Correlations among subjective performance qualities and objective acoustical parameters of the didjeridu

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ABSTRACT

Traditional didjeridus have a broad range of unknown bore geometries, and consequently have advantages for examining relationships between subjective and physical parameters. This study involved 7 experienced players assessing each of 38 traditionally made didjeridus in terms of 8 subjective parameters. Their assessments were then correlated with detailed measurements of acoustic input impedance spectra and geometry. There was a small, but useful, consistency in the rankings of the 7 players, although it was surprising that *backpressure* was the least consistent term, because this term is widely used by both didjeridu and brass players. A high degree of positive correlation existed between most of the parameters (*clarity*, *resonance*, *loudness*, *vocals*, *overtones* and *overall quality*). The other two parameters studied (*backpressure* and *speed*) were correlated with each other, although not significantly correlated with the other parameters. The parameters *clarity*, *resonance* and *backpressure* made the most important contributions to the *overall quality* of an instrument. In general there was a strong negative correlation with the characteristic impedance of the instrument for *overtones*, *vocals*, *resonance*, *loudness* and *overall quality*. The parameter *speed* was found to be positively correlated with the frequency of the first (or lowest) frequency resonance. Assessments of PVC pipes were consistent with these results. The overwhelming preference of the assessors was for instruments with a low magnitude of impedance across the spectrum, particularly in the 1 to 2 kHz region; a feature that allows time-varying resonances of a player's vocal tract to have a dominant influence over the spectral envelope of the sound.

1. INTRODUCTION

The didjeridu (or didgeridoo) is an onomatopoeic English name for an unusual and ancient musical instrument originally developed by the indigenous peoples of Northern Australia, where its many tribal names include the yidaki, yiragi and mago. A distinctive sound is produced when the player, traditionally an initiated male of that area (Moyle, 1981), places his lips at the narrower end of the instrument and uses the technique of 'circular breathing' to blow continuously (Fletcher 1983, 1996). An unusual feature of this instrument is that it has an irregular bore that has been largely constructed by termites that eat the interiors of small eucalypt trees. This makes the didjeridu a convenient musical instrument for investigating how the subjective assessments of players are related to the measurable physical properties.

The unknown appetite of the termites that shape the bores of didjeridus has two interesting consequences.

The first consequence is that the didjeridu, unlike most other lip-valve instruments, usually has a relatively wide bore along its entire length without the usual constriction at the mouth end. The bore diameter is comparable to that of the player's vocal tract and consequently a varying geometry of the tract can produce the wide range of timbre that characterise the sound produced by this instrument (Tarnopolsky *et al.*, 2005, 2006; Fletcher *et al.*, 2006).

The second consequence is that the characteristics of a traditional instrument cannot be reliably determined from its external appearance because crucial information on the bore profile and roughness is unknown (Knopoff 1997; Amir 2003, 2004; Caussé *et al.*, 2004). Unlike orchestral instruments, traditional didjeridus cover a very wide range of quality and there are no manufacturers' insignia to indicate quality. The didjeridu is thus a convenient instrument for 'double blind' studies of the relationships among the subjective assessments made by players and objective assessments made via physical measurements (see Smith *et al.*, 2007 for a detailed discussion). Furthermore, the important role played by cyclic breathing and the simultaneous use of the vocal folds during playing both help provide a wide range of qualities that might be assessed by players.

It has thus proved possible to determine how the overall quality of a didjeridu, as judged by experienced players, is correlated with features in its measured acoustic input impedance spectra (Smith *et al.*, 2007). Most significantly, the ranked quality of an instrument was found to be negatively correlated with the magnitude of its acoustic input impedance, particularly in the frequency range from 1 to 2 kHz. This is explained by the observation that resonances in the player's vocal tract can inhibit acoustic flow, and consequently sound production, once the magnitude of their impedance peaks becomes comparable with or greater than those of the instrument (Fletcher *et al.,* 2006). The tract resonances can then produce the varying formants or peaks in the spectral envelope that characterise this instrument. Thus an instrument with low impedance and relatively weak resonances in this frequency range might be expected to allow the player greater control of the formants in the output sound and thus lead to a higher perceived playing quality.

Players generally use a number of subjective qualities when assessing any musical instrument. It can, however, be difficult to correlate such subjective qualities with objective physical properties of these instruments (e.g. Pratt and Bowsher, 1978; Plitnik and Lawson, 1999). In this paper we extend our earlier report (Smith *et al*., 2007) to investigate the correlations among a set of 7 additional subjective parameters and the measured objective parameters. The study involved 7 experienced players who assessed each of 38 traditionally made didjeridus in terms of 8 subjective parameters; *backpressure*, *clarity*, *resonance*, *loudness*, *vocals*, *overtones*, *speed* and *overall quality*. The data were then examined to determine;

(i) the consistency of the rankings for each subjective parameter among different players (i.e. how consistently do players agree about what is meant by each subjective term?)

(ii) the degree of correlation between pairs of rankings for different subjective parameters (i.e. how independent are the subjective parameters?)

(iii) the relative contribution of each subjective parameter towards the assessed overall quality of an instrument, and

(iv) the degree of correlation of each subjective parameter with measured acoustic and geometric properties.

2. MATERIALS AND METHODS

2.1 The didjeridus

Thirty eight traditional didjeridus covