'Dubro' Resophonic Guitar: Glissando Gestures

V. J. Law and D. P. Dowling

Abstract Whether in the Hawaiian, Bluegrass, Rock 'n' roll, film sound track or animated cartoon genre, the swoop (glissando) sound made on a slide-guitar is one the most instantly recognizable in western music. This paper reports on the complex acoustical and perceptual glissando of the opening few seconds of Warner Brothers '*Looney Tunes'* ascending glissando, and its counterpart (descending glissando), both played on a '*Dubro*' resophonic guitar. The aim is to analyze these guitar themes in an attempt to provide both a historical development, as well as a technical understanding of the generated sound. With the resophonic guitar tuned to open G (D-G-D-G-B-D), the radiated sounds, includes the guitarist gestures and the glissando sound of steel and glass bottleneck**,** Using the toolbox within Audacity software (time-domain, standard autocorrelation, spectrogram and noise reduction), the recorded tracks are transcribed for tempo, consonant, dissonant, string squeaks, and incoherent/coherent noise. This study also attempts to map the complex psychoacoustic tonal quality of a resophonic guitar, which has been demonstrated to impact emotionally on the listener. It is found that dynamic slide movement divides the string scale length into two coupled longitudinal vibrating segments, each producing a coherent continuous mirrored exponential varying pitch that extends to the guitar brilliance region (4.5–20 kHz). Incoherent or 'hiss-like' noise is found within the lower psychoacoustic warm region (0–0.5 kHz). This incoherent noise is linked to a slip-stick friction process between the slide and string. Slide material and slide direction varies the intensity of the noise that has a Voss-Clarke *1/f*-like response with a Brownian ~ −7 dB/10 Hz roll-off. It is proposed that the guitarists fretting arm musculoskeletal system plays a role in the generation incoherent or hiss-like noise.

Keywords Dubro · Resophonic guitar · Bottleneck · Glass · Steel · Glissando · Incoherent noise

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1 Introduction

Chordophones have an important cognitive and emotional role in the development of world music [1], and western music, where the guitar is the main instrument in this classification of stringed instruments. When playing a string instrument, the listener's perceptual experience can invoke a strong psycho physiological response (chills and tears [2], change in heartbeat and respiration rate [3], pupil dilation response [4], and dance [5]. Over riding these emotions is whether the music is played in the major or minor cord: where a major cord instills joy and happiness, and calmness and sadness is found in minor cords [6]. The average tempo of a composition also influences the listener's emotions. For example, an Allegro composition of 140 beat per minute (BPM) has been found to increase listener's blood pressure and heart rate, whereas Andante of 80–82 BPM produces calmness [7]. For a human body mechanism to produce these responses, Voss and Clarke [8] proposed that the natural chemical oscillations within nerve membranes are a likely candidate. Arguably the resonant guitar (or, resophonic guitar [9, 10] played with a bottleneck slide provides one of the most distinctive glissando [11] sounds within the family of string instruments. For example, Freddie Travares's crystal-clear attention grabbing opening 2 s for the Warner Brothers instrumental theme '*Looney Tunes'* (based on the song Merry-go-round broke down) [12, 13]. Travares's credited guitar work on Elvis Presley's '*Blue Hawaii'* [14] is another, if not well known, example of the guitar glissando. It is no surprise then that '*Loony Tunes'* is associated with comedy and happiness and '*Blue Hawaii*' is associated with mellow emotions. Ry Cooders reworking of Blind Willies Johnson slide guitar chords in the film '*Paris, Texas*', goes one further by introducing vibrato at the end of each fading cord to evoke the feeling of doubt, sadness and yearning of the American dry desert landscape [15].

Beyond the resophonic guitar patents [9, 10], online commentary of partitioning the resophonic guitar psychoacoustic pitch/frequency bands [16], mechanical modal analysis of the resophonic guitar [17, 18] and the development of virtual slide guitar software [19], detailed mapping of the resophonic guitar psychoacoustic space has not be documented as played by a guitarist. The aim of this work is to analysis the radiated sound of a *'Dubro'* resophonic guitar with the guitarist playing the instantaneously recognizable opening seconds of the ascending glissando of the '*Looney Tunes'* instrumental theme and its counterpart associated with the instrumental theme music to the film '*Paris, Texas'*. The capture and analysis of these guitar themes and guitarist gestures maps the perceived sound by the musician and nonmusicians alike thus providing a greater insight to the resophonic guitar psychoacoustics space.

This paper is organized as follows: Sect. 2 reviews the origins of the resophonic guitar and open G tuning. Section 3 provides the experimental. Section 4 describes Benchmarking of the guitar under steel- and glass-bottleneck at a fixed fret position when strumming a using a plastic plectrum [20]. The frequency range of the benchmark extends through three psychoacoustic regions: warm (0–2 kHz), bright (2–4.5 kHz) and the lower brilliance region (4.5–8 kHz) [16]. Section 5 explores the ascending and descending glissando in these three psychoacoustic regions. In Sect. 6

the extended brilliance range up to the human audible threshold limit (20–22 kHz) is examined for ascending and descending glissandos. In Sect. 7, the background detailed in Sects. 4, 5 and 6, informs and identifies the incoherent noise produced by the guitarist gestures. Finally, Sect. 8 provides a discussion on this work.

2 Development of Resophonic Guitar

2.1 Pythagoras String Instrument Theory

The employment of music in the treatment of disease dates back to the earliest times including when David strummed his harp before Saul [21]. Later Pythagoras [ca, 570–495 BC] became interested in understanding the notes and scales used in Greek music for the healing of disease. In particular, the use of the stringed instrument, called the lyre. It is from this time the use of a mathematical approach to help achieve a greater understanding of western music became established. Pythagoras studies found that when two strings with the same length, tension, and thickness, sounded the same when they were plucked, or picked. This means they have a unison sound to the human ear (or consonant), when played together. He also found that if the strings have different lengths (keeping the tension and thickness the same); the strings have a different sound and generally sounds bad (or dissonant) when played together. He also noted that strings having different lengths produce sounds but were consonant rather than dissonant. Pythagoras called the relationship between two notes an interval. Since these discoveries, music containing consonant tones has treated disorders of the ear and epilepsy, sciatic gout and a range of mental disorders [21]. Today, when two strings of the same length are plucked, or picked we say they have the same pitch and, if one string is plucked, or, picked at exactly one-half of the length of the other string, the pitch is doubled and are consonant when played together. This interval is called an octave (harmonic). Furthermore, if one string has a length that is two-thirds the length of the other, the strings again sound consonant when played together and this interval is called a Perfect Fifth. Finally, if one string has a length that is three-quarters the length of the other, the strings again sound consonant, when played together and this interval is a Perfect forth. Hence, the length of the strings being a certain ratio defines interval. Musically speaking the intervals discussed have ratios of: unison (1:1), octave (2:1), a perfect fifth (3:2) and perfect forth (4:3) and so on. The frequency response of the human ear however can only spatially differentiate a limited number of tones within an octave, which are 12 half tones or semitones.

