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Research Paper

On the Audibility of Electric Guitar Tonewood

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Electric guitar manufacturers have used tropical woods in guitar production for decades claiming it as beneficiary to the quality of the instruments. These claims have often been questioned by guitarists but now, with many voices raising concerns regarding the ecological sustainability of such practices, the topic becomes even more important. Efforts to find alternatives must begin with a greater understanding of how tonewood affects the timbre of an electric guitar. The presented study examined how the sound of a simplified electric guitar changes with the use of various wood species. Multiple sounds were recorded using a specially designed test setup and their analysis showed differences in both spectral envelope and the generated signal level. The differences between the acoustic characteristics of tones produced by the tonewood samples explored in the study were larger than the just noticeable differences reported for the respective characteristics in the literature. To verify these findings an informal listening test was conducted which showed that sounds produced with different tonewoods were distinguishable to the average listener.

Keywords: electric guitar; tonewoods; spectral analysis; instrument timbre; exotic woods; guitar tone.

1. Introduction

The electric guitar is an instrument belonging to the family of chordophones (Koch, 2001). The world's first electric guitar was presented in 1931 and was immediately well received by the musical community (Wilkowski *et al.*, 2014). The Gibson ES-150, created in 1935, further contributed to this popularity and today the electric guitar has become one of the most widely used musical instrument. Little, however, is known regarding its acoustic properties, compared to its older sisters, the classical and acoustic guitar, on which many scientific publications have been written (Janson, 1983; Fletcher, Rossing, 1998; Torres, Boullosa, 2009; 2011; Bennett, 2016).

The guitar produces sound through the vibration of strings. In the acoustic guitar, the amplification of these vibrations occurs due to the string body coupling, which diverts them to the guitar's sound box (Fletcher, Rossing, 1998; Janson, 1983). The electric guitar uses electromagnetic transducers to capture the string vibrations and transmit them in the form of an electrical signal through processing equipment (like effect pedals) to an amplifier (Koch, 2001; Paté *et al.*, 2013; Ahvenainen, 2018). Due to these differences, it could be assumed that the wood used in the construction of electric guitar components has a much smaller effect on the instrument's timbre than in the case of an acoustic guitar. It cannot, however, be said that an electric guitar's tonewood is without impact, as vibrations coming from the body can feedback into the vibrations of the strings, due to the string-body coupling (Fleischer, Zwicker, 1998; Paté *et al.*, 2015). This suggests that the species of wood used to create the elements that make up an electric guitar might have a substantial effect on the sound of the instrument, but this effect must be measured and quantified.

2. Motivation

In the music industry, producers of electric guitars have long touted expensive and exotic woods as essential to the quality of their product, while musicians have often met these claims with scepticism. Only recently has the discussion regarding the impact of tonewood on the signal generated by the instrument gained interest (Puszyński, 2014; Wilkowski *et al.*, 2014;). The issue of wood is also important in other ways, as various types of wood, many exotic – e.g., mahogony, rosewood, ebony (Ahvenainen, 2018) – are used to build guitars. The researched literature suggests the need to optimise the usage of these species with regard to ecological sustainability (Martinez-Reyes, 2015; Ahvenainen, 2018; Ahmed, Adamopoulos, 2018).

The research carried out in the field of electric guitar properties shows that the material used for the fingerboard of the guitar neck affects the occurrence of 'dead spots' (Fleischer, Zwicker, 1998; Paté *et al.*, 2013; 2015). Additionally, research shows that the material of the body significantly influences the loudness parameter of the instrument (Puszyński *et al.*, 2015), however, the transducer displacements caused by its vibrations are too small to considerably impact the generated signal (Puszyński, 2014).

The aforementioned literature suggests a need for a deeper study of the subject. The first objective would be to verify whether the differences observed in the signal obtained from various guitar body materials are audible to listeners at all. A decision was made to focus our analysis only on the sound produced by the guitar's pickups, as the sound of the unplugged electric guitar, while noticeable to the guitarist, is not heard by the audience.

3. Experimental method

In order to minimise the number of unaccounted variables, the electric guitar's design was heavily simplified to a more easily reproducible shape. The timber samples were precisely cut into rectangular planks of the same dimensions and mounting holes for the guitar hardware were drilled using a CNC (computerized numerical control) machine.

The dimensions of the samples were chosen specifically to recreate the proportions and dimensions of a traditional electric guitar as much as possible (Fig. 1). To assure the broadest chances of noticeable variations among the models sound timbre, vastly different wooden materials were used to make the samples: sapele, rosewood, plywood, and pine. Both sapele and rosewood are staple tonewoods in guitar building but are used in different parts of the instrument. Sapele is usually used for the body and neck of a guitar, while rosewood, due to its hardness, is usually used for the fretboard. Pine was chosen as a lighter, softer and more easily acquirable alternative, while the plywood sample was included to see whether a vastly different structure of the material might have a noticeable effect.

The densities of these materials were as follows: sapele – 640.3 kg/m^3, pinewood – 466 kg/m^3, plywood – 705.4 kg/m^3, rosewood – 961.2 kg/m^3.

A set of guitar hardware was used to mimic a genuine guitar most closely (Fig. 2). The bridge, nut, and tuning peg were mounted in distances such as on a traditional s-type guitar with a scale length of 647.7 mm. A hardtail bridge with a string through bridge mounting system was chosen.

Fig. 2. Rosewood sample being set up for testing.

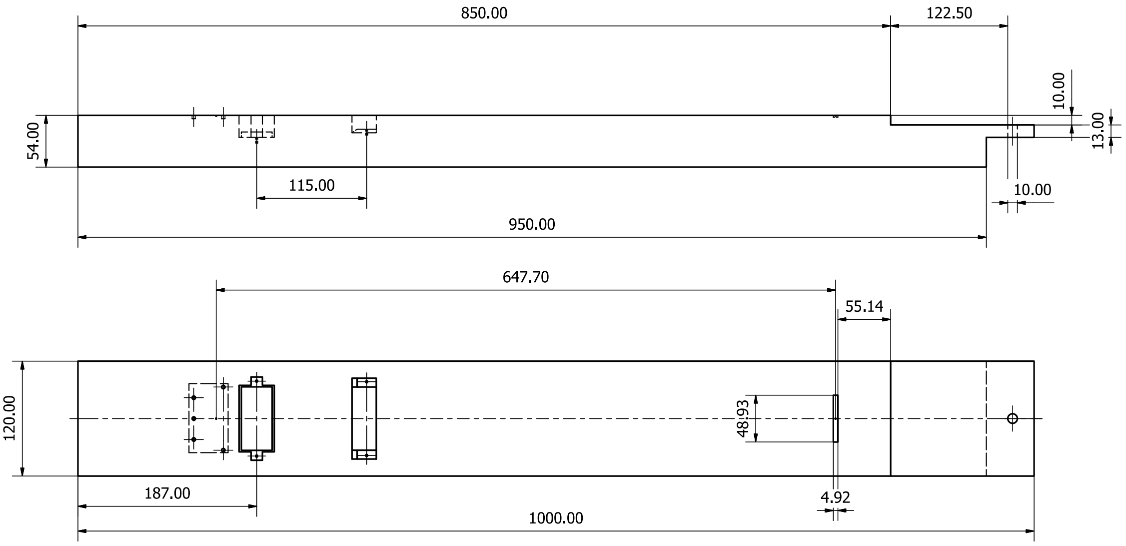

Fig. 1. Schematic drawings of the wood samples used as bases for the simplified electric guitar model. All presented values are in mm.

For a more thorough picture of the possible tone implications both a humbucker and a single coil pickup were utilised. The humbucker was mounted at the same distance from the bridge as the bridge pickup on lp-type guitars, while the single coil was located in the position of a neck pickup on a traditional s-type guitar (Fig. 3). The same set of pickups and mounting hardware was used for each wood sample to guarantee consistency and to remove their characteristics as a factor influencing the results of the comparison.

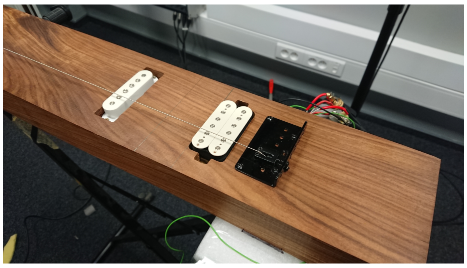

Fig. 3. Guitar bridge, humbucker, and single coil mounted to the rosewood sample and with the string tuned.

To check the range of differences between all samples after setting them up with hardware a set of distances was measured (Table 1). Only the signals generated by the guitar pickups were analysed. The microphones set around the model (Fig. 2) were used to record the sound produced by the string, but these signals are beyond the scope of this article.

In order to remove string excitation as a variable a special mechanism was designed to provide a repetitive pluck. This mechanism consisted of a spring from a hair clip connected to a hinge on one side and to a latch on the other (Fig. 4). When closed the spring is under tension and bounces away when released. After attaching a guitar pick to the springs free end this motion is used to repeatedly pluck a string. The whole mechanism was mounted on a wooden frame and clamped to the samples. Special care was put into the repeatability of the mounting position to ensure that the string is plucked at the same spot, at the same angle, and with the same strength.

For each of the wooden samples, measurements were carried out for three different open strings, in accordance with the standard guitar tuning: E2 (82.4 Hz), D3 (146.8 Hz), E4 (329.6 Hz). Measurements involved recording the pickup output for ten consecutive mechanism induced impulses. New strings were mounted each time to assure that string wear would not affect the results. Signals were recorded using a Focusrite Scarlett 18i8 USB audio interface into Reaper DAW (digital audio workstation) software. The recorded impulses were analysed using custom software written in Python using the librosa library.

Fig. 4. Plucking mechanism constructed to repeatably excite the tested string. The cork and elastic bands are used to dampen the springs vibration and make the mechanism quieter.

4. Results

The recorded signals were subjected to a suite of parametric analyses. The results for both the humbucker and the single coil pickups were highly similar, so only those regarding the humbucker will be shown and discussed. Calculated tonal parameters (spectral centroid, roll-off, bandwidth) showed clear differences between signals recorded with different wood samples.

The spectral centroid of the signal, which is a strong indicator of the perceived brightness (Schubert, Wolfe, 2006) of the played sound, showed particularly distinct deviations (Fig. 5). For the pitch E2 the centroid ranged from 306 Hz to 347 Hz, for D3 it did from 410 Hz to 560 Hz, while for E4 the values ranged between 1500 Hz and 2260 Hz. These are differences that should be easily perceptible to the listener (Carral, 2011) but this issue will be expanded on in a further chapter.

Table 1. Repeatability of test set-up: Ranges of distances measured for different wood samples [mm].

Note	Scale length	String height at bridge	String height over humbucker	String height over single	String height at nut	Plucking mechanism to string distance	Plucking point to bridge distance
E2	645	9.7	6.8–7.7	6.1–7	5.8–6.1	15.3–17	80.7–80.9
D3	645–646	8.2–8.7	6–6.3	4.8–5.3	4.3–4.9	11–13	80.5–80.7
E4	645–646	7.9–8.1	5.4–6	4.5–4.9	4.1–4.6	9–11.5	81.2–81.4

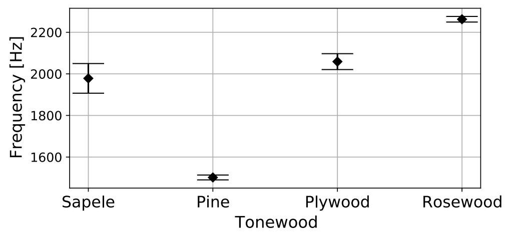

Fig. 5. Comparison of spectral centroid values with standard deviations recorded for the pitch E4 with the humbucker, for different tonewoods. Please, note that the chart values do not start at zero.

The second parameter worth inspecting is roll-off (Fig. 6), which is defined as the frequency below which 85% of the signal's energy lies (Tzanetakis, Cook, 2002). Once again, we can see visible changes between values recorded for each of the materials. For the pitch E2 the centroid ranged from 413 Hz to 464 Hz, for D3 it did from 514 Hz to 647 Hz, while for E4 the values ranged between 3220 Hz and 4810 Hz. The relative differences between these parameters measured for individual tonewoods are comparable. Charts showing spectral centroids and roll-off for the same pitch show highly similar relations, from which we can deduce that the changes caused by a model's material do not highly affect the higher frequencies of the produced signal. It is, however, worth noting how the changes in timbre related to tonewood are highly dependent on the pitch of the played sound. For E2 sapele and rosewood have similar parametric values, for D3 plywood and rosewood are similar, while for E4 the highest similarity is between sapele and plywood. The rest of the calculated tonal parameters supported similar conclusions. An additional important thing to notice is that the standard deviations of these parameters are small enough to give a high level of confidence in the repeatability of the plucking mechanism.

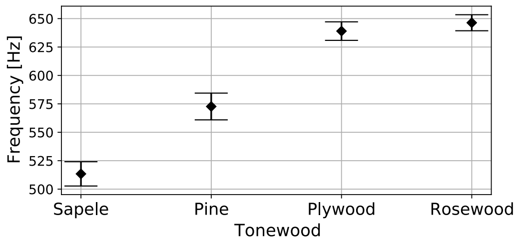

Fig. 6. Comparison of roll-off values with standard deviations recorded for the pitch D3 with the humbucker, for different tonewoods. Please, note that the chart values do not start at zero.

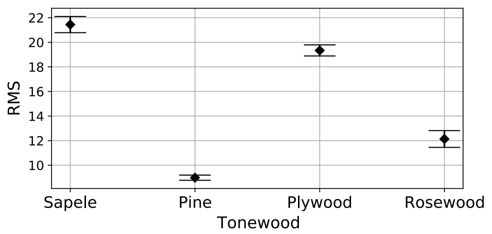

Fig. 7. Comparison of RMS values with standard deviations recorded for the pitch E2 with the humbucker, for different tonewoods. Please, note that the chart values do not start at zero.

Analysis of the changes in the RMS (root mean squared) of the recorded signals yielded similarly vast differences (Fig. 7). This confirmed the findings of earlier studies which reported that the tonewood of an electric guitar noticeably affected the signal level generated by the instrument (Puszyński *et al.*, 2015). These changes were once again highly dependent on the string's pitch. The temporal parameter of decay time highly correlated with the recorded signals' energy, which indicates that the shape of the amplitude envelope of the plucked string signal remains similar regardless of the wood used to create a sample.

To gain further insight into the studied phenomenon the recorded signals were subjected to spectral analyses. The impulses were divided into three sections. The first one (0–0.3 s) is the attack phase of the sound in which the signal contains many transients. This is what would be heard when the guitar is playing a fast passage, approx. 200 BPM (beats per minute). The second segment (0.3–1.3 s) contains the sound after it has stabilised. This is what would be heard during a slower play, approximately 50 BPM. The third section (1.3–505 s) contains the sound's decay and would only be heard if the sound is left to ring out. Presenting frequency spectra of each section separately shows how the sound produced by the instrument evolves with its decay. Within these spectra a different character of change can be seen that cannot be shown through tonal parameters. The amplitude ratios between particular harmonics clearly vary between different wood species. This is evident when we compare which harmonics are dominant in each segment of the sounds.

When comparing sapele and plywood for the D3 pitch (Figs 8 and 9) we can see that the sapele sample produced a sound that is characterised by the 3rd, 2nd, and 4th harmonics through the first two sections and the 2nd, 1st, and 3rd harmonics in the later phases of decay. This is in stark contrast to the plywood sample which begins with the 4th, 5th, and 3rd being prevalent and evolves into the 3rd and 5th dominating. These changes are extremely important to how the sound is perceived, as they can change the interval that is dominant in the aliquot series. Close comparison of these two sounds shows, in the second decay time frame, that the two strongest harmonics create an interval of a fifth for sapele and a major sixth for plywood. One interval is consonant, while the other is imperfectly consonant, which is a change that could have a large impact on how the instrument is perceived by the listener.

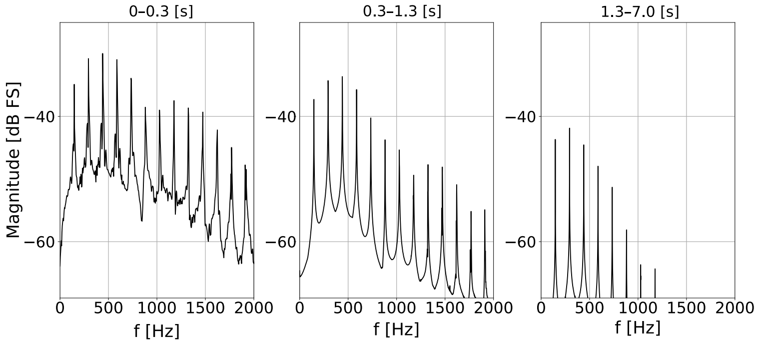

Fig. 8. Averaged spectra recorded for the pitch D3 with the sapele sample.

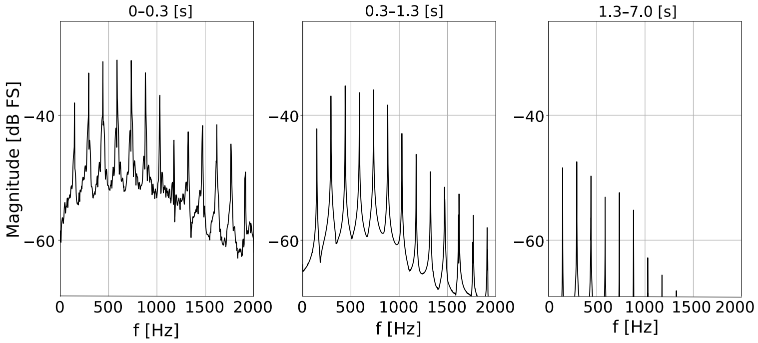

Fig. 9. Averaged spectra recorded for the pitch D3 with the plywood sample.

The comparison of sapele and plywood for the pitch E2 (Figs 10 and 11) shows another way in which individual harmonics can be important. In the sound recorded for sapele we can see that the 7th harmonic, while not dominant, is visibly present. This is in contrast to the sound recorded for plywood in which this pitch is much less present (over 5 dB lower). The 7th harmonic in the aliquot series produces the interval of a minor seventh with the fundamental frequency of the played pitch. This interval is dissonant, and its presence will highly affect the timbre of the instrument.

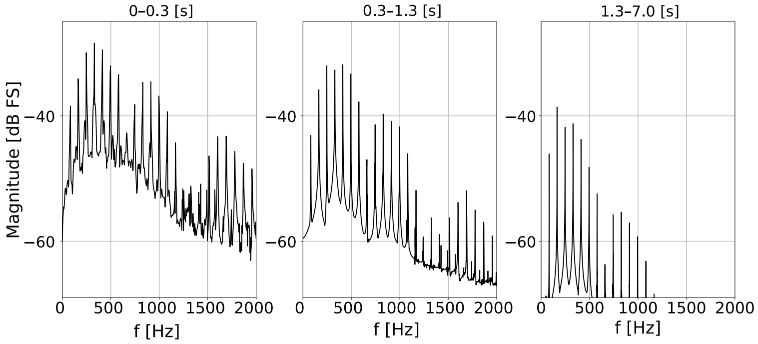

Fig. 10. Averaged spectra recorded for the pitch E2 with the sapele sample.

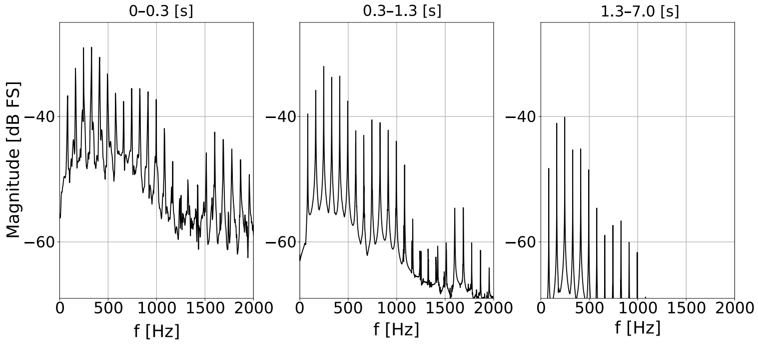

Fig. 11. Averaged spectra recorded for the pitch E2 with the plywood sample.

These changes will of course be different for each pitch played and their deeper understanding would require testing of a guitar's full spectrum frequency response. This does, however, show that the tonal changes associated with different wood samples can affect the produced sound in complex ways. For the sake of brevity, no more spectra will be presented. The changes between different wood species for each pitch have a similar range and character to the ones presented. Despite having recorded a vast array of differences related to the guitar's tonewood, we could find no clear correlations between the wood's characteristics and the produced sound. The observed relations are convoluted and cannot be reliably explained on the sole basis of the obtained results. These changes differed between each examined pitch and the phenomenon as a whole remains inconclusive.

5. Evaluation of the perceptibility of timbre changes

The analyses presented in the previous section clearly showed that the sounds produced by the simplified electric guitar models were changed through the use of different tonewoods. This gives credence to the claims of guitar manufacturers but does not fully exhaust the topic. Even if the wood used in the construction of a guitar can change the signal that is produced, it remains to be tested whether the scope of these changes is vast enough to be perceptible to the listener. Just noticeable differences have been examined for a number of parameters, including spectral centroids and changes in the levels of harmonics. After normalisation with the base frequency of a note this value for a spectral centroid has been found to be 0.15 (Carral, 2011), while the measured results presented above, after normalisation, show a difference of over 1. It has also been shown that listeners can distinguish between sounds in which the level of a single harmonic has been changed by 1 dB (Green, 1988; Ozimek, 2002; Carral, 2011) and, as stated earlier, between different wood samples harmonic levels changed values up to 5 dB. This points towards the conclusion that the changes in sound caused by the use of a different tonewood would be perceived by the listeners.

In order to validate this claim, an informal listening test was conducted using the two-alternative forced choice method (Frederick, Speed, 2007). Due to 2020 restrictions this test was conducted remotely, and participants used their own headphones. The listeners were presented with a recorded pluck for one tonewood (A) and then presented with plucks for the same tonewood and a different one (B) in a random order (AAB or ABA). They were tasked with indicating which one was the same as the reference. Such comparisons were presented for each possible permutation of reference and comparison woods. These comparisons were conducted for the D3 pitch as recorded by the humbucker pickup, the D3 pitch as recorded by the single coil pickup, and the E4 pitch as recorded by the humbucker pickup. These were chosen to study perceptibility in both higher and lower pitches, as well as for different guitar pickup styles. 67 listeners participated in the tests – 21 with a formal musical education, 22 with hobbyist musical experience, and 24 with no musical expertise. The listeners' age ranged between 20 and 55 and the majority of them were students.

The collected data showed that on average in 91.7% of answers participants were able to correctly distinguish between the reference and comparison sound. This is vastly above the commonly used threshold of 75%, which has been shown to be adequate for tests employing the randomisation of stimuli order (Ulrich, Vorberg, 2009). This shows that the differences caused by the change of a guitar's tonewood are perceptible to the listener. The pitch of the sound did not strongly affect the percentage of correct answers, as the percentage of correct answers for the D4 and E4 humbucker recordings were respectively 93.3% and 92.2% (Fig. 12). A stronger difference was

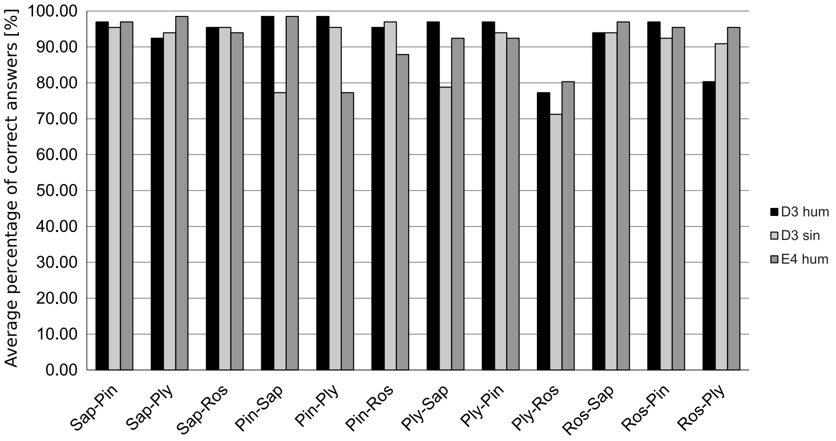

Fig. 12. Average percentage of correct answers in the conducted test for each wood combination and pitch. Legend: Sap – Sapele, Pin – Pine, Ply – Plywood, Ros – Rosewood, X-Y: X – Reference wood, Y – Comparison wood.

visible between the signal obtained through the humbucker and single coil pickups, as the single coil sounds were correctly recognised 89.7% of the time, in comparison to the humbucker's 93.3%.

People that declared no musical education correctly recognized the sounds at an average rate of 86.5%, which is noticeably lower than those with musical experience. This is well above the percentage level of correct responses commonly taken as an estimate of discrimination thresholds in 2AFC tasks, which allows to conclude that most listeners should notice the difference in timbre caused by a change in tonewood.

The test also showed that certain wood combinations were much harder to distinguish. The comparison of plywood to rosewood netted an average of only 76.3% between all comparison configurations. This shows potential in regard to the possibility of replacing traditionally used tonewoods with less expensive and more sustainable alternatives, but more in depth research is required on this topic specifically.

6. Conclusions

The tonewood used in the construction of an electric guitar can have an impact on the sound produced by the instrument. Changes are observed in both spectral envelope and the produced signal levels, and their magnitude exceeds just noticeable differences found in the literature. Most listeners, despite the lack of a professional listening environment, could distinguish between the recordings made with different woods regardless of the played pitch and the pickup used. The conducted test does not allow any conclusions regarding a more holistic outlook on a guitar's timbre, as the observed relations are complex beyond the scope of the obtained results. Further tests regarding the guitar's entire frequency response are required. It should also be noted that these tests were conducted based on a simplified guitar model, which might have overemphasised the researched phenomenon.

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