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A review of didjeridu (didgeridoo) acoustics

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The didjeridu is the principal musical instrument of the world's oldest continuous culture and its sound is an acoustic icon of Australia. This lip-valve instrument usually produces a single, sustained, low drone note. The musical interest comes from rhythmic changes in timbre, including those associated with 'circular breathing', wherein exhalation from lungs to instrument with raised velum is alternated with expulsion of air from the mouth and inflated cheeks while air is quickly inhaled through the nose with the velum lowered. In an additional technique, players phonate at frequencies usually above that of the instrument, producing complicated heterodyne components. This paper reviews research from our lab. Measurements of the acoustic impedance spectrum in the mouth during playing show that impedance peaks produce antiformants or minima in the output sound spectral envelope. The instrument's slight flare and irregular bore geometry produce resonances that do not fall in harmonic ratios. Instruments judged good by players have particularly weak resonances in the formant frequency region so that the vocal tract impedance peaks can dominate the sound spectrum more easily.

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1. BACKGROUND AND INTRODUCTION

The didjeridu (or didgeridoo) is called the yidaki in the language of the Yolngu people of the region now known as northeast Arnhem Land in Northern Australia, East of Darwin, the region whence the instrument comes. It has become an icon of the 65,000-year indigenous Australian culture[1]. At the 2023 ASA Fall (or southern Spring) meeting in Sydney, the authors were invited to review the acoustics of this unusual and interesting instrument, particularly the work from the acoustics lab at UNSW Sydney.

Fig.1. Benjamin Lange (Marra man and an author on Tarnopolsky *et al.,* 2005, 2006) plays the didjeridu. (Photo: Kate Callas.)

Traditionally, the didjeridu is a wooden tube, typically about 1.2 to 1.5 m in length. It is made from a branch or narrow trunk of a eucalypt tree whose interior has been made nearly hollow by termites; the extent of termite infestation can be judged by listening while striking the intact trunk or branch with a stick. The termite galleries and nests are cleared out and smoothed with long sticks, and the ends smoothed with a sharp tool. The bore is thus irregular but flared, which produces resonances whose frequencies are not usually related harmonically. A ring of beeswax around the smaller end makes it comfortable to seal around the lips. The bark is usually removed and pigments are sometimes used to add traditional or modern designs.

The didjeridu is sounded by blowing air between the lips to produce sustained auto-oscillation, in a manner rather like that used in playing the trombone or tuba. (For the details of regeneration in brass instruments, see Elliott and Bowsher, 1982; Yoshikawa, 1995; Boutin *et al*., 2020 and the review by Campbell *et al*., 2021). Compared with orchestral brass instruments, didjeridu performance has several unusual features. First, the pitch is usually determined by the lowest resonance of the bore, which is never the case for brass instruments. Very brief soundings of the second resonance, at a pitch typically from a ninth to an eleventh above the drone note, are sometimes used to interrupt the low note and to create another complex rhythm (Jones, 1968). Sometimes, the second resonance is sounded to give brief ‘toots’ to end a performance. ‘Bugling’, *i.e.* rapidly sounding the first, second and third resonance in sequence, is possible, but seems to be very rare in traditional performance.

A further striking feature is that continuous playing (often of just the one low drone note) is sustained without interruption for periods of several minutes or more, using a technique known as ‘circular breathing’. While exhaling through the instrument, the player fills his cheeks with air; he then lowers his soft palate and raises the back of the tongue, sealing the mouth from the throat. He then deflates the cheeks and advances the tongue to expel stored air into the instrument while he simultaneously and briefly inhales through the nose (see Fig. 2). This process has been monitored using MRI (Wiggins and Storey, 2010) and ultrasound (Zolotas and Bird,

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[1] It is hard to determine the antiquity of this instrument: relatives of the same termites that make a didjeridu commence the recycling of a discarded instrument long before archaeologists can find it.

2010). These large differences in vocal tract configuration and length produce a strong variation in timbre between the inhalation and exhalation phases. Consequently, the breathing rhythm is imposed on the drone note. These rhythms can be complicated and form an important musical feature of the performance. (An onomatopoeic representation of one such rhythmic timbre variation is suggested as a possible origin of the English name: didgeridoo/didjeridu.) Different tongue shapes and positions give further timbre variations, and simultaneous phonation and playing produces heterodyne tones that add more remarkable changes in sound, particularly in contemporary performance styles.

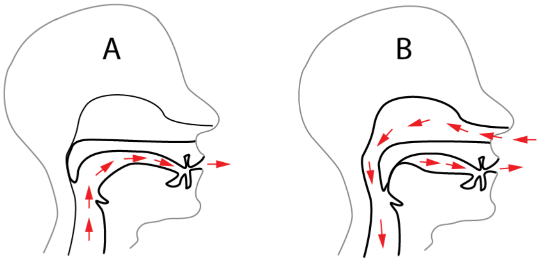

Fig. 2. A stylized diagram illustrating the process of 'circular breathing'. Figure 2A shows the configuration with the velum raised to block the nasal cavity while pressure from the lungs blows air through the mouth into the instrument while simultaneously filling the mouth and inflating the cheeks. Figure B shows the velum lowered to allow rapid inhalation through the nose while the tongue has moved back to seal off the mouth cavity. The stored air is then expelled by compressing the cheeks and moving the tongue forward.

Acoustical investigations of the yidaki/didjeridu acoustics have included stroboscopic studies of lip motion (Wiggins, 1988). Fletcher (1983, 1996) showed that changing the tongue shape while playing changed the frequencies of formants, which are enhanced frequency bands in the output sound. Fletcher also modelled the interaction of the lip with the standing wave in the bore and Hollenberg (2000) made a numerical model of the lip auto-oscillation. MRI taken while a didjeridu was being played confirmed that different positions of the tongue were involved in producing different timbres (Fletcher *et al.* 2001). Amir (2004, 2005) compared several widely different didjeridus, measured their resonant frequencies and recorded spectrograms as they were played.

The bore of the instrument near the narrow end where the lips are placed has a diameter of tens of mm. Consequently, its characteristic impedance is smaller by an order of magnitude or more than that of most lip-valve instruments. This is expected to allow strong peaks in the acoustical impedance of the player's vocal tract to dominate the spectral envelope of the sound produced, which is one reason why the breathing rhythm is so strongly imposed on the timbre (Fletcher, 1996; Amir and Alon, 2001; Wolfe *et al*., 2003; Caussé *et al*., 2004).

The influence of the vocal tract on performance on various woodwind and brass instruments has been of particular interest to our laboratory and the didjeridu was a good place to start. We also thought it appropriate for an Australian team to investigate this instrument (Music Acoustics, 2005). First, we review our research on the influence of the vocal tract. The next section discusses the effects of simultaneous vocalisation and playing. The section after that looks at the determinants of instrument quality.

2. HOW THE VOCAL TRACT MODIFIES THE SPECTRAL ENVELOPE

An important property of musical wind instruments is the acoustic impedance spectrum at the mouthpiece: $Z_{\text{in}} = p_{\text{in}}/u_{\text{in}}$, where p_{in} is the acoustic pressure at the input and u_{in} the acoustic component of airflow into the instrument. Similarly, for the vocal tract, $Z_{\text{tract}} = p_{\text{tract}}/u_{\text{tract}}$. Continuity requires that u_{in} *into* the instrument equals that *out of* the mouth, which is $-u_{\text{tract}}$. Consequently, the pressure difference across the lips $p_{\text{tract}} - p_{\text{in}} = u_{\text{in}}(Z_{\text{in}} + Z_{\text{tract}})$; the vocal tract and the instrument are acoustically in series (Backus, 1985).

Measuring Z_{in} for the instrument is usually easy. Measuring Z_{tract} while a player mimes playing is also relatively easy. Ensuring that the miming configuration matches that used in playing is difficult, however, because the condition of the glottis (the aperture between the vocal folds) is important: Mukai (1992) reports that experienced players of wind instruments often play with the glottis almost closed, but the degree of closure is difficult for the player to assess when miming. Measuring Z_{tract} during playing is required, but that is less easy because of the large acoustic pressure inside the mouth during performance.

We measured Z_{tract} using a broadband source with frequency components 0.2 to 3.0 kHz spaced at 5.383 Hz ($= 42.1\ \text{kHz}/2^{13}$). It was delivered by a capillary acting as a source of acoustic current, fixed to another short tube connected to a microphone (Tarnopolsky *et al.*, 2006). This impedance head was positioned inside the mouths of participant players, near the lips. Simultaneously, the radiated sound pressure was measured near the other end.

An example measurement is shown in Fig. 3A, with radiated sound pressure in blue and $|Z_{\text{tract}}|$ in red, both plotted against frequency. This example shows the near coincidence of the frequency of maxima in Z_{tract} with that of minima in the envelope of the sound spectrum. Peaks in $|Z_{\text{tract}}|$ coincide with antiformants at about 1.5 and 2.0 kHz, leaving a prominent formant (a maximum in the spectral envelope) at about 1.8 kHz, near a minimum in the envelope of $|Z_{\text{tract}}|$.

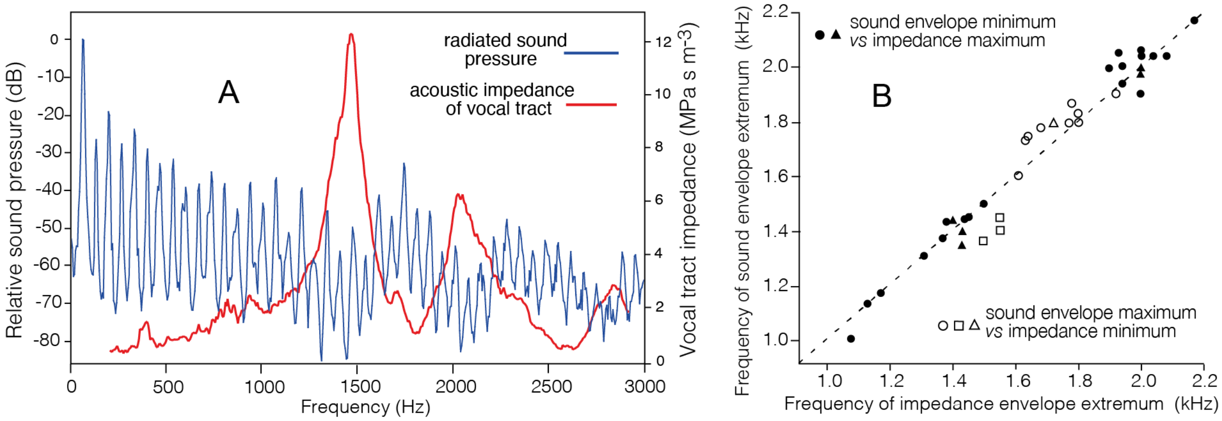

Fig. 3. Part A shows the spectrum of the radiated sound (blue) and the magnitude of the acoustic impedance of the vocal tract (red) measured just inside the lips of a didgeridu player during performance. The player positions his tongue close to the hard palate, which generates a characteristic strong formant at 1.8 kHz. Similar measurements with the tongue low showed no strong impedance maxima and no strong formants. In part B, the filled symbols plot the frequency of minima in the spectral envelope vs. that of the nearest maximum in the impedance spectrum of the vocal tract. Open symbols plot the frequency of maxima in the spectral envelope vs. that of the nearest minimum in the impedance spectrum. The dashed line indicates $y = x$. Modified from Tarnopolsky *et al.* (2005, 2006).

In Fig. 3B, a collection of similar measurements for three participants (indicated by different symbols) is shown in a different format. The filled symbols show the frequencies of the minimum of the sound envelope plotted against that of the nearest maximum in $|Z_{\text{tract}}|$. The open symbols plot maxima of the sound envelope against the nearest minimum in the envelope of $|Z_{\text{tract}}|$. Again, peaks in the $|Z_{\text{tract}}|$ create antiformants and minima in $|Z_{\text{tract}}|$ correspond to formants.

A simple, but approximate first-order analysis of the acoustic circuit of the tract-lips-instrument system shows that the minima in $|Z_{\text{tract}}|$ coincide approximately with the formants. A less approximate numerical analysis using the harmonic-balance technique (Gilbert *et al*., 1989) gives the same conclusion (Fletcher *et al*., 2006), in agreement with the experimental findings (Tarnopolsky *et al*., 2006).

The formants produced in the range 1 to 3 kHz (see Fig. 3B) are salient, presumably because this includes the range of the second formant (F2), whose variations are used to distinguish phonemes in speech (*e.g*. Yallop and Fletcher, 2007).

3. SIMULTANEOUS PLAYING AND VOCALISATION

One technique of didjeridu performance, popular particularly in modern performance, involves vocalising (or 'singing') while playing. The airflow into the instrument is thus modulated by the vibrating vocal folds (at frequency g) as well as by the vibrating lips (at frequency f). Both vibrating elements 'clip' the total current when they close, so the interaction is nonlinear and gives rise to heterodyne or interference components with frequencies of $mg \pm nf$, where m and n are integers (Fletcher 1966). If the frequencies f and g are close together, very strong 'beats' can be produced in the sound.

The difference or Tartini tones ($m, n = 1{,}1$ at frequency $g - f$) can be impressive. If g is sung a perfect fifth above the playing frequency ($g = 3f/2$), then $g - f = f/2$, one octave below f- see Fig. 4D. If sung a fourth above ($g = 4f/3$), then $g - f = f/3$, a twelfth below f. For an instrument with, say, $f = 72$ Hz (as in Fig. 4D), these difference tones have frequencies of 36 and 24 Hz respectively. Human auditory sensitivity is poor in this range, but the integer multiples of these difference frequencies are also present and this augments the sensation of a strong, low pitch.

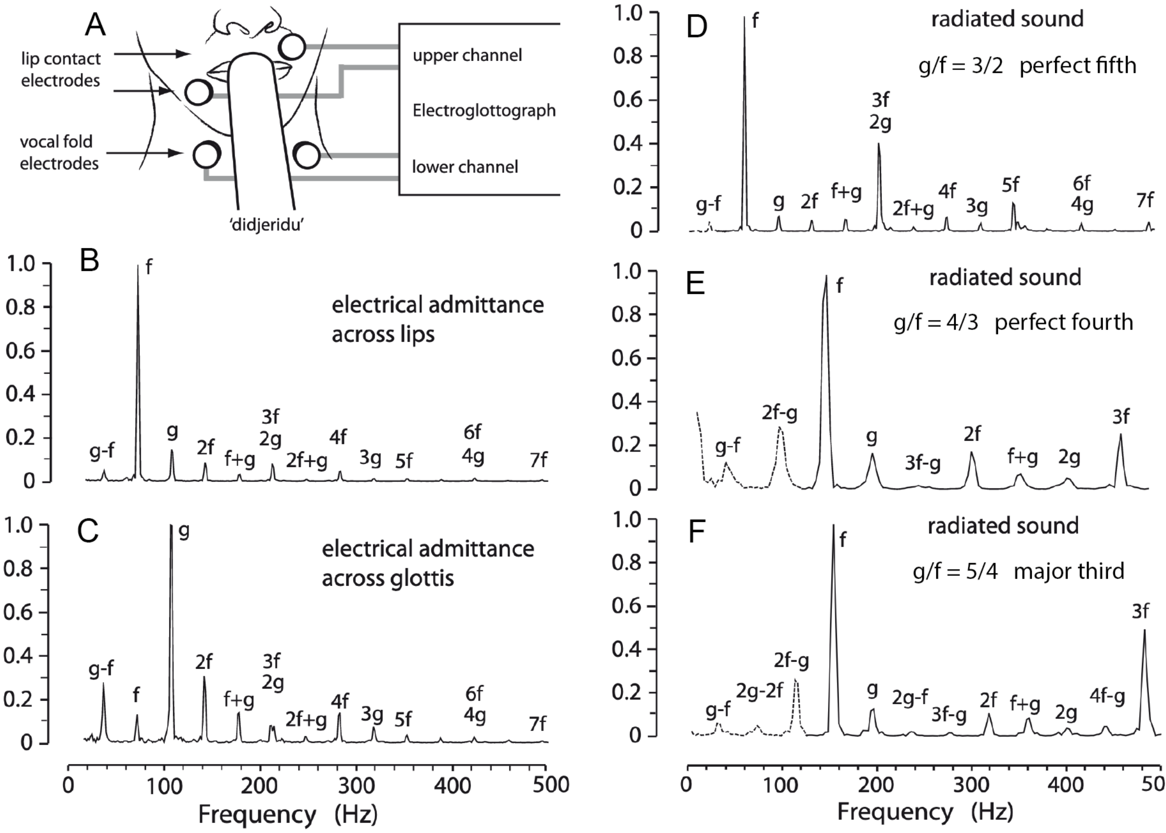

Fig. 4. Figure A shows the system used to monitor simultaneously the contact of lips vibrating at frequency *f* and vocal folds vibrating at frequency *g* by measuring the electrical admittance (at 2 MHz) between pairs of electrodes positioned as shown. B and C show the electrical admittance measured simultaneously across the lips and vocal folds respectively. D shows the radiated sound when *g* was a perfect fifth above *f* (*f* = 71 Hz). Figures E and F show the radiated sound from shorter instruments when *g* was a perfect fourth or a major third above *f* (*f* = 155 and 164 Hz respectively). For clarity, the sound spectrum has been increased by a factor of 10 only for frequencies below f. (Modified from Wolfe and Smith, 2008.)

We studied simultaneous vocalisation and playing by fixing the electrodes of an electroglottograph on either side of the neck at the level of the vocal folds and measuring the electrical admittance between them at 2 MHz. Another skin electrode pair, connected to a different electrical channel, is positioned near the upper and lower lips. A schematic is shown in Fig. 4A; more details in Wolfe and Smith (2008). The changing contact between the colliding vocal folds, and also the lips, is clearly seen in the magnitude of the electrical admittances shown in figures 4B and 4C.

For the measurement shown in Figs 4B, 4C and 4D, the subject (JW) vocalized at $g = 106$ Hz, a fifth above the playing frequency $f = 71$ Hz. The radiated sound spectrum shows components at both f and g, but also components at all the heterodyne frequencies, which in this case are integral multiples of the difference frequency $g - f = f/2 = 35$ Hz.

This model experiment used a cylindrical duct instead of a real didjeridu – the former being much easier to characterise, to model and to reproduce. However, it has the disadvantage (in this context) that its second impedance peak lies very close to $3f$ and thus the duct operates as an efficient impedance matcher at that frequency, leading to a stronger harmonic at $3f = 2g$ than would be expected in a didjeridu.

Figures 4E and 4F provide examples using a shorter instrument where the player sings at frequencies respectively a perfect fourth and a major third above the playing frequency.

When the vocalization frequency g is varied in a glide, the heterodyne frequencies also glide, some in either direction, giving complex sensations of pitch and timbre (Fletcher, 1996). Further, the lip frequency is also flexible: lipping down and to a less extent lipping up are relatively easy on the instrument, as the model of Hollenberg (2000) predicts. The resultant multiple varying heterodyne frequencies give a large range of timbres that are often used to imitate the cries of animals.

The behavior of the system is yet further complicated by the effects that the standing waves due to one oscillator have on the motion of the other – see Figs 4B and 4C where components of the lip vibration frequency are apparent in the vocal fold motion, and *vice versa*. In the 2008 study, we varied the intended glottal configuration from whisper (vocal folds at small separation) to relaxation. In this case, the vocal fold signal suggested that the folds were ‘driven’ by the strong sound signal in the mouth that was produced by the vibrating lips. This agreed with the subjective experience – it felt as though the larynx was singing without intent or effort, at the playing frequency, which was below the participant’s normal singing range.

For comfortable (neither loud nor soft) playing levels with no intended vocalisation, the sound pressure level inside the mouth was between about 130 and 145 dB with respect to 20 μPa. These sound levels are similar to those produced inside the mouth while singing or humming. This may have implications for understanding source-filter interactions in the voice (Wolfe and Smith, 2008).

4. WHAT MAKES A GOOD DIDJERIDU?

The simple answer is termites!

However, relating objective acoustical measurements of an instrument, without a player, to the subjective qualities reported by players is often a difficult goal in music acoustics. The traditional didjeridu offers advantages in such a study because (i) it is inherently ‘blind’—neither player nor researcher have knowledge of the internal bore profile produced by the termites—and (ii) there are extremely wide variations in instrument quality— the termites’ objective is a good meal rather than a good instrument.

To determine instrument quality, Amir (2004) measured the sound produced when two musicians played a collection of 8 instruments ranging from traditional to manufactured instruments. Caussé *et al*. (2004) had two players compare eight ‘very good’ didjeridus from a collection of about 50. A team including the present authors (Smith *et al*. 2007) performed a study where seven experienced players ranked 38 didjeridus selected from a large reference collection held by a didjeridu wholesaler and mail order shop in Northern Australia (the Didjshop). These didjeridus had been previously assessed with qualities ranging from the ‘very finest’ to ‘second rate’; they were made by local indigenous craftsmen who were not traditional custodians and consequently these particular instruments would not have had secret spiritual significance.

Our team measured the acoustic input impedance spectra and some geometrical parameters of those 38 didjeridus. Figure 5A displays the measured impedance spectra $Z(f)$ of four didjeridus: from the highest quality ranking (top) to the lowest quality (bottom) with two examples of intermediate rankings. One immediately obvious feature is that the better didjeridus have much weaker resonances in the 1-2 kHz region, indeed, there is a strong negative correlation between the maximum value of $Z(f)$ in the 1-2 kHz range and ranked quality – see Figure 5E. These low values allow the impedance of the vocal tract to dominate at frequencies above 1 kHz, resulting in strong formants in the output sound – see section 2.

Figure 5B shows that the characteristic impedance Z_0 is also negatively correlated with quality; higher values of Z_0 will increase the average value of $Z(f)$ at all frequencies and make it harder for the vocal tract impedance to dominate. This agrees with Caussé *et al*. (2004) who also found instruments with a lower input impedance were found to be of higher quality.

Because the didjeridu is played nearly always near the frequency of the first impedance peak, one might expect that Z_1, the magnitude of this peak, has an important role in determining the vibration. However, Figure 5C shows a negative correlation between Z_1 and the ranked quality. This may be the result of a compromise. We found that high quality instruments have a weaker, but still significant correlation with higher values of the ratio Z_1/Z_0, and also with higher values for the Q factor of the first resonance. It appears that players tend to prefer a strong first resonance, provided that it is still consistent with low values of $Z(f)$ at high frequencies that allow the player control of the timbre.

The overall internal shape of a typical didjeridu is a heavily truncated cone, with a highly irregular surface. Consequently, and unlike other lip reed instruments such as trombone or tuba, the impedance peaks of the didjeridu (denoted by Ri) are not necessarily harmonically related (e.g. Fletcher, 1983). Because the angle and truncation of the roughly conical shape varies widely among instruments, so too does the spacing between impedance peaks. Consequently, the harmonics *nf* of a note played at frequency *f* need only occasionally and 'accidentally' coincide with the impedance peaks at frequencies *R*i (Fletcher 1983, 1996; Wiggins, 1988; Amir, 2003, 2004; Caussé *et al*., 2004; Tarnopolsky *et al.,* 2006; Smith *et al*., 2007). Perhaps there is a particular relationship between the *nf* and *R*i that makes an instrument preferable?

Figure 5D shows the harmonicity for each instrument calculated from the slope of a linear relationship between *Rn* and (2*n*-1)*f*, usually for the first 6 harmonics (typically less than around 700 Hz). No significant correlation with quality was observed. Other studies have similarly found a wide range of harmonicity (Amir, 2004; Caussé *et al*., 2004). This result could possibly seem strange to acousticians who have studied high quality brass instruments: good brass instruments exhibit a dozen or so impedance maxima, several of these having sharp peaks and nearly all falling close to a harmonic series ($2f$, $3f, 4f$ etc.) (*e.g.* Campbell *et al*., 2021). In brass instruments, each of these higher frequency peaks is used to determine the frequency of a note. However, the brass player does not (usually) require properties of her vocal tract to dominate the timbre of the note.

The formants that give the didjeridu its characteristic sound fall in the range roughly 1-2 kHz. The harmonicity of resonances in brass instruments is important, in part, because a higher harmonic of a low note that falls near an impedance peak will be strongly radiated. This is much less important in the didjeridu. The 1-2 kHz range of the important didjeridu formants corresponds roughly to the 20th to 30th harmonic of the normal drone note. Consequently, changes in the playing frequency of only a couple of percent (a fraction of a semitone) can shift a harmonic from impedance maximum to minimum or *vice versa* (Smith *et al*., 2007).

In our study, the seven players gave a score for each instrument in the following seven subjective parameters used by the Didjshop; *backpressure, clarity, resonance, loudness, vocals, overtones,* and *speed*. Details of correlations between these individual subjective parameters and the measured acoustical parameters are presented elsewhere (Smith *et al.,* 2011).

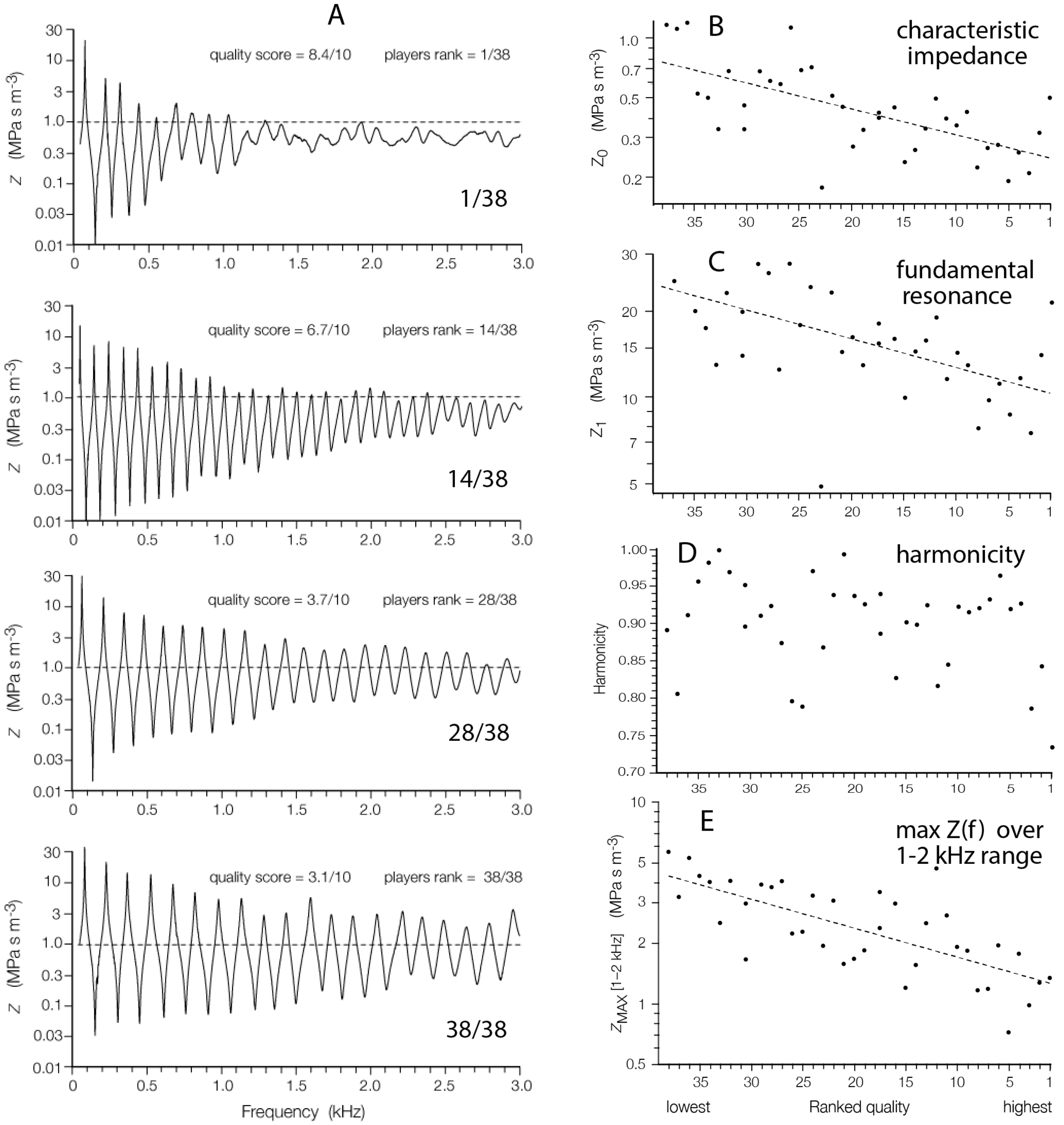

Fig. 5. Figure 5A on the left shows semilogarithmic plots of the magnitude of the measured acoustic impedance *Z*(*f*) as a function of frequency *f* for 4 different traditional didjeridus of different quality. The horizontal dashed lines indicate a reference value of *Z*(*f*) = 1 MPa.s.m^{-3}. The highest ranked (best instrument) is denoted by 1 and the lowest ranked (worst) by 38. Figures 5B, 5C and 5E show semi-logarithmic plots of measured parameters against ranked quality; Figure 5B shows the characteristic impedance (Z_0), 5C shows the magnitude of Z_1, the first impedance peak and 5E shows the maximum value of *Z*(*f*) in the 1-2 kHz range. Figure 5D shows the harmonicity of the first 6 impedance maxima. Modified from Smith *et al.* 2007, 2011.

Fig. 6. Photographs illustrating the seven didjeridu ranked as the highest quality of the 38 didjeridus studied. Instruments labelled A–G were ranked from 1 to 7, respectively. The difficulty in judging an excellent instrument by appearance is evident. This composite image was composed from images of the individual instruments that were adjusted for correct relative scale. From Smith *et al.* 2007.

The crucial feature that determines the quality of a didjeridu is a low value of $Z(f)$ in the 1-2 kHz range. In traditional instruments this is a consequence of the unknown irregular internal bore. Are there approaches whereby $Z(f)$ might be reduced in this frequency range?

Occasionally, a forked section of a tree is suitably eaten by termites. This allows the manufacture of a 'forked didjeridu' or 'didjeriduo', a non-traditional instrument with a branched bore and two possible mouthpieces. The impedance of this additional bore will appear in parallel with that of the main bore and, depending upon the particular geometry, it is possible for the extra impedance of this additional bore to reduce the overall impedance in the important region of 1 – 2 kHz (Schneider *et al.* 2007).

Cylindrical plastic tubes are often used as cheap and widely available substitutes for a traditional didjeridu, however they are usually ranked by players as being substantially inferior (e.g., Neuenfeld, 1997; Amir, 2004; Smith *et al*., 2007). This is consistent with their high values of $Z(f)$ in the 1-2 kHz region (Smith *et al*. 2007). Experiments show that these high values of $Z(f)$ can be reduced by (i) increasing bore diameter, (ii) increasing internal damping and wall losses, (iii) addition of tunable Helmholtz resonators along the bore and (iv) adding a flared terminal section (Schneider *et al*., 2008).

5. DIRECTIONS IN MUSIC

Well beyond the country of the Yolngu, in recent years the didjeridu has been adopted by first nations people across the continent and has become an icon of Australia. It has also been adopted (some might say appropriated) by Australians more generally and a keen subset of musicians internationally, where it has been incorporated in popular music and in orchestral and chamber music.

The prominent Australian composer Peter Sculthorpe, 1929-2014, wrote and adapted works to feature the didjeridu (https://en.wikipedia.org/wiki/Peter_Sculthorpe), particularly the orchestral works *Earth Cry*, *Requiem* and some of his string quartets.

The celebrated indigenous didjeridu soloist and composer, William Barton, combines his Kalkadunga heritage and concert music tradition to extend the possibilities of the instrument in 'cross-over' music (https://www.williambarton.com.au). A proficient singer, he takes advantage of the multiple possible interference tones produced by simultaneous vocalisation and playing to produce an astonishing range of timbre, far beyond the simple cases discussed above.

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