2.2 Vincenzo Galilei's Fret Fingerboard

In the late Renaissance period, the composer, experimentalist, mathematician, and father to Galileo Galilei, Vincenzo Galilei [ca, 1520–1591], developed Pythagoras linear ideas for string instrument to perhaps the first non-linear theory of stringed instruments. From his work we get the rule of eighteen i.e., the division of the active vibrational length of the string [string length (*SL*)] by 18, to obtain the first fret position ($fret_1$) on the string fingerboard (Eq. 1) and dividing the remaining string length by 18 again to get the second fret, and so on. The distance from front of the nut at the headstock to the bridge is defined as *SL*. Today we use the more precise calculation of 17.817, although the rule of eighteen is still commonly used. This rule places the string octave at the twelfth fret', thus providing an equal temperament between each fret. However, the exact overall length from nut to bridge varies slightly with each string, due to the different mass of each string. In this case, the bridge is orientated at an angle to make a slightly longer sounding length for the lower strings and a shorter one for the high strings, thereby, altering each string scale length minutely to improve intonation across all strings in relation to each other for more accurate tuning when playing up the neck. Equations 1 and 2 help to demonstrate this relationship [22].

$$fret_1 = \frac{SL}{17.817} \tag{1}$$

Equation 2 computes the *nth* fret position from the front of nut at the headstock.

$$fret_n = SL - \left(\frac{SL}{\left(2^{n/12}\right)}\right) \tag{2}$$

The posture of the guitarist is in the seated position with the finger board held by the left hand at about 45° to the horizontal. The area between the thumb Interphalangeal joint and the Metacarpophalangela joints of the left hand are warped around the neck two allow the bottleneck (placed on the ring finger) to act a mobile fret. In this position the left hand is moved up- and -down the fingerboard using the musculoskeletal arm system (with minimal wrist flexion). To produce the rich and complex Delta and bluegrass sound, the index, second and fourth finger do not mute (dampen) the strings. In addition, the guitarist uses a 0.5 mm thick plastic plectrum held in the right-hand to down-stroke the cord string while the palm and lower fingers mute (dampen) the remaining strings.

Using Eq. 2, the fret-offset distance to the nut (fret = 0) can be plotted as log to the base 10 on the horizontal axis against the Fret number, as shown in Fig. 1. This example is for a Dubro guitar that has a 19 fret fingerboard with a fixed *SL* value of 61.2 cm, see experimental section. The exponential trend-line fitted to the data points is associated with the fitting parameter. The trend-line deviation towards fret = 0 and fret = 19, indicates that equal temperament is not directly achieved. In

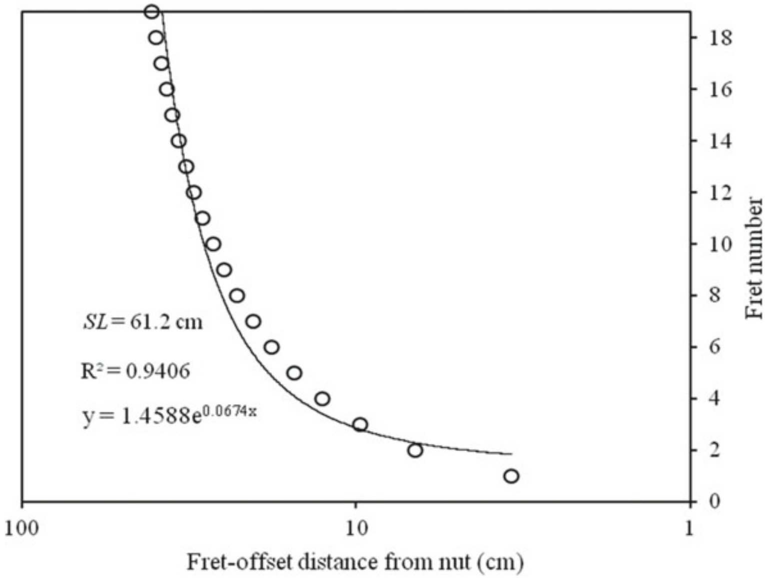

Fig. 1 Fret distance from nut plotted on a $\log_{10}$-linear scale with the data points represented by open-circles, fitted with a Microsoft Excel exponential trend-line

practice however, equal temperament is achieved by altering the bridge orientation and string tension as mentioned above.

Unlike non-fretted instruments (violin), the guitar fretted fingerboard allows people with limited musical knowledge to know when to stop at a given target pitch. This is because the additional tactile and visual cues add to the audible cues to provide an all round cognitive feedback system between the guitarist and the sound of the guitar strings when plucked or picked.

2.3 Origins of the Six-String Acoustic Guitar

The six-string acoustic guitar as we know it today has its origins in post Braque Europe, in particular in Spain where Antonio de Torres Jurado [1817–1892] developed the classical hour glass look and the introduction of the evolutionary "fan" bracing pattern within the guitar's body. Using a circular aperture (hole) in the top plate as the principle mode of acoustic amplification and sound projection (see Helmholtz Eq. 3) [23], his design improved the volume and tone of the guitar when using the rapidly accepted standard guitar tuning of (lowest pitch, thickest string) E-A-D-G-B- E (highest pitch, thinnest string).

$$f_0 \approx \frac{v}{2\pi}\sqrt{\frac{A}{V_{oL_{eq}}}} \quad (3)$$

where f_o is the resonant frequency of aperture in the guitar top plat, v is the speed of sound (at 20 °C, $v \approx 343$ m s^{-1}), A is the area of the aperture, V_o is the volume of the guitar body and L_{eg} is the equivalent length of the neck plus end correction.

f-holes were originally developed for the violin in the Braque period and Antonio Stradivari [1644–1737], is widely regarded as having produced the best design in sound projection and pleasing appearance. Later the physicist Félix Savart [1791–1841] brought this innovation to the guitar, thereby helping to separate the guitar from its classical roots and gain a new audience in the form of country and jazz. In 2015, a study of *f*-hole sound projection revealed that the axial-length of the *f*-hole rather than its area that determines the acoustic power projection [23].

2.4 The Steel-String Acoustic Guitar

The first steel-strings for the banjo and guitar are generally considered to have been offered by Christian F Martin [1796–1867] in the mid 1920s, when Hawaiian music became popular in the USA. The union of the steel-strings with the guitar produced a brighter and louder sound that could complete with horns, pianos and drums at mid west American barn dances. Here it's worth noting that a direct and contemporary comparison between the 5 steel-string banjo and the 6 steel-string guitar can be found in the 1972 film Deliverance [24]. The emerging expressive music (Cajon, country, Folk and Bluegrass music) also meant that standard guitar tuning had to change to an open G (lowest pitch, thickest string first) D-G-D-G-B-D (highest pitch, thinnest pitch last) to enable the G major chord (G-B-D) to be strummed on all six strings without the use of the guitarists fret hand, or a capo.

As open G tuning only requires the re-tensioning of only three strings, this new tuning style was readily adopted in bands with a wide spread of music genre. Open G tuning requires the sixth and five strings pitch to be lowered in to D_2 and G_2 respectively. The next three strings (4, 3, and 2) remain the same while the first string (1) with the highest pitch and thinnest string is lowered in pitch from E_4 to D_4. Table 1 tabulates this process, where the last row provides the comparative frequency compression (brightness) of open G tuning with respect to standard tuning.

2.5 Lap-Steel-Guitar and Slide-Guitar

It is said 'that in the 1890s, Joseph Kekuku [1873–1932], accidently strummed a Spanish guitar with a discarded bolt and from that day Kekuku become the inventor of the Hawaiian '*lap-steel-guitar*'. This guitar music requires the guitar to be played

Table 1 Standard and open G tuning of a guitar with pitch values rounded to the nearest whole number

	Standard		Open G	
String	SPN[a]	Pitch (Hz)	SPN[a]	Pitch (Hz)
6	E_2	82	D_2	73
5	A_2	110	G_2	98
4	D_3	*147*	D_3	*147*
3	G_3	*196*	G_3	*196*
2	B_3	*247*	B_3	*247*
1	E_4	330	D_4	294
Frequency range (center point)		248 (128)		221 (110.5)

The rows emphasized with italic (string 4, 3, and 2) have no change of tuning
[a] Scientific pitch notation (based on 400 Hz), subscript denotes the octave in which the note is played

in a flat and horizontal position across the guitarist's knee. Bolts, nails, back of a pocketknife and steel combs all give a pleasing descending—glissando sound that invokes a vision of Hawaiian palm beaches and rolling surf. Around the turn of the nineteenth century, the Steel guitar began to be held against the body as in the Spanish style with the guitarist using a metal, or glass cylindrical object worn on the fretting finger. These fretting techniques, known as '*Slide-guitar'* in the Mississippi Delta: where in the Deep South, Blind Willie Johnson [25], Elmore James [26] and others developed and popularized Gospel Delta blues and Bluegrass. By the early 1920s, the term bottleneck came in use, due to a common idea that the remnants of broken glass bottles left over from bar room fights were picked-up and played on the guitar frets, and if not up to the task than another bottleneck could be picked-up from the floor and used.

In practices, the bottleneck divides the guitar string into two coupled vibrating string-lengths, with the extreme ends of the two sting lengths fixed and the opposing ends coupled through the damping action point of the bottleneck. When it comes to the sound quality '*slide-guitar'* guitarists consider that glass slides offer a smoother playing feel, and produces a warmer and thicker sound that emphasizes the low to mid overtones within the harmonic series compared to metal slides that give a longer sustain that is also brighter and harsher [16].

3 Experimental

This study firstly investigates the sound generated by the Dubro DM-33 Hawaiian resonator guitar (Fig. 2a). The name *'Dubro'* is a portmanteau of '*Dopyera Brothers*' who invented this type of resonant guitar. The guitar has a chrome-plated brass

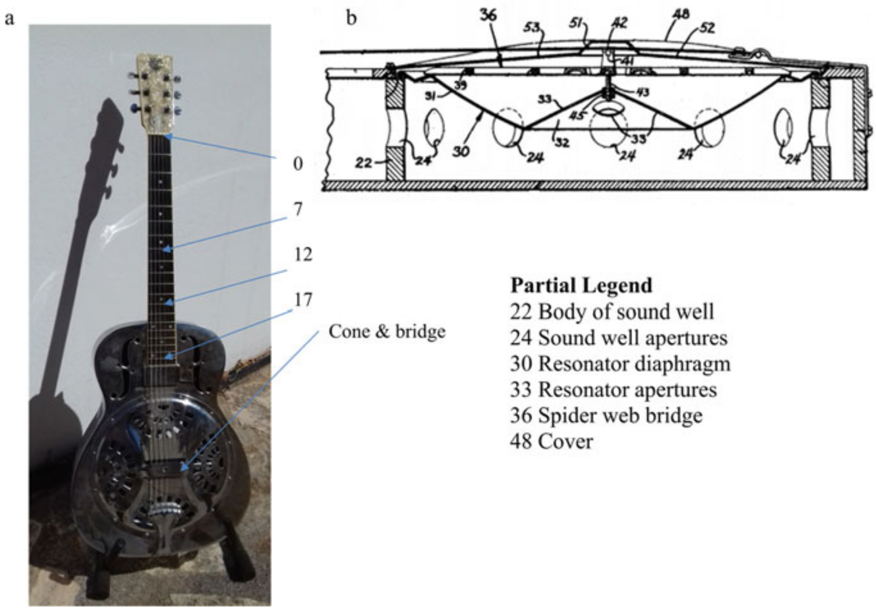

Fig. 2 **a**–**b** Photo of the Dubro DM-33 resonator guitar (**a**). Cross-section of Dubro cone/resonator diaphragm based on R. Dopyera's 1932 US patent (**b**)

metal body with sandblasted palm trees, two rolled *f*-holes (axial length 112 mm × 15 mm at their widest point), and a 19-fret rosewood fingerboard with pearl dot inlays (Fig. 2a). The average scale length of the strings is 61.2 cm, and the string action is 3.5 mm, to minimize accidental fret notes. The Dubro is a relatively complex string instrument, compared to the classical acoustic guitar, where the primary mechanical sound amplification is produced by a 26.7 cm diameter outward facing resonator cone/diaphragm, at the top of which is attached a biscuit bridge (Fig. 2b and R. Dopyera US patterns [9, 10]). The purpose of the cone is twofold, (1), to project the string vibrational sound out and away from the guitar and (2), send part of the sound in to sound-well and out via body ports. The two main ports being rolled *f*-holes that are **set** symmetrically **set** either side of the strings. Using this arrangement, the cone produces a harsh mid-high frequency range (1 kHz and above) while the *f*-holes project sound energy in the low to mid frequency range 70–150 Hz. The mechanical complexity of the Dubro does mean regular carful maintenance and regular tune-up is required. A range of short videos of resophonic guitar tuning can be found on YouTube, see for example [27, 28].

3.1 Recording of the Dubro Guitar

For this study, the digital recordings of the acoustic resophonic guitar were made during a performance in Kastollos, Crete in August 2020. The guitar radiated sound is recorded using a Zoom H4n handy recorder (frequency response ~ 30 Hz to 22 kHz) positioned one meter in front of the guitar. The sound levels were set using an alto ZMX122FX mixer and the track recordings saved in waveform audio files on a SD card. The choice of a microphone rather than an electric pick-up is deliberate as this gives both acoustical and perceptual information of the guitar sound as played by the guitarist.

The posture of the guitarist is in the seated position with the fingerboard held by the left hand at about 45 degrees to the horizontal. The area between the thumb Interphalangeal joint and the Metacarpophalangela joints of the left hand are warped around the neck two allow the bottleneck (placed on the ring finger) to act a mobile as the left hand is moved up- and -down the fingerboard using the musculoskeletal arm system (with minimal wrist flexion). The bottleneck divides the strings into two vibrating portions that are designated as string bridge (S_b) and string nut (S_n) respectively. The guitarist may choose to mute (dampen) S_n to generate a crystal-clear tone as in the case of Freddie's swoop in the opening seconds of '*Looney Tunes'* (Fig. 3a) or un-mute (Fig. 3b) to provide a rich and complex sound that is character of Delta blues. Steel and glass bottleneck slides are used in the recordings. The steel has a length = 51 mm, inside diameter = 19 mm and outside diameter = 26.5 mm and glass has a length = 70 mm, inside diameter = 20 mm and outside diameter = 2.5 mm). In the following text the slides are designates as s-slide and g-slide. In addition, the guitarist uses a 0.5 mm thick plastic plectrum held in the right-hand to down-stroke the cord string while the palm and lower fingers mute (dampen) the remaining strings.

Track transcription is performed within a Lenovo laptop running Microsoft Windows 10, therefore the xxx.wav files are fully combatable with Microsoft's Resource Interchange File format (RIFF) specification. Audacity® version 2.4.2 (a

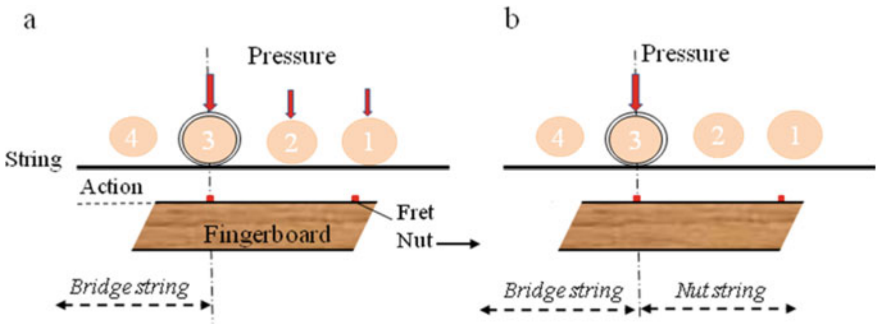

Fig. 3 a–b Cross-section schematic of slide and fingers in the S_n muted position (**a**). Cross-section schematic of slide and fingers in the S_n un-muted position (**b**)

Table 2 Audacity software project rate and display information

	Lower Frequency (Hz)	Upper Frequency (kHz)	Sampling rate (s s^{-1})	Display video bandwidth (Hz)	Screen shot
Waveform	N/A	N/A	44,100 32-float	N/A	Yes
Spectrum analyzer	30	22	44,100 32-float	N/A	
Spectrogram default maximum	30 30	8 22	44,100 32-float	50	Yes

free, open-source, cross platform audio software) is used to transcribe the guitar sound recordings [29]. The software uses a sampling rate of 44,100 Hz with a dynamic range of 32-bit float to provide a coupled time-domain and spectrogram (3-D plot of sound intensity (color) as a function of frequency and time) of the selected audio track recording. Frequency spectrum analyzer is also available. Table 2 provides the basic metadata for these displays.

Generally, open-access spectrometer software is limited in its ability to provide real-time frequency analysis due to the latency within the software. The latency is because of the lack of processing power to handle the large amount of time-series data that is needed to be converted into the frequency-domain using a Fast Fourier Transform (FFT) algorithm. To overcome this problem Audacity toolbox contains a set autocorrelation algorithms used to identify the SPN frequencies. This option measures how many times SPNs are repeated within the selected waveform record length. This is achieved by taking two copies of the waveform data set, and moving one waveform data set piecewise ($n = 1$) followed by multiplying the two waveform data sets together. The piecewise process is repeated, up to the selected size option. This mathematical noise reduction tool is one of many embedded delay time-series analysis tools used in chaos theory to extract periodic signals (overtones, octave, and harmonics) out of incoherent noise [30].

In the case of the spectrogram, a noise reduction algorithm (NRA) uses the FFT with a Hann window to sample the local neighborhood noise to obtain an incoherent noise profile. Subtracting the noise profile from the whole of spectrogram leaves the coherent acoustic signature of the resophonic guitar. Three operator parameters (amplitude, sensitivity, and frequency smoothing bands) settings determine the impact upon the guitars acoustic signature and the surrounding noise floor. The RNA is used here to estimate of the specific incoherent noise contribution for ascending and descending glissandos, rather than to clean-up the musical signature of the guitar. In mathematical terms this noise reduction technique is called spectral noise gating [31] and is used the compare the SPN and glissando modes of the bottlenecks. Other pixel thresholding methods may be applied using different software platforms, such as LabVIEW [32].

4 Benchmarking

Viewing the stereo sound tracks from the recordings, revealed that there was no different in X- and Y-tracks presumably this because the closeness of the microphones to each other (0.01 m), with respect to the guitar position (1.5 m), even though microphones have an XY orientation. Given this, only the X-tracks are used. The purpose of the Benchmarking the plectrum down-stroke is to establish both the acoustic signature of the guitar and the guitarist's gesture. Two Benchmarks are made, (1) strumming open G and (2) the first-string triad (strings: 3, 2, 1). The first-string triad is frequently used in the Rock 'n' roll genre [33] and therefore is included in this study. The knowledge gained from the Benchmarking informs the identification process of ascending and descending glissandos and incoherent noise.

4.1 Open G Tuning Benchmark

To establish the plastic plectrum down-stroke Benchmark, the guitar is strummed, and recorded, for 35 s. An initial analysis of the total waveform record-length yielded an average BMP of 144. A more detailed standard autocorrelation of a 2.2-s period encompassing both down and up cords yields the tones and overtones. To produce the greatest definition, the autocorrelation algorithm is set with a Hann window and sample size of 2048.

Figure 4 provides the computation where the correlation delay time is on the horizontal axis and SPN level on the vertical axis. In this representation and Figs. 7 and 8, frequency decreases to the right, therefore the root tones are to the right and the higher overtones progress to the left. Note, the delay time 0.01 and 0.025 corresponds to the at-rest human heart beat range (60–100 BPM). Using this representation, the tones G_1, B_1, and overtones C_2, D_2 and G_2 fall within the at-rest heat beat range, and the higher overtones (B_2, and D_3) are in the + 38 BPM elevated/stressed human heart beat range.

4.2 First-String Triad Benchmark

The plastic plectrum down-stroke of the first-string triad (strings: 3, 2 and 1), with the bottleneck slides damping the fifth fret produces corresponding values of s_b ~ 45 cm and S_n ~ 15.3 cm, respectively. In this style of strumming, the second-string triad (strings: 6, 5 and 4) are damped by the guitarist palm. This procedure changes the open G cord by five semitones without changing the original open G tuning.

Figure 5a–d shows two typical strumming cord acoustic waveforms (5a–b) and their associated default spectrogram (5c–d) for both s-slide and g-slide positioned on the fifth fret. In the case of the waveforms, there are two features of note. First is the

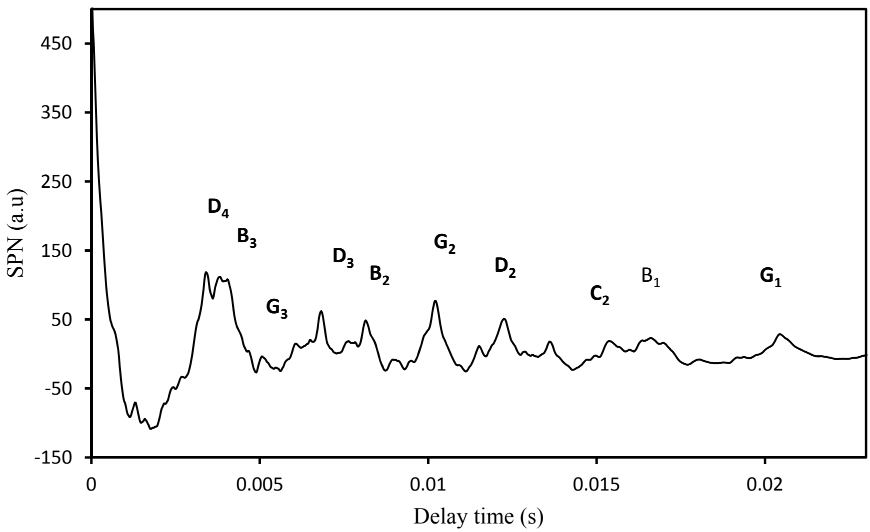

Fig. 4 Standard autocorrelation of the 2.2 s Benchmark. The root tones are to the left and the higher overtones to the rights. The human heart beat range is between G_1 and D_3

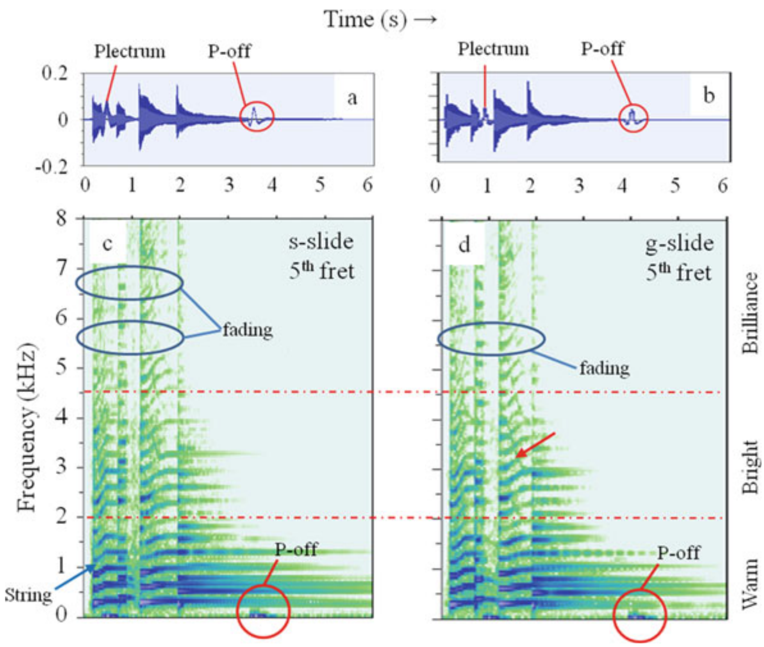

Fig. 5 **a–d** Waveforms and spectrograms obtained from the first-string triad with bottleneck damping on the fifth fret: s-slide 4a–c, g-side 4b–d

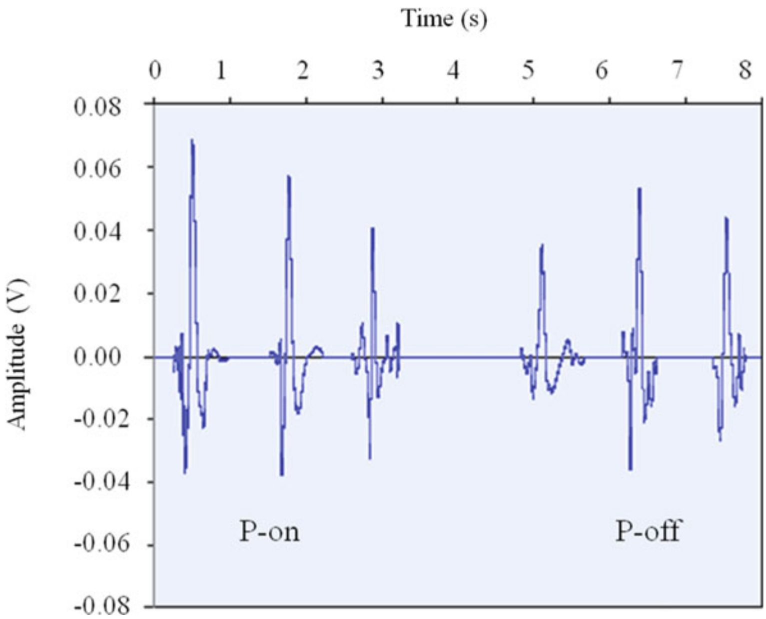

Fig. 6 Typical bottleneck pressure-on and pull-off signatures

truncation of the first and second envelopes by the third envelope that fades out to completion. Note also and that the s-slide fades by an additional 0.5 s compared to the g-side. Second, for both s-slide and g-slide, a string speak caused by an involuntary guitarist gesture is present in the first envelope (plectrum annotation in Fig. 5a–b). Note also, string squeaks are not found in the second or third envelope. In addition, at the end of the completed cord, a 10–20 Hz non-complex resonance is present. Not shown in these figures, but shown in Fig. 6, are further examples of complex resonances that appear at the start of additional recorded cords. The resonances have similar timestamps to the guitarist applied bottleneck pressure-on (p-on) and release (here called pull-off), thus bracketing the cord.

The two default spectrograms in Fig. 5c–d provide a greater insight to the fifth fret bottleneck position. To aid the reader’s eye, the psychoacoustic terms: warm (0–2 kHz), bright (2–4.5 kHz) and brilliance (4.5–8 k Hz, which extend to 22 kHz, see Sect. 6) are located on the right-hand frequency axis of the spectrograms. Within the two spectrograms there are five features of note, these are listed as follows:

1. The bottleneck p-off points at the end of the cord are located at the lower-end of the warm region.
2. An intermodulation of tones are observed in the psychoacoustic brilliance region that are caused by energy being transferred up- and down- in frequency range where addition and subtraction of consonant and dissonant tones result in fading in-and-out in the higher frequency range. Unlike electromagnetic signals, the origin of the acoustic energy (in this case the strings and body of the guitar) is

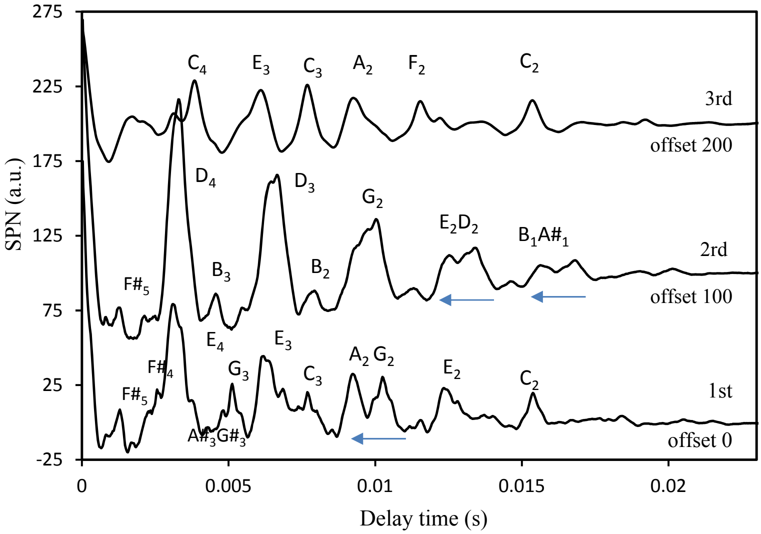

Fig. 7 First-string triad (3, 2, and 1) with s-slide damping the fifth fret

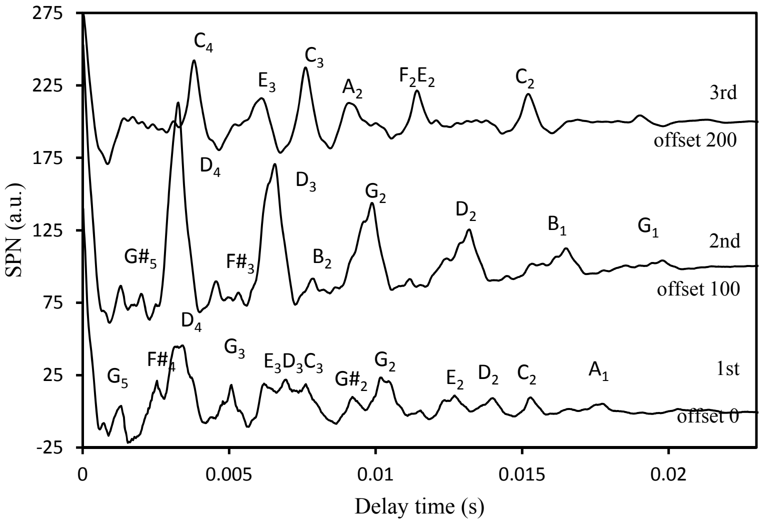

Fig. 8 First-string triad (3, 2, and 1) with g-slide damping the fifth fret

directly altered by the vibration mode of the strings and body, and the medium that the sound is traveling through. Thus, each pitch has a non-zero bandwidth [34, 35] that periodically fads when subtraction occurs.

3. A series short rising tones of approximately + 0.5 kHz (blue arrow annotation) that have an initial timestamp corresponding the picking of the strings. A second

set of descending glissandos of approximately—2 kHz (red arrow annotation) are launched after the raised tones are also present.

4. There is a marked difference in the s-slide and the g-slide sustain periods within the warm and bright regions. In the warm region, the s-slide produces a stronger spectral density compared to g-slide. However both slide produce similar short sustain periods.
5. The string squeaks caused by an involuntary guitarist gesture appear mixed and muddled within the warm region.

Figures 7 and 8 shows the standard autocorrelation (Hann window and 2084-sample size) of the waveform for the s-slide and g-slide damping the fifth fret. Note for clarity, the sound level of the second and third envelopes are offset by + 100, and + 200, respectively. For each envelope, the major overtones and the root along with prominent flat (dissonant) overtones are labeled.

In Fig. 7 (s-slide), the first envelope overtones $E_{3\text{-}4}$ and $G_{3\text{-}2}$ and $C_{3\text{-}2}$ are clearly defined, along with the flat (dissonant) $F\#_{4\text{–}5}$ and $A\#_3$. Note also G_2 transposes up in pitch to A_2 within the duration of the envelope period. In the second envelop the $D_{4\text{-}2}$ and the $B_{3\text{-}2}$ are present, in addition $A\#_1$ transposes up in pitch to the root B_1, and D_2 transposes up in pitch to E_2 within the envelope period. The F#5 is also present. In contrast, the third envelope contains the major overtones $C_{4\text{-}2}$, E_3, A_2 and F_2, with the flat (dissonant) tones less prominent.

Figure 8 reveals that the first envelope contains the overtones $G_{5\text{-}2}$, $E_{2\text{-}3}$, and the roots B_1 and A_1, along with the flat (dissonant) tones $F\#_4$ and $G\#_2$. In the second envelope, $D_{4\text{-}2}$ and $B_{3\text{-}1}$ are present along with $G\#_5$ and $F\#_3$, but at reduced amplitude compared to the s-slide. Again, in contrast, the first two envelopes, the envelope exhibit the major tones $C_{4\text{-}2}$, E_3, A_2 and F_2), with the flat (dissonant) tones less prominent.

5 Ascending and Descending Glissandos

This section looks at the glissando sound production between the seventh and twelfth fret for open G tuning and different bottleneck material (steel and glass). Using Eq. 2, S_b therefore varies between approximately 30 and 40 cm, and S_n varies between approximately 20 and 30 cm. For ease of comparison, spectrograms of a first-string triad ascending glissando using the s-slide is presented followed by two pairs of comparative '*Looney Tunes*' and it counterpart tracks.

