel 4 lies slightly behind the instrumentalist. While the 13 channel microphone setup is a direct extension of the 5 channel setup as it used the same locations of the original five, the 32 microphone setup is laid out in such a way that there are minimal channels that correspond directly between the 13 and 32 channel data. Looking at a visual representation of the dominating channels can give insight to an approximation of where the channels align between the different sets of data.

Table 5.4: Dominating channels for 13 vs. 32 channel saxophone recordings

	Frequency (Hz)						
Channels	250	500	1000	2000	4000	8000	Full
13	9	9	4	10	10	10	9
32		15	15	22	22	22	6

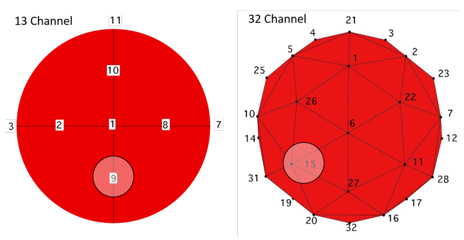

Figure 5.26: Saxophone- 500 Hz

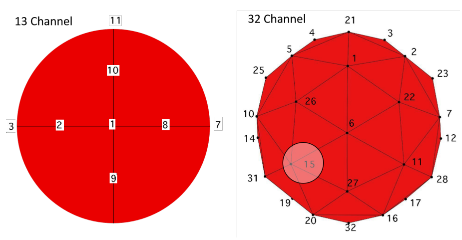

Figure 5.27: Saxophone- 1000 Hz

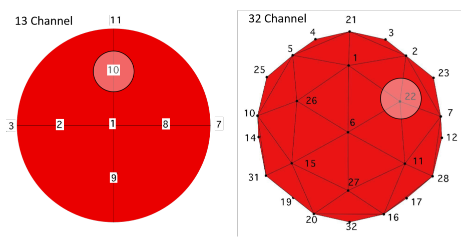

Figure 5.28: Saxophone- 2000 Hz

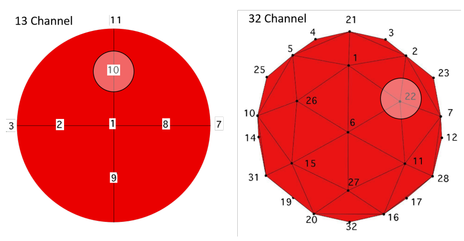

Figure 5.29: Saxophone- 4000 Hz

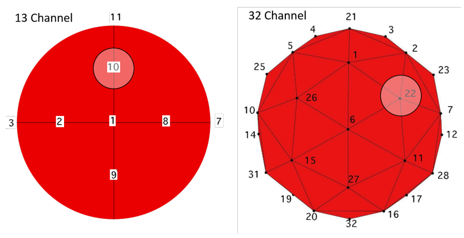

Figure 5.30: Saxophone- 8000 Hz

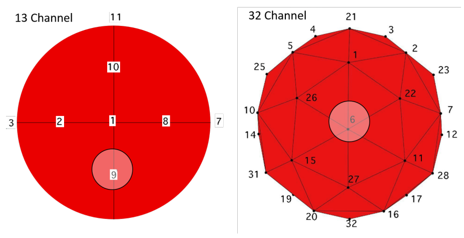

Figure 5.31: Saxophone- Full spectrum

5.5 Summary

Data of 5 vs. 13 channels for the violin and flute in addition to 13 vs. 32 channel data for the saxophone was analyzed. Results from the comparisons show similarities for each instrument. However, differences attributed to increasing the channel number suggest that more channels improve the accuracy of time-varying directivity quantification for a given musical instrument.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The main motivation for this thesis was to propose a method of quantification for the time-varying directivity properties of musical instruments. Throughout this thesis, the following were concluded.

1. A set of quantifiers was established and confirmed to be an adequate tool for quantifying time-varying directivity.
2. Quantifiers are suitable for instrument comparison but less conclusive for comparisons of different musical pieces when using 5 channel data.
3. Regarding number of channels used, more is better, as additional channels improve the accuracy of the represented radiation pattern of the instrument.

The details of how these conclusions were reached are outlined below.

6.1.1 Quantification

Weinreich qualitatively described the directivity of the violin over time as having a certain “flashing brilliance” and “directional tone color” that gives the violin its a unique sound (1997). Through the development of time-varying directivity metrics, the directional quality of the violin has been analyzed quantitatively. This quantification method also provided a way to compare the time-varying directivity of different instruments and excerpts. Quantifiers were applied to a variety of instruments for 5 channel Mozart and Brahms symphonies, 13 channel solo excerpts, and a solo saxophone 32 channel excerpt. Previously established quantifiers included Average Maximum DI, Average Change in Maximum DI, and Location Change Count. These quantifiers were further developed and addressed using a study of the time windowing technique and an examination of the effect of window length on metric values. From this, the following set of five quantification methods were chosen to be used in analysis.

- Average Maximum Directivity Index
- Average Change in Maximum Directivity Index
- Location Change Ratio
- Dominance Ratio
- Dominating Location

For each instrumental recording analyzed, a plot was produced showing the Maximum Directivity Index magnitude and channel location over a series of overlapping 10 millisecond windows. These plots were produced for a set of octave bands incorporating the range of the instrument as well as the full

frequency spectrum. Using the Maximum Directivity Index data, magnitude of maximum DI was used to calculate the Average Maximum DI and the Average Change in Maximum DI. With the maximum channel data, spatial metrics including Location Change Ratio, Dominance Ratio, and Dominating Location were evaluated. Variables including instrument, excerpt, frequency, directionality, and time all play a role in the quantifier values. Given the complex nature of the variance of directivity over time for a musical instrument, a variety of metrics were put to use in order to better account for a wide assortment of variables.

6.1.2 Instrument Trends

Trends were seen within and between groups of instruments in analyzing the Mozart and Brahms symphonies separately. Brass instruments are generally the most directional. Because of this, brass instruments have some of the highest values for Average Maximum DI and Average Change in Maximum DI. The woodwinds and strings have Maximum DI results that compare somewhat closely, although the lower pitched instruments of both groups tend to have higher values for Average Change in Maximum DI. The brass instruments had the lowest Location Change Ratios and Dominance Ratios as expected given the directional nature of brass instruments. The woodwind and string values are quite similar for the ratio metrics. The lower pitched instruments have some of the higher Location Change Ratios within each instrument category. The contrabassoon in particular shows extremely high Location Change Ratio values compared to the other instruments. In general,

the Dominance Ratio shows more variance than the Location Change Ratio for most instruments and frequency bands. The "directional tone color" of the violin that Weinreich described may be related to high Average Change in Maximum DI, high Location Change Ratio, and low Dominance Ratio, although the violin does not stand out as exceptional compared to the other instruments for any of the quantifiers.

6.1.3 Excerpt Trends

There were not obvious trends seen in comparing one symphony to the next. The specific musical instrument itself seems to play a larger role in the value of time-varying directivity quantifiers. The evaluated instruments demonstrate similar Average Maximum DI and Average Change in Maximum DI between symphonies in many cases. The Location Change Ratio matches somewhat closely between symphonies, and the Dominance Ratio translates for some instruments better than others. It is difficult to make concrete conclusions regarding excerpt comparison when there are so many other factors involved including the physical instrument, musician, and player technique. The variables of interest exclusively related to differences in symphony excerpts include the played pitches, dynamics, and articulation. It becomes difficult to isolate these variables and make conclusions with limited recorded data.

6.1.4 Spatial Resolution and Comparison

Channel number as a variable in recorded data was examined with comparisons between 5 and 13 channel data for a violin and flute as well as 13

and 32 channel data for the saxophone. Making concrete comparisons between recording types was somewhat difficult but improved with increased channel numbers. Ultimately, the use of more channels gives more detail of the radiation patterns and provides more accuracy in time-varying directivity quantification.

Through the established system for the analysis of time-varying directivity, complex directional characteristics of musical instruments can be quantified and studied further. By using this system for future time-varying directivity research, a better understanding can be obtained of how instruments radiate energy over time as they are played.

6.2 Recommendations for Future Work

This section will discuss future directions for research in time-varying directivity based on the findings as well as limitations found in the presented thesis.

6.2.1 Additional Instruments

Although this thesis included a wider variety of instruments than previously studied at the University of Nebraska, there were still some instrumental limitations. For example, the brass instruments represented in the recordings included only the trumpet and the French horn. The woodwinds were fairly well represented, but the inclusion of additional woodwinds such as the English horn and bass clarinet could improve the scope of the current

findings. Additionally, the piano would be an interesting instrument to use in further research.

6.2.2 Higher Resolution Recordings

The accuracy of quantification values and the ability to distinguish between closely-related instruments may be improved with the use of recordings involving higher spatial resolution, or more microphones. A set of recordings with the same instruments, musicians, and excerpt but differing in channels used for acquisition could help isolate the variable of channel number and give a better understanding to the importance of spatial resolution and the extent of the drawbacks associated with lower resolution recordings.

6.2.3 Optimal Number of Channels

As previously stated, recordings using more channels offer improved accuracy for time-varying directivity quantification. This brings up a question of what the ideal number of channels is for obtaining optimal spherical sampling. It is likely that this number is frequency dependent, as wavelength plays a major role in the characteristics of an instrument's radiation patterns. A lower number of channels may be sufficient at lower frequencies where the directivity pattern is nearly omnidirectional. Finding the optimal number of channels as a function of wavelength to be used in recordings is a suggested area of future research.

6.2.4 Improved Excerpt Comparisons

Although the 5 channel Mozart and Brahms symphonies provided enough detail to make comparison and conclusions across instrument families, the ability to make comparisons between excerpts was less conclusive. With the development of increased resolution recordings using an optimal number of channels, more subtle differences and improved comparisons can be made. Within this thesis, only Mozart and Brahms excerpt comparisons were considered. Additional musical genres that differ more extremely may provide opportunities to draw more conclusions regarding the use of time-varying directivity metrics to compare excerpt types.

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Appendix A

Symphonic Excerpts

A.1 Mozart Symphony excerpt bars 1-82

Symphony No.40 in G minor, K.550

Mozart

Symphony No. 40
in G minor
K. 550

The Oboe and Clarinet parts printed in the two systems at the top were added later by Mozart to replace the Oboe part in the fourth system.

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

Symphony No.40 in G minor, K.550

A.2 Brahms Symphony excerpt bars 1-107


11
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
K.-Fag.
(F) Hr. (C)
Trpt. (C)
Pk.
1. Viol.
2. Viol.
Br.
Vcl.
K.-B.


44 (130)
A
19
Ob.
Klar. (C)
Fag.
(F) Hr. (C)
Trpt. (C)
1.Viol.
2.Viol.
Br.
Vcl.
K.-B.
pizz.
arco
27
Pk.
cresc.
f cresc.
p cresc.


(131) 45
35
B
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
K.-Fag.
(F) Hr. (C)
Trpt. (C)
Pk.
Trgl.
1. Viol.
2. Viol.
Br.
Vcl.
K.-B.
46
p legg.
p grazioso
dim.
pizz.
f dim.
J. B. 4


58
C
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
(F) Hr. (C)
Trgl.
1. Viol.
2. Viol.
Br.
Vcl.
K.-B.
p legg.
pizz.
arco
67
dim.
pp


(133) 47
80
D
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
K.-Fag.
(F)
Hr.
(C)
Trpt. (C)
Pk.
Trgl.
1. Viol.
2. Viol.
Br.
Vcl.
K.-B.
a 2
p cresc.
cresc.
ff
ffz
p
pizz.
arco
tr
D
J. B. 4


97
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
K-Fag.
(F) Hr. (C)
Trpt. (C)
Pk.
Trgl.
1. Viol.
2. Viol.
Br.
Vcl.
K-B.
ff sempre
a 2


(135) 49
114
E
gr.Fl.
kl.Fl.
Ob.
Klar. (C)
Fag.
(F)
Hr.
(C)
1.Viol.
2.Viol.
Br.
Vcl.
K.-B.
a 2
1.
pizz.
E
123
arco


131
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
1. Viol.
2. Viol.
Br.
Vcl.
K.-B.
a 2
f
139
ff
dim.


(137) 51
151
1.Viol.
2.Viol.
Br.
Vcl.
K.-B.
dim.
p
pp dim. sempre
161
pizz.
ppp
168
F
gr. Fl.
kl. Fl.
Ob.
Klar. (C)
Fag.
(F) Hr. (C)
Trgl.
pp ma ben marc.
pp
dim.
mf
J.B.4

Appendix B

MATLAB

```
close all;
clear all;
clc;

fs = 44100;

ch1  = audioread('m_cello_ch-01.wav');
ch2  = audioread('m_cello_ch-02.wav');
ch3  = audioread('m_cello_ch-03.wav');
ch4  = audioread('m_cello_ch-04.wav');
ch5  = audioread('m_cello_ch-05.wav');

time = floor(length(ch1)/fs);

rec(:,1)  = ch1;
rec(:,2)  = ch2;
rec(:,3)  = ch3;
rec(:,4)  = ch4;
rec(:,5)  = ch4;

%Start of octave band filtering code
% End of octave band filtering code
    fc = 1000    %User defined
    fl = fc/sqrt(2);
    fu = fc*sqrt(2);
    fstop1 = fl/1.05;
    fstop2 = fu*1.05;
    D = fdesign.bandpass('Fst1,Fp1,Fp2,Fst2,Ast1,Ap,Ast2',...
                     fstop1,fl,fu,fstop2,100,1,100,fs);
    H = design(D,'butter');
    i = 1;
    while i <= 5
        rec(:,i) = filter(H,rec(:,i));
        i = i + 1;
```

```
    end

window = 1;
length = 0.01;
shift = 0.005;
number_of_windows = (time/shift)-1;


meansq = zeros(number_of_windows,5);
meansq_ave = zeros(number_of_windows,1);
DI = zeros(number_of_windows,5);
DI_max = zeros(number_of_windows,1);
DI_max_loc = zeros(number_of_windows,1);

while window <= number_of_windows
    x = 1;
    y = 1;

    while x <= 5;
        signal = rec((window-1)*(fs*shift)+1:(window+1)...
         *(fs*shift), x);
        meansq(window,x) = mean(signal.^2);
        x = x + 1;
    end

    meansq_ave(window,1) = sum(meansq(window,:))/4;

    while y <= 5;
        DI(window,y) = 10*log10(meansq(window,y)/...
         meansq_ave(window,1));
        y = y + 1;
    end

    DI_max(window,1) = max(DI(window,:));
    DI_max_loc(window,1) = find(DI(window,:) == max(DI(window,:)));
    window = window + 1;
end

%DI_max
%DI_max_loc

%Start of code only used for directivity pattern numbers
    c1  = DI(:,1);
    c2  = DI(:,2);
    c3  = DI(:,3);
    c4  = DI(:,4);
    c5  = DI(:,5);
```

```
%End of code only used for directivity pattern numbers

DI_all_channels = [c1 c2 c3 c4];
[max_DI,max_location] = max(DI_all_channels,[],2);

%Average maximum Directivity Index
avg_max_DI = mean(max_DI);

%Average change in maximum DI
diff = [];
for q = 1:(number_of_windows-1)
    diff = [diff abs(max_DI(q+1) - max_DI(q))];
end
avg_change_DI = mean(diff)

%%Number of channel changes
changes = 0;
finish = size(max_location,1);
for i = 1:(finish-1)
    if max_location(i) == max_location(i+1)
        changes = changes;
    else
        changes = changes + 1;
    end
end
channel_changes = changes;
location_change_ratio = changes/number_of_windows

%%dominance ratio
L = numel(max_location);
w = [1 2 3 4];
a = hist(max_location, w);
[numMaxCh, I] = max(a);
index_max_ch = I
dominanceRatio = (numMaxCh/number_of_windows)

WAVtime = time - shift;
time = (shift:shift:WAVtime);
time = time';

figure('Position',[100 100 900 370])
set(gcf,'color','w');
[ax p1 p2] = plotyy(time,max_DI,time,max_location,...
'plot','scatter');
title(strcat({'Cello- '},num2str(fc),{' Hz'}))
%title('Cello- Full Spectrum')
xlabel('Time (s)')
set(gca,'XMinorTick','on');
```

```
ylim(ax(1),[0,10]);
set(ax(1),'YTick',[0:0.5:7])
ylabel1 = ylabel(ax(1), 'Max DI (dB)');
set(ylabel1,'position',[-2.5,2.5,0])
box(ax(1),'off')
ylim(ax(2),[-13,6]);
set(ax(2),'YTick',[1:5])
ylabel2 = ylabel(ax(2), 'Channel Number');
set(ylabel2,'position',[1.13*WAVtime,3,0])
text(0.5,-1.0,strcat({'Average Max DI:  '},...
num2str(avg_max_DI)))
text(0.5,10.6,strcat({'Total Ch. Changes:  '},...
num2str(channel_changes)))
text(0.5,10.0,strcat({'Location Change Ratio:  '},...
num2str(changes_ratio)));

text(0.7*WAVtime,10.6,strcat({'Max Location Channel:  '},...
num2str(index_max_ch)))
text(0.7*WAVtime,10.0,strcat({'Dominance Ratio:  '},...
num2str(distributionRatio)));
```

Appendix C

Plots

C.1 Maximum Directivity Index Plots

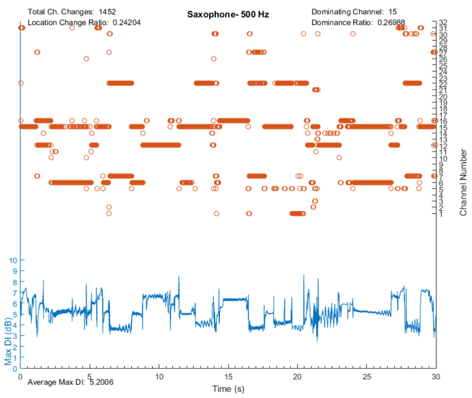

Figure C.1: Sax- 32 ch. at 500 Hz

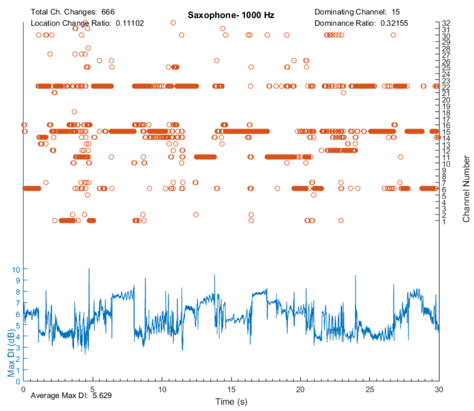

Figure C.2: Sax- 32 ch. at 1000 Hz

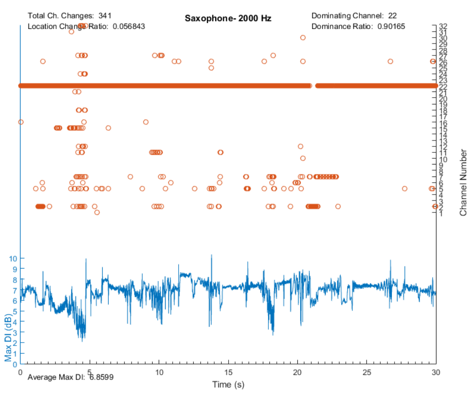

Figure C.3: Sax- 32 ch. at 2000 Hz

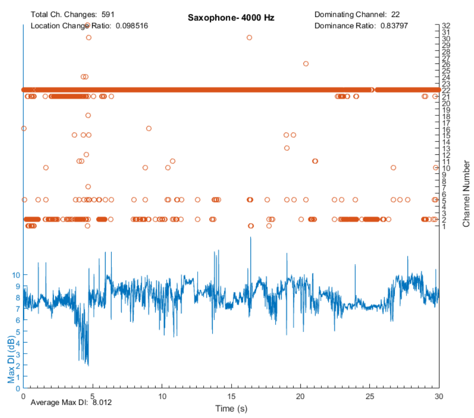

Figure C.4: Sax- 32 ch. at 4000 Hz

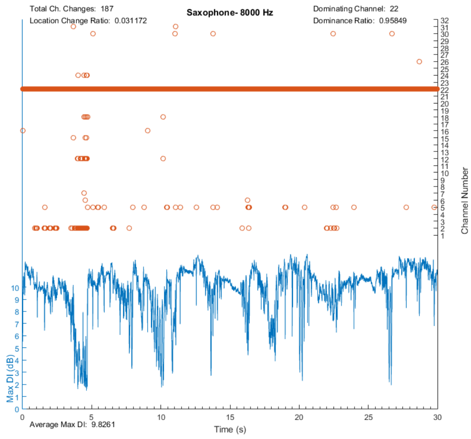

Figure C.5: Sax- 32 ch. at 8000 Hz

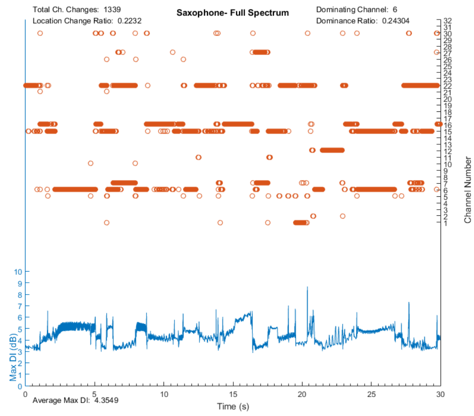

Figure C.6: Sax- 32 ch. full spectrum

C.2 5 vs. 13 Channel Violin Plots

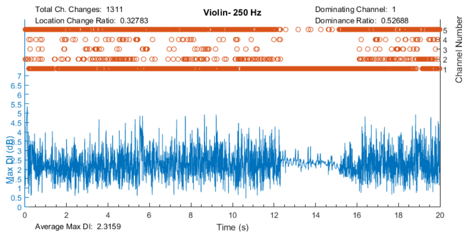

Figure C.7: Violin- 5 ch. 250 Hz

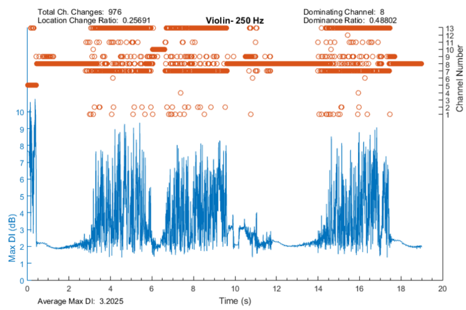

Figure C.8: Violin- 13 ch. 250 Hz

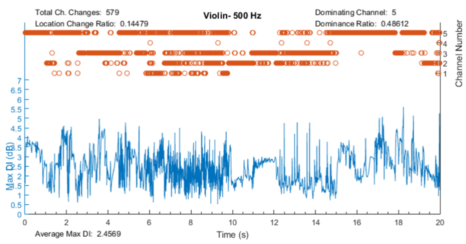

Figure C.9: Violin- 5 ch. 500 Hz

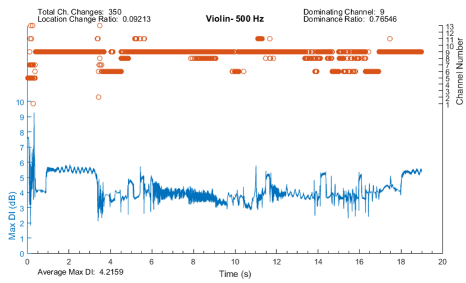

Figure C.10: Violin- 13 ch. 500 Hz

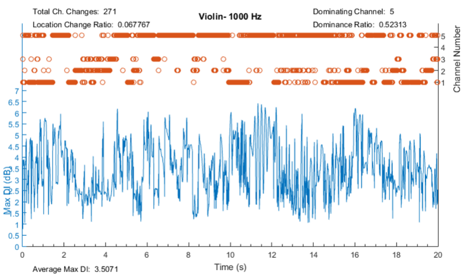

Figure C.11: Violin- 5 ch. 1000 Hz

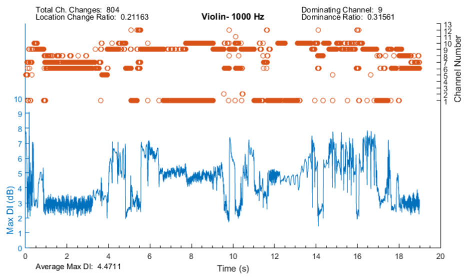

Figure C.12: Violin- 13 ch. 1000 Hz

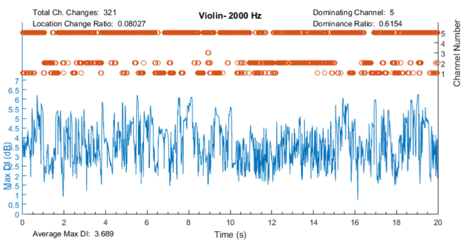

Figure C.13: Violin- 5 ch. 2000 Hz

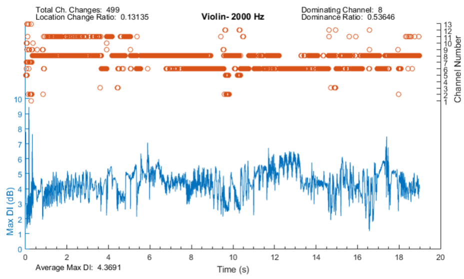

Figure C.14: Violin- 13 ch. 2000 Hz

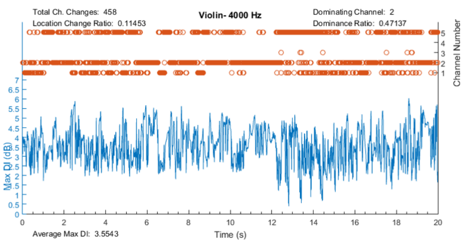

Figure C.15: Violin- 5 ch. 4000 Hz

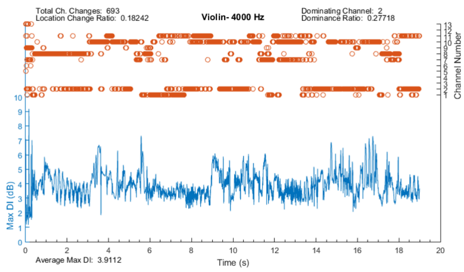

Figure C.16: Violin- 13 ch. 4000 Hz

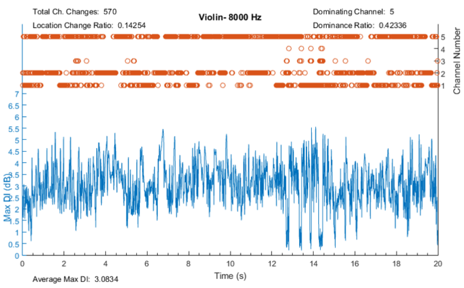

Figure C.17: Violin- 5 ch. 8000 Hz

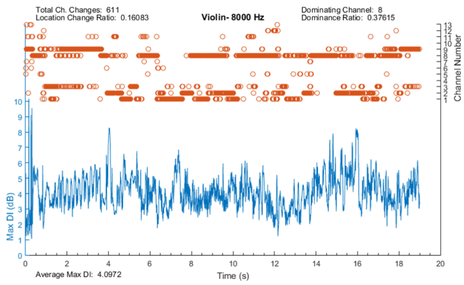

Figure C.18: Violin- 13 ch. 8000 Hz

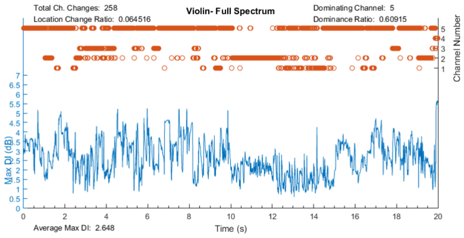

Figure C.19: Vi- 5 ch. full spectrum

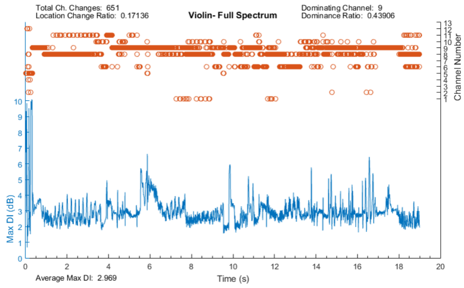

Figure C.20: Vi- 13 ch. full spectrum

C.3 5 vs. 13 Channel Flute Plots

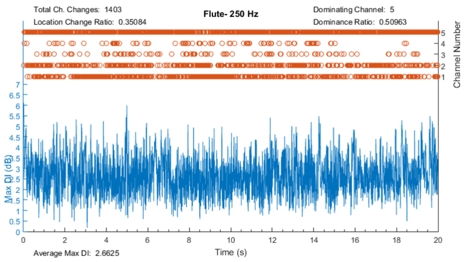

Figure C.21: Flute- 5 ch. 250 Hz

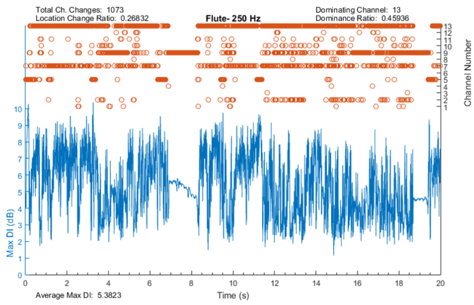

Figure C.22: Flute- 13 ch. 250 Hz

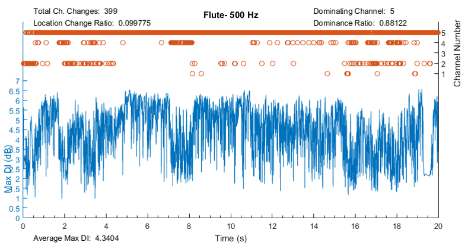

Figure C.23: Flute- 5 ch. 500 Hz

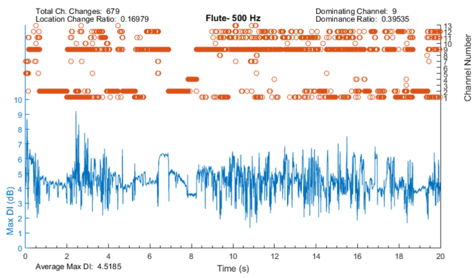

Figure C.24: Flute- 13 ch. 500 Hz

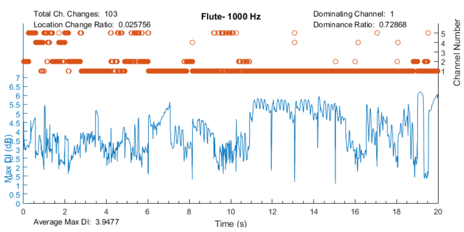

Figure C.25: Flute- 5 ch. 1000 Hz

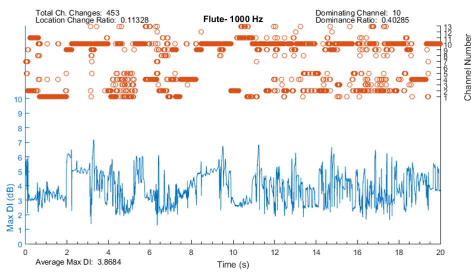

Figure C.26: Flute- 13 ch. 1000 Hz

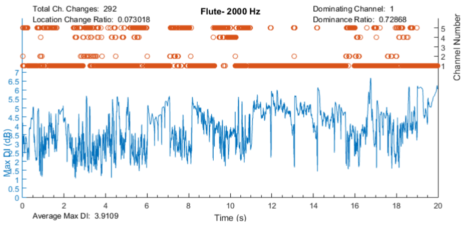

Figure C.27: Flute- 5 ch. 2000 Hz

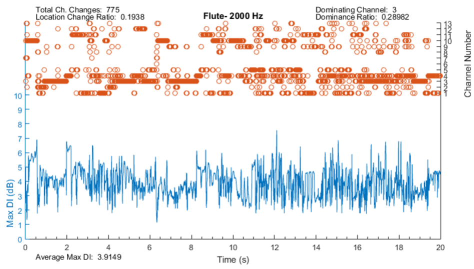

Figure C.28: Flute- 13 ch. 2000 Hz

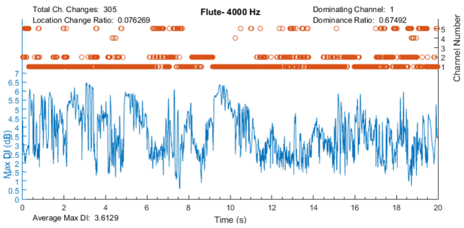

Figure C.29: Flute- 5 ch. 4000 Hz

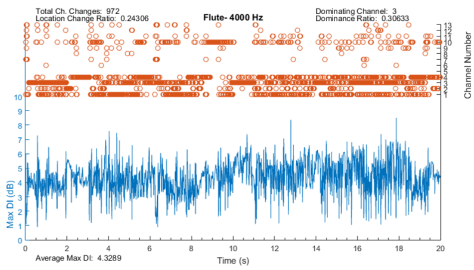

Figure C.30: Flute- 13 ch. 4000 Hz

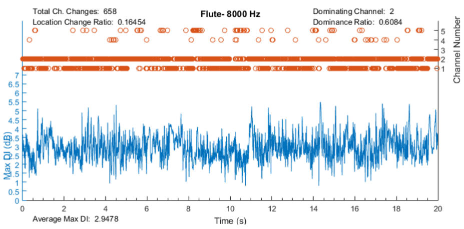

Figure C.31: Flute- 5 ch. 8000 Hz

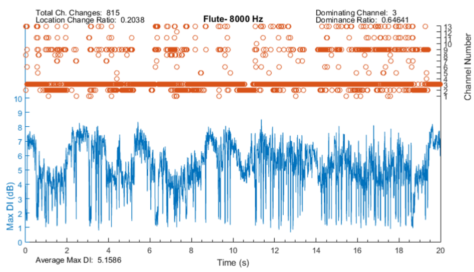

Figure C.32: Flute- 13 ch. 8000 Hz

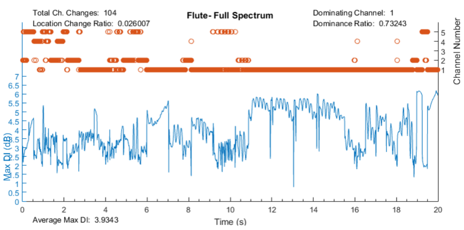

Figure C.33: Fl- 5 ch. full spectrum

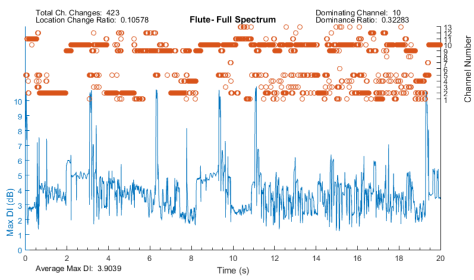

Figure C.34: Fl- 13 ch. full spectrum