Musical Acoustics Analysis of Instrument Pairings

ECE446 Final Report

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PRA0102, Group 3

1 Abstract

This study investigates how the acoustic properties of instruments from different cultures contribute to their unique sounds and compatibility when paired. By analyzing the waveforms and spectral characteristics of various instruments (namely, the kazoo, tongue drum, flute, timpani, and kalimba), we assess their frequency distributions/harmonics, flatness, and spectral entropy. Results indicate that instrument pairings from the same cultural region exhibit lower spectral entropy, concentrated harmonics, and higher spectral magnitudes, creating more harmonious interactions. In contrast, cross-cultural pairings display greater randomness and reduced harmonic compatibility. These findings suggest a strong link between the cultural origin of instruments, their acoustic properties, and their perceived musical compatibility, offering insights for sound design and innovative cross-cultural music production.

2 Introduction

Music is central to cultures worldwide, with the acoustic properties of instruments defining their unique sounds. This project examines how the materials and sound waves of various instruments influence their sonic qualities, focusing on cross-cultural pairings, such as combining Chinese and European or Brazilian instruments. By exploring these interactions, we aim to uncover new possibilities for sound design, music production, and cross-cultural collaboration.

2.1 Background

Cultural differences in music are often easily recognizable, primarily due to variations in music theory—such as scales, harmonies, rhythms, and meters. For instance, a Scottish jig played on a trumpet is still recognizable but may feel out of place, while the same jig on bagpipes fits perfectly within its cultural context. This illustrates how instrumentation influences timbre, which is shaped by the sound's frequency spectrum and envelope. Our goal is to explore instrument pairings not only between Chinese and Western instruments, as discussed in this research (Liu et al. (2022)), but also across other cultures. We aim to examine the physical characteristics of these instruments and how they interact both within and across different cultural contexts, offering scientific insights into the reasons behind diverse cultural instrumentations.

3 Objective

The materials and acoustic properties of instruments from different cultures influence their sonic characteristics and compatibility.

4 Study Design

This section covers how we recorded data for solo and chamber performances, along with the sheet music used. We also explain the data processing methods for generating waveforms, spectra, spectrograms, and other analyses.

4.1 Instrument Origin and Materials

The instruments that we have used for acoustic analysis are listed in Figure 1. (Montagu (2007))

Instrument	Origin	Materials	Notes
Kazoo	United States (19th century)	Membrane, metal or plastic body	Alters voice through vibrating membrane
Tongue Drum	Africa & Caribbean	Metal or wood	Inspired by slit drums, modern design
Western Concert Flute	Europe (France, 19th century)	Metal (silver, gold, alloys)	Standardized modern concert flute
Timpani	Middle East, Europe	Copper or fiberglass, animal/synthetic skin	Introduced to Europe during Crusades
Kalimba	Africa (Zimbabwe, Shona)	Wood, metal tines	Thumb piano, part of lamellophone family

Figure 1: Summary of Instrument Origins and Materials

4.2 Data Collection

This section explains the preparation and all steps required for data collection.

4.2.1 Preparation

The first step is preparing all instruments, equipment, and recording spaces. A spacious recording area with sound insulation and minimal sound disturbance from external sources is essential for optimal sound quality. We performed the recordings in the Myhal Multimedia room. To ensure the quality of the recordings, a sample of the recording space's ambient noise should be collected to either qualify the collected results or reduce unwanted noise during the analysis stage using audio signal processing techniques. The microphone used was a Fifine K669B microphone with a pop filter, and the software used to record was Sound Recorder (the built-in Windows audio recording software). All instruments discussed in the previous section should be gathered and tuned to A440 prior to recording. To ensure that all instruments play at the same tempo, a metronome should be set to 80 beats per minute; all excerpts and scales will be played at this tempo.

4.2.2 Recordings

For solo recordings, the microphone was placed 50 cm in front of the player. Woodwinds played one octave scales in the keys of C major, G major, and A minor. Percussion instruments played the short excerpt shown in Figure 2, which was created using Musescore (Studio (2024)).

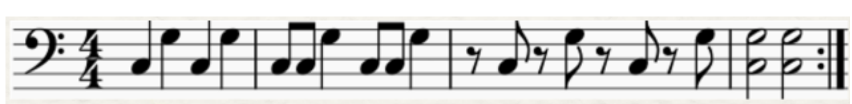

Figure 2: Music Score for Percussion Instruments

For the chamber recordings, paired performances of the first 12 bars of Variations on a Theme of Twinkle Twinkle Little Star (the first few bars are shown in Figure 3, Studio (2024)) were performed. Each woodwind instrument recorded an excerpt alongside every percussion instrument. The musicians were positioned 2 meters apart, with a microphone placed equidistantly between them to minimize sound delay.

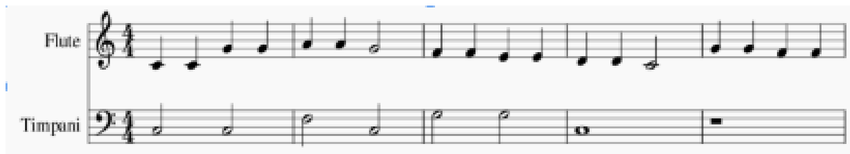

Figure 3: Sheet Music of "Twinkle Twinkle Little Star"

4.3 Data Processing

We clip all audio samples to a consistent length: 7 seconds for woodwind, 13 seconds for percussion, and 37 seconds for chamber recordings of "Twinkle Twinkle Little Star." Collaboration is facilitated through Google Drive and Google Colab.

Using the `librosa` library, we convert the audio clips into waveforms, spectra, and spectrograms, and extract features like centroid, roll-off frequency, flatness, and entropy. These features are then analyzed with ANOVA, focusing on fundamental frequency and audio power (RMS) for final comparison.

5 Results and Discussion

This section begins by presenting the analysis and results of the solo and chamber recordings individually. Subsequently, it provides a comprehensive discussion of the overall findings, examining how they align with the project's objectives.

5.1 Solo Recordings

To explore acoustic characteristics among various types of instruments from different and similar cultures, we began by analyzing woodwind and percussion instruments individually. Following this, we conducted a comprehensive comparison of all the instruments collectively to ensure the analysis was thorough and inclusive.

5.1.1 Checking the Effectiveness of the Analysis

To ensure the stability and accuracy of the recordings, we began with a time-domain analysis. As illustrated in Figure 4, the peaks of the tongue drum waveform align with the corresponding notes in the musical score. Additionally, the duration of each peak matches the time span of the respective note types, such as quarter, eighth, and half notes.

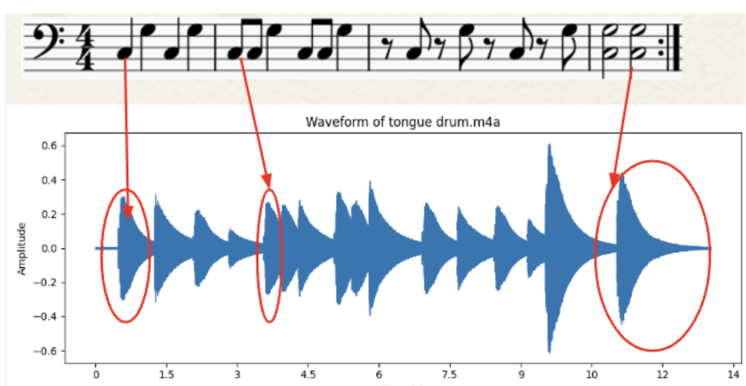

Figure 4: Comparison between Tongue Drum Waveform with the Music Score

5.1.2 Woodwind Instruments Analysis

We examines two woodwind instruments: the flute from Europe and the kazoo from the Americas. In the time-domain analysis, both instruments exhibit similar waveform patterns when playing scales. However, there are notable differences in the duration and amplitude of individual notes. The kazoo, in particular, displays more irregular patterns and greater variability in amplitude compared to the flute. Quantitatively, the kazoo's randomness is reflected in its higher entropy magnitudes at peak values, averaging around 4, whereas the flute's peak entropy magnitudes are lower, stabling around 2. (Figure 5 - Figure 8)

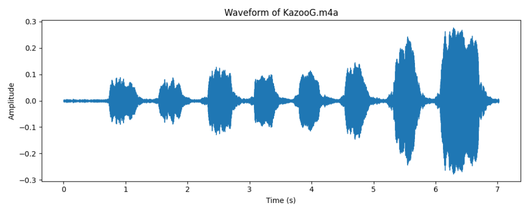

Figure 5: Kazoo Waveform in G Major

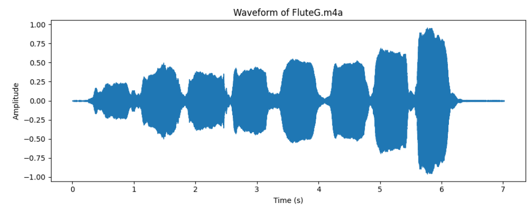

Figure 6: Flute Waveform in G Major

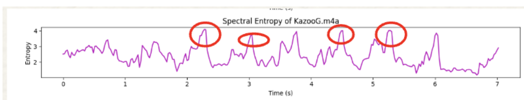

Figure 7: Kazoo Entropy Plot

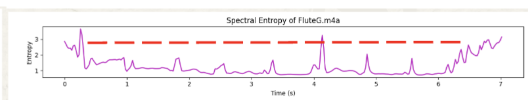

Figure 8: Flute Entropy Plot

When comparing the spectrums (Figure 9 - 10), the flute exhibits distinct peaks at harmonic frequency ranges between 440 Hz and 880 Hz, whereas the Kazoo shows a more diffuse distribution of peaks across the frequency axis. Despite being played similarly, the flute consistently produces a more harmonic sound, with longer note durations and greater sustain. The tonal characteristics of the flute are also evident in its narrower flatness range (0.00-0.02), attributed to its sound production method, which enhances resonance. In contrast, the Kazoo produces a noisier sound with a broader flatness range (0.05–0.1) due to its reliance on vocal vibrations for sound generation (Figure 11 - 12).

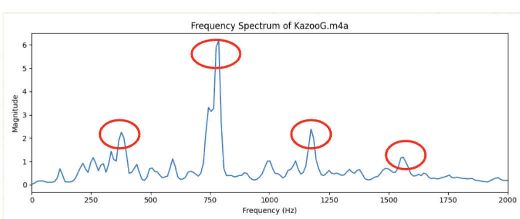

Figure 9: Kazoo Spectrum

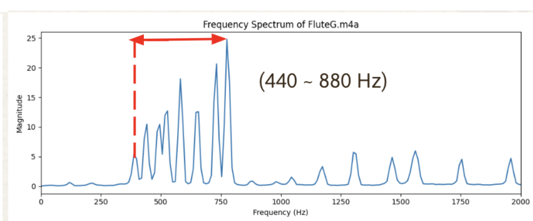

Figure 10: Flute Spectrum

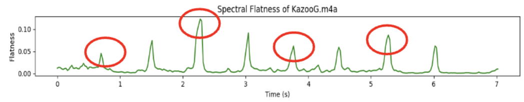

Figure 11: Kazoo Flatness Plot

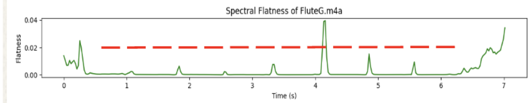

Figure 12: Flute Flatness Plot

5.1.3 Percussion Instruments Analysis

The comparison of percussion instruments was conducted by analyzing their spectral entropy plots. Spectral entropy measures the randomness in a signal's frequency distribution, with higher values indicating greater disorder. A threshold of 3 was used to distinguish randomness levels, with the analysis focusing on the peak entropy magnitudes.

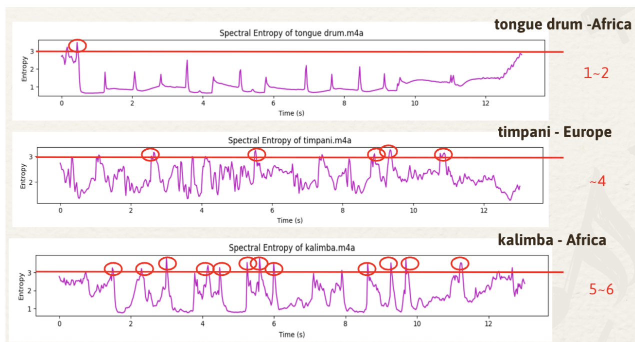

Figure 13: Spectral Entropy Plots for Percussion Instruments

As shown in Figure 13, the African tongue drum exhibits most of its entropy peaks below the threshold, indicating lower sound randomness due to its richer harmonic content. The European timpani demonstrates moderate randomness, with entropy magnitudes around 4 observed across 5–6 peaks. In contrast, the African kalimba shows the highest entropy magnitudes, reaching approximately 6 across 10 peaks, indicating the greatest degree of randomness among the instruments analyzed.

5.1.4 Analysis of Variances of Single Instruments

Our ANOVA plots (Will Kenton (2024)) based on fundamental frequency, shown in Figure 14, summarize the acoustic characteristics of each instrument. We found that woodwinds exhibit more stable harmonic regions, reflecting their harmonic structure (180–400 Hz for the Kazoo, 400–800 Hz for the Flute). In contrast, percussions display dominant peaks within specific frequency ranges (Figure 14).

The broad peak distribution of the tongue drum aligns with the spectral entropy analysis in Section 5.1.3, highlighting its harmonic relationships due to its playing mechanism. Notably, the Kalimba, with the highest entropy, exhibits a wider peak range starting at a higher fundamental frequency compared to the timpani. This is because the plucked idiophone nature of the Kalimba produces a broad array of overtones, spreading energy across a wider frequency range. In comparison, the timpani's membrane-striking mechanism generates moderately harmonic overtones with energy concentrated in specific frequencies.

These independent acoustic analyses provide a foundation for understanding chamber recording behavior, which is explored in the next section.

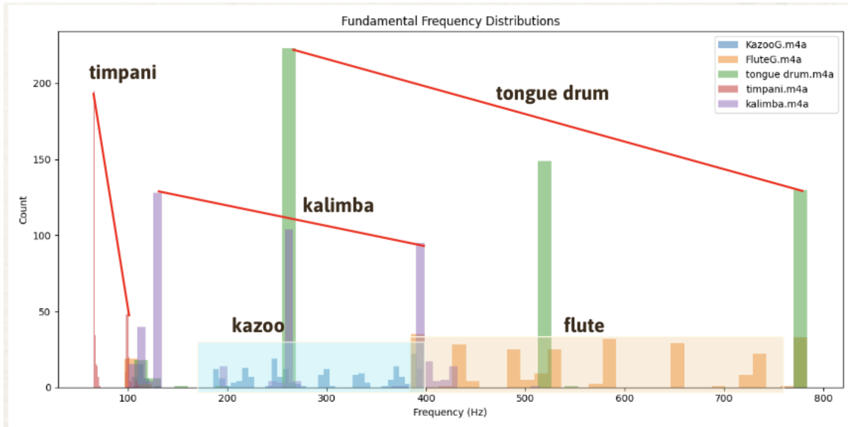

Figure 14: ANOVA Plots for Single Recordings

5.2 Chamber Recording

To investigate the effects of instrument pairings from different regions, we focus on pairs from both the same region and different regions.

5.2.1 Checking the Effectiveness of the Analysis

We examine the spectrograms of all the chamber recordings, and it is evident from Figures 15 and 16 that each time the notes change in "Twinkle Twinkle Little Star," there is a corresponding effect on the frequency in the spectrogram, demonstrating the effectiveness of the plots.

Figure 15: Sheet Music

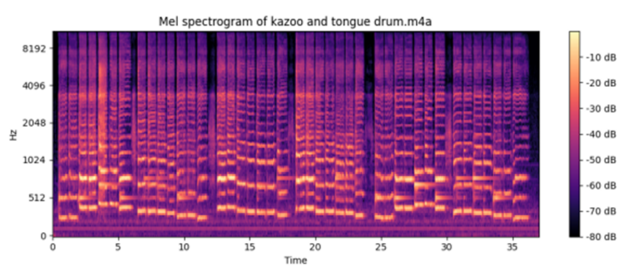

Figure 16: Spectrogram

5.2.2 Comparison of Flute+Timpani (Europe+Europe) and Kazoo+Timpani (the Americas+Europe)

We compare pairs of instruments from the same and different cultures. The flute and timpani are from Europe, while the kazoo is from the Americas. Spectrogram analysis of the flute and kazoo playing the C major scale shows that the **flute** has fewer low-frequency components and a stronger presence above 500 Hz, while the **kazoo** produces more energy below 500 Hz. (Figure 17 - 18)

Similar to the kazoo, the timpani also produces many low-frequency components, as shown in Figure 19.

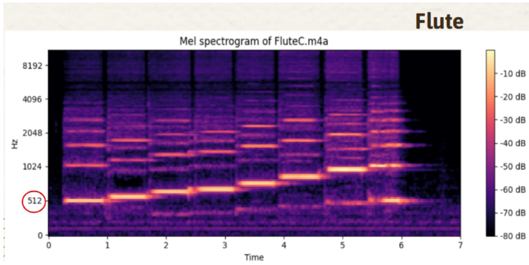

Figure 17: Flute Spectrogram

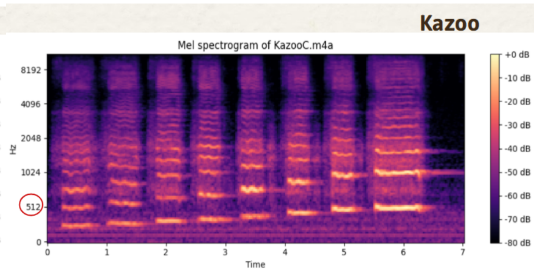

Figure 18: Kazoo Spectrogram

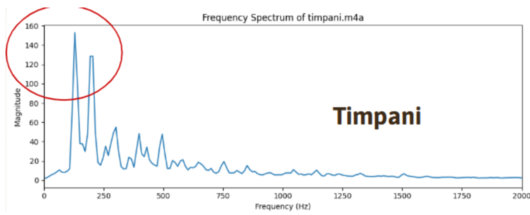

Figure 19: Spectrum of Timpani

When paired, the results differ. Despite both the kazoo and timpani producing low-frequency components, the **flute+timpani** combination shows higher low-frequency magnitudes than the **kazoo+timpani** combination (Figures 20–21). The stronger low frequencies (above 35 Hz) in the **flute+timpani** pair suggest that the flute allows the timpani's low frequencies to resonate without interference. In contrast, the weaker low frequencies (below 15 Hz) in the **kazoo+timpani** pair may indicate that the kazoo's lower frequencies mask those of the timpani, reducing the complementary timbres. This shift could result from the **flute** and **timpani** sharing similar acoustic properties, as they are both European instruments.

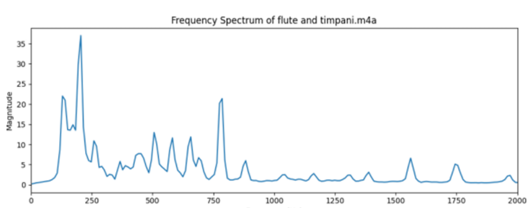

Figure 20: Flute+Timpani Spectrum

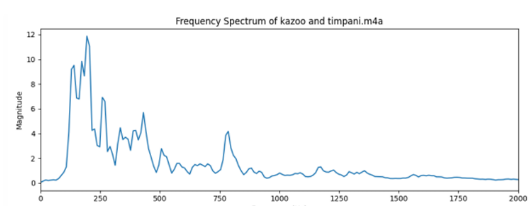

Figure 21: Kazoo+Timpani Spectrum

5.2.3 Spectral Entropy Comparison

We examine the spectral entropy between pairs of instruments from the same culture and pairs of instruments from different cultures. Spectral entropy quantifies the randomness in a signal's frequency distribution, with higher values indicating greater disorder. By setting a threshold of 3, we consider values above this limit to indicate inharmonious sound, and we compare the results across different categories, counting the number of occurrences in each case.

Our analysis shows that pairs of instruments from different cultures exhibit a higher number of inharmonious sounds. For example, the combination of **flute** and **kalimba** (Europe + Africa) has more than 20 occurrences, while the combination of **flute** and **tongue drum** (Europe + Africa) has more than 10 occurrences as shown in Figure 22. In contrast, the combination of **flute** and **timpani** (both from Europe) shows only 5-6 occurrences, indicating that instruments from the same culture tend to produce less disordered (dissonant) sound compared to those from different cultures.

Our analysis of ANOVA plots in Figure 23 further supports this finding. The highest note played in ”Twinkle Twinkle Little Star” is A4 (440 Hz). The frequency distribution for the **flute** and **timpani** pairing is mostly below 440 Hz, with a few harmonics at multiples of the fundamental frequency. In contrast, the pairings of **flute** with **kalimba** or **flute** with **tongue drum** show a broader frequency range (greater disorder), particularly above 440 Hz, highlighting increased randomness in these combinations.

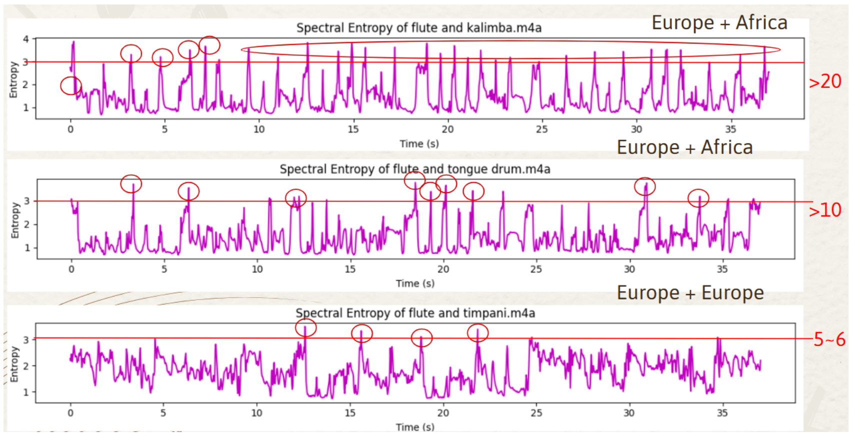

Figure 22: Spectral Entropy Plots

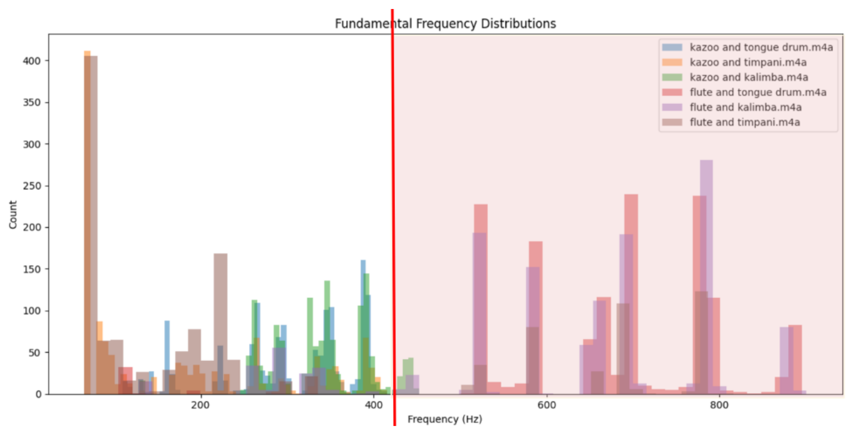

Figure 23: ANOVA Plots

In summary, the analysis shows clear differences in frequency interaction between instruments from the same region and different regions, highlighting the influence of cultural background on acoustic pairing.

5.3 Discussion

There are a few notable results from the previous section that can lend us insight into the science behind cultural instrumentation. First, we saw that instrument pairings from the same region displayed smaller values of spectral entropy – their spectral power distributions were much more collected and centered around their harmonics. In contrast, instrument pairings from different regions displayed larger values of spectral entropy, with their spectral power distributions showing a much noisier and spread-out behaviour. Furthermore, when examining the spectrograms of the recordings, pairs from the same region exhibited much larger absolute magnitudes in their spectra, while pairs from different regions exhibited smaller absolute magnitudes. It was interesting to note that recordings with smaller spectral entropy and larger spectral magnitudes strongly correlated to what we believed sounded "better" when listening to the recordings as well. This analysis strongly points towards a connection between the similarity of the instruments' regions, their spectral characteristics, and how "well" the pairings sound together. Therefore, we conclude that the acoustic properties of instruments from different cultures influences the sonic characteristics and compatibility that we hear.

6 Conclusion

In conclusion, this project underscores the important role that the acoustic properties of instruments from different regions play in shaping their unique sounds and influencing their compatibility in cross-cultural pairings. Our analysis revealed that instrument pairings from the same region tended to have lower spectral entropy values, with their spectral power distributions more concentrated and harmonically aligned with multiples of frequency. In contrast, pairings from different regions showed higher spectral entropy values, with more dispersed and noisy spectral power distributions. This highlights how the acoustic characteristics of instruments from diverse cultures shape the sonic qualities and compatibility we experience, offering valuable insights for innovative musical collaborations and sound design. However, due to the limited sample size, this analysis represents just one approach to studying the acoustic properties of instruments and understanding cross-cultural pairings.

As a next step, we plan to expand the database to include a broader range of woodwind and percussion instruments from Africa, Europe, and the Americas. With additional samples, we aim to refine the accuracy of the acoustic analysis by examining patterns in waveforms, spectra, and spectrograms to gain a deeper understanding of sound production mechanisms. By incorporating these new samples, the study will offer greater depth and provide a more comprehensive understanding of cultural instrument compatibility.

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7 APPENDIX

All the recordings and documents can be viewed on the Google Drive.

All the code for acoustic analysis can be viewed on the Google Colab.