Figure 9a–b, depicts the default spectrograms for first-string-triad with steel and glass bottleneck for the descending glissando (twelfth to seventh fret). Annotated on the right-hand vertical axis is the warm, bright and brilliance regions and the horizontal dashed-lines (at 2 and 4.5 kHz) delineate the regions. Within these two spectrograms, three contrasting features are observed and are listed as:

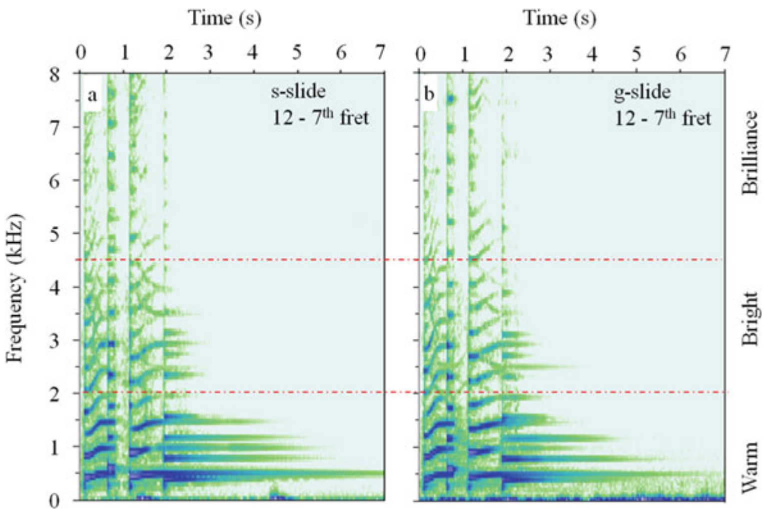

Fig. 9 **a**–**b** First-string triad: s-slide descending glissando (twelfth to seventh fret) for s-slide 9a, and g-slide 9b

1. The root and overtones within the warm psychoacoustic region have differing sustain lengths, where the s-slide produce longer and stronger tones compared to the g-side.
2. As the slides physically moves perpendicular across the strings (at rate of approximately 50 mm s^{-1}) a mirrored bifurcation occurs where the glissandos have an exponential trajectory with a frequency shift of approximately 2.2 kHz with time. These mirrored glissandos extend through the bright region and fades into the brilliance region.
3. There is a marked and contrasting noise floor between the two bottlenecks? In the case of the g-slide, a greater incoherent (hiss-like [19]) noise is present at the lower end of the warm region (0–0.5 kHz) as compared to the s-slide bottleneck. Section 6 further quantifies these noise features.

Figure 10a–b depicts the default spectrogram for the '*Looney Tunes'* ascending glissando (seventh to twelfth fret, 10a) and its counterpart descending glissando (twelfth to the seventh fret, 10b). Both spectrograms are for s-slide. Again, the psychoacoustic regions are annotated on the right-hand vertical axis. The spectrograms reveal a number of contrasting features.

1. The inclusion of the thicker strings (4, 5, and 6) generates a high-frequency content that ranges to the top of the bright psychoacoustic region.
2. Now as the slides physically moves perpendicular across the strings at a rate of approximately 50 mm s^{-1} mirrored bifurcation of the glissando occurs. As in Fig. 9a–b, the frequency shift is some 2.2 kHz, however in this case the glissando extend through the bright and well in to the brilliance region. To separate apart these mirrored glissandos it is reasonable to assigned the string

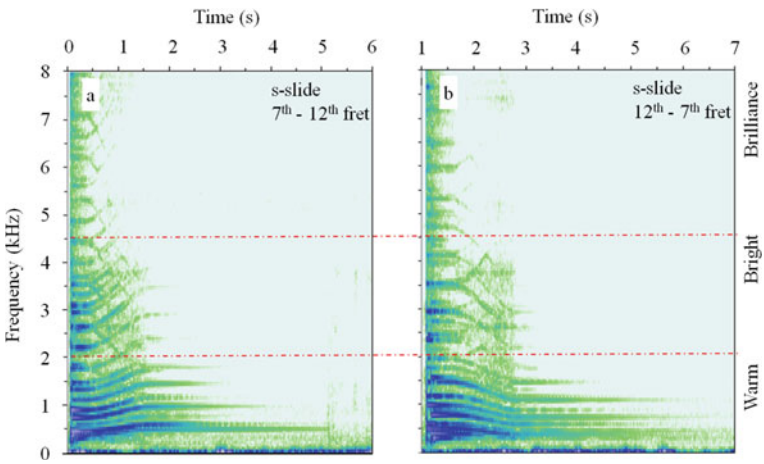

Fig. 10 **a**–**b** '*Looney Tunes'*s-slide ascending glissando (seventh to twelfth fret) 10a; and s-slide descending glissando (twelfth to seventh fret) 10b

ascending glissando with increasing fret number, hence the mirrored glissando is assigned to the slip-stick friction process of the slide.

3. The noise floor at the lower-end of the warm (0–0.5 kHz) region is raised with incoherent, or hiss-like, noise. For comparison, see Fig. 9a.

Figure 11a–b provides the default spectrogram for the '*Looney Tunes'* ascending glissando (seventh to twelfth fret, 10a), and its counterpart (twelfth to the seventh

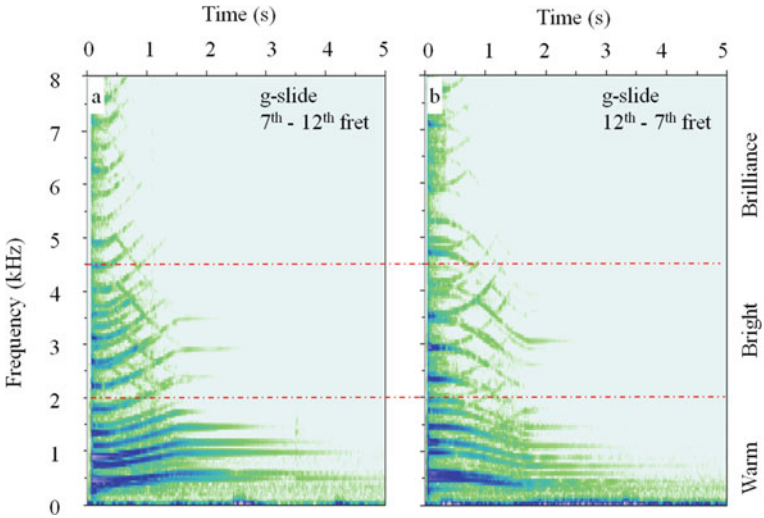

Fig. 11 **a**–**b** '*Looney Tunes'* g-slide ascending glissando (seventh to twelfth fret) 11a; and g-slide descending glissando (twelfth to seventh fret) 11b

fret, 10b). Both spectrograms are for the g-slide. Again the right-hand vertical axis depicts the psychoacoustic regions. Main features of note are:

1. As in Fig. 10a–b, mirrored bifurcation of the glissandos produce exponential trajectories as the slide moves perpendicularly across the strings at a rate of approximately 50 mm s^{-1}.
2. Incoherent, or hiss-like, noise is prominent has marked increase in lower-end of the warm region (0–0.5 kHz) as compared to the s-slide (Fig. 10a–b).
3. Taking Figs. 9a–b, 10a–b and 11a–b together, psychoacoustic feature of ascending and descending seventh to twelfth glissando may be summarized. Firstly, the sound of the first-string triad slide extends to the bright region, whereas the thicker strings extend the guitar response in to brilliance region. Secondly, pronounced mirrored glissandos are produced when all six strings are played with the slides. Third, incoherent, or hiss-like, noise in the lower-end of the warm region is produced by the g-slide first-string triad mode, and when all strings are played using either the s-slide or g-slide.
4. For a slide acoustic guitar, Pakarinen et al. [19] has demonstrated that slide divides the damped string into two longitudinal excited string segments, where the main sound originates from the slide to bridge string segment (here labeled S_b) and second excitation originates from the slide to nut (here labeled S_n) segment. This excitation process appear to hold in the resophonic guitar, although a string portion from bridge to the tailpiece must vibrate due to the up-and-down motion of bridge, albeit a smaller bandwidth of S_b and S_n. Given this scenario, vibrational energy is continuously flowing between the string segments as slide moves across the string. Following this, it is reasonable to assign the origin of the mirrored exponentially varying pitch glissandos. Hence, an ascending glissando associated with increasing fret number (7_12) originates in S_b, whilst the mirrored descending glissando has it origin in S_n.

Pakarinen et al. [19] has also identified incoherent, or hiss-like, noise in the steel-string acoustic guitar and assigned this noise to contact points as the side moves across the string. When they synthesized this form of noise they used a noise pulse train thereby evoking an impact and friction modal, otherwise known as slip-stick friction between the surface of the string and slide/Bow [36]. The low-frequency nature of the noise also suggests there is Voss-Clarke flicker noise ($1/f^{\alpha}$ noise) content [8]. Section 6 further explores this psychoacoustic noise for the resophonic guitar.

6 Resophonic Guitar Upper Psychoacoustic Brilliance (0–22 kHz) Region

Given the lack of full range psychoacoustic data for the resophonic guitar, this section looks at the *'Dubro'* resophonic guitar's radiated sound in the 0 to 22 kHz frequency range to understand the interaction and delineation of each psychoacoustic region.

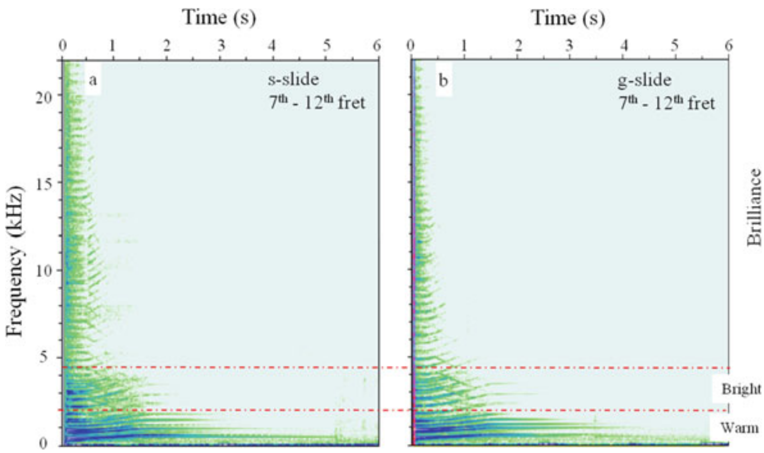

Fig. 12 a–b. Extended frequency range of '*Looney Tunes*' g-slide ascending glissando (seventh to twelfth fret) 12a, and g-slide ascending glissando (twelfth to seventh fret) 12b

This is achieved by using the Audacity spectrogram with a selected full frequency range (22 kHz) for '*Looney Tunes*' ascending s-slide (11a) and g-slide glissando (11b).

Figure 12a–b provides the comparison between the s-slide and g-slide ascending glissando. In the case of s-slide (12a), the ascending glissando overtones extend through the warm region with typical sustain periods of 3 s and to a lesser extent (0–2 s) in the bright region. Whereas the initial plastic plectrum attack overtones have sustain periods of typically 0.5 s throughout the 4.5–22 kHz brilliance region. In addition there is some evidence of weak glissando overtones with typical sustain periods of 1 s. In comparison, the g-slide (12b) produces weaker sustain periods in all three psychoacoustic regions. The least marked being in the brilliance region where the initial plectrum attack overtones have sustain periods decaying from 1 s at 4.5 kHz to 0.25 s at 22 kHz. Within the decay process, the ascending glissandos overtones also become less pronounced.

7 Noise Reduction

Figure 9a–b has revealed, that for a first-string triad ascending glissando, the g-slide induces more incoherent (or hiss-like) noise at the lower-end of the warm region, when compared the s-slide. The aim of this section is therefore threefold: First to isolate and remove the incoherent noise to, or below, the noise floor of s-side glissando, thereby providing an estimate of the noise contribution. The second is to extend the noise reduction knowledge to the '*Looney Tunes*' (Figs. 10a and 11a) and the counterpart descending glissandos (Figs. 10b and 11b). Third, identify and map the characteristic morphology of the noise [8].

7.1 First-String Triad Bottleneck Noise Reduction

The first step in estimating the incoherent noise contribution is to identify and isolate the noise. This is performed by first defining the noise profile (np) within the spectrogram (13b). The selection criterion is based on that incoherent noise contains random pixel variables with a well-defined statistical characteristic as compared to the coherence pixel regions of glissando.

The removal step uses three parameters to control the noise reduction process. These parameters are noise reduction level, sensitivity, and frequency-smoothing band. The noise reduction controls the volume reduction (in dB) applied to the noise. The sensitivity controls the amount the signal to be considered as noise (using a scale of 0 to 24). In addition, the frequency-smoothing band controls the spread of the smoothing in neighboring bands, therefore altering the original sampling rate (using a scale of 0–12 and is set to zero so that direct comparison between the original and modified dataset is made) (*N. B. Further details on how the three parameters are used, see Audacity software* [29–31]). A series of iteration processes follows, where the noise reduction value and sensitively value is changed, with the aim of reducing the incoherent noise with minimal damage to the coherent glissando feature within the spectrogram. Figure 13a–d shows the overall process in spectrogram format where Fig. 13a is the first-string triad for the s-slide (taken from Fig. 9a). Figure 13b is the first-string triad for the g-slide along with the incoherent noise profile region selected. Figure 13c is the noise-reduced image using a noise reduction value of 12 dB and a sensitivity value of eight. A comparison of Fig. 13c with the s-slide (13a) reveals similar coherent features and the incoherent spectral densities for both slides is in the 0–0.4 kHz range. Thus the indicating the g-slide incoherent noise contribution is in the order of 12 dB.

Figure 13d, depicts the removed residue noise spectrogram in the low-frequency region of the acoustic spectrogram**.** It is noted that the isolated noise inevitably captures part of the overtone structure, and therefore some of overtone in Fig. 13c is lost. The overall discrimination process may not be perfect, but it is more beneficial in this case when compared to a low-pass filter that would remove higher frequency noise in the bright and brilliance regions [29–32].

7.2 Incoherent Noise Reduction

To quantify the visible incoherent noise in the audio spectrogram Figs. 10a–b and 11a–b, the same attenuation process as in Fig. 13b–d is undertaken. To allow a direct comparison throughout, only the noise attenuation (dB) is altered, whist

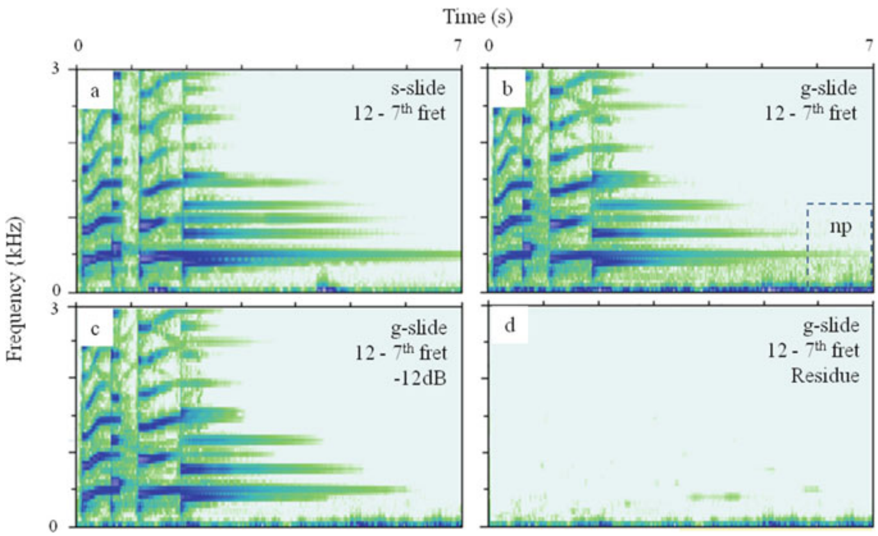

Fig. 13 a–d First-string triad ascending glissando spectrogram for s-slide 13a. First-string triad ascending glissando for g-slide 13b. The g-slide reduced noise profile after noise reduction (–12 dB) 13c. The g-slide residue noise spectrogram 13d

the sensitivity or frequency-smoothing band values are fixed at eight and zero, respectively.

Table 3 depicts the required incoherent noise reduction values to achieve the desired noise floors for each spectrogram. The results support the general concept that a g-slide produces more (3 dB) incoherent, hiss-like, noise than an s-slide. In addition, a descending glissando (twelfth to seventh fret) also produces more incoherent. This finding suggests that the guitarist gesture whether emotional or and musculoskeletal (movement of the upper extremity as the left moves away from the body when play a descending glissando) may also have a role in the production of slide noise.

Table 3 Incoherent noise reduction algorithm variable parameter values

Spectrogram figure	Noise reduction (dB)	Sensitivity level	Frequency-smoothing band
10a (s-slide: 7–12 fret)	9	8	0
10b (s-slide: 12–7 fret)	12	8	0
11a (g-slide 7–12 fret)	9	8	0
11b (g-slide:12–7 fret)	12	8	0

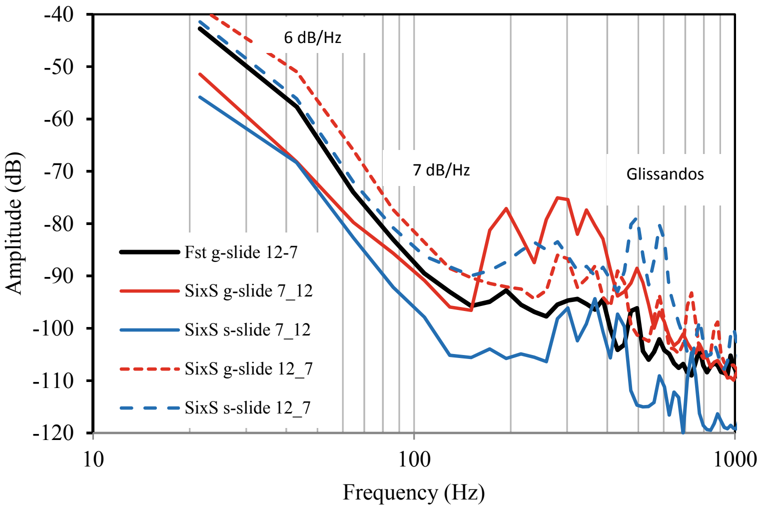

Fig. 14 Frequency spectra of all five residue datasets (see Fig. 13d and Table 3)

7.3 *Characteristic Noise Morphology*

Using the Audacity FFT algorithm, the five-residue noise datasets obtained in Sects. 7.1 and 7.2 are analyzed for their spectral morphology (color). Figure 14 depicts the FFT results as log–log plot, where frequency (Hz) plotted on the horizontal-axis and the sound amplitude (dB) plotted on the vertical-axis. In this representation, all five datasets exhibit a $1/f$ -like response: e.g. − 6 dB per 10 Hz in the 10–20 Hz frequency band and − 7 dB per 10 Hz in the 30–150 Hz frequency band. Note the 6 dB roll-off in 10–20 Hz band is most likely an artifact of the microphone cut-off frequency. In addition, the structures above 150 Hz are the captured coherent portions of the glissandos and are not considered further as they are not the primary interest here.

Using the first-string triad (Fst, solid black line) as a comparative control, remaining four six-string triads are partitioned around the control. Where the descending glissando for both steel and glass produce the greatest residue noise and therefore are above the control. The opposing ascending glissandos produce the least noise and therefore are positioned below the control. The limited measurements present here appear to indicate that the direction of the slide movement along the fingerboard determines the relative residue noise level, also. One possible cause for this differentiation in the musculoskeletal locomotion force required to extend and retract the guitarist fret arm [37, 38], as similarly observed in violinist [39]. In the case of guitar descending glissando, the guitarist musculoskeletal systems extends the left arm, hand and hence bottleneck from the twelfth to seventh fret so altering the body’s center of gravity from the seated position (and vice-versa for the ascending glissando). These varying locomotion conditions are known to induce ulnar nerve entrapment, and therefore merit further investigation.

8 Discussion

This paper has presented a study of the *'Dubro'* resophonic guitar psychoacoustic response to a plastic plectrum applied in the down-stroke for ascending and descending glissando where both steel and glass slide are used. The *'Dubro'* is chosen for its enhanced mechanical sound amplification as compared the classic acoustic and electrical guitar. The slide is placed on the ring finger on of the left hand with the index, second and fourth finger not used to mute (dampen) the strings. This style of slide play provides the rich and complex guitar Delta bluegrass sound. The work has focused on a guitarist's gesture (rather than a mechanical modal based method [17, 18]) to help provide the human psychoacoustic perception of the *'Dubro'*.

The measured radiated sound recordings extend through the psychoacoustic warm (2–4.5 kHz), bright (4.5–8 kHz) and brilliance region up to a frequency of 22 kHz where the initial attack, rather than chord overtones are present. It is worth noting that online commentary declares that the resophonic guitar brilliance may extend to 20 kHz [16]. As the guitarist musculoskeletal system physically moves the slide perpendicular across the full six strings (at approximately 50 mm s^{-1}) between the seventh to twelfth fret, glissando overtones are generated that instantly undergo mirrored bifurcation forming two exponential trajectories: one decreasing in pitch and the other increasing in pitch.

The glissando overtones extend throughout the bright psychoacoustic region and the lower brilliance region for both s-slide and g-slide. In the case of the s-slide, the overtones are weakly present in the mid brilliance region (8–15 kHz). The exponential trajectory of the glissandos as the slide traverses perpendicularly across the strings demonstrates *Vincenzo Galilei's* non-linear theory of fretted string instruments (Eqs. 1 and 2 and graph 1).

Fading in the brilliance psychoacoustic region is also indentified, and is attributed to intermodulation (or, addition and subtraction) of overlaying consonant and dissonant tones. Due to the inner ear's inability to separate high pitch overtones, a listener may perceive the fading process as roughness or timbre in the guitar overall sound. Incoherent, hiss-like, noise is identified and shown to be associated with the slip-stick friction processes between the moving slides and the vibrating strings, where the intensity of the noise is more pronounced on the thicker (wound) steel strings. The g-slides produce a higher intensity (some 3 dB) incoherent, hiss-like, noise than the s-slide.

The direction of slide movement is observed to produce a variation in the amplitude of the incoherent, hiss-like, noise. Slide movements away from the gustiest body centre of gravity (associated with a descending glissando) produce an increase in noise amplitude. As musculoskeletal pain and stress in string instrument players is common [37–39] the measured noise may be a significant finding. This aspect of the work requires further research both in guitarist gesture and in mechanical based modals.

The time-domain and frequency-domain information presented here provides control-data (slide contact gestures) for improved slide-music and slide-noise synthesis within virtual slide guitar systems as reported by Pakarinen, Puputti and Välimäki 2008 [19]. In their work an Omni-directional contact-noise building block is used that did not differentiate the direction of slide movement. Our new work (this paper) indicates that a bidirectional contact-noise building block should be used to synthesize possible differences in musculoskeletal induce noise.

To conclude this work, the opening seconds of the original Warner Brothers instrumental theme '*Looney Tunes'* as played by F. Travares is used as a control. In the original Travares recording, muting (damping) of the strings is performed to make the non-complex (crystal-clear) sound. Our findings reveal that the mirrored bifurcation is present when the strings are not muted. This finding supports the two vibrating string portion mechanism when the slide employ with muting and damping.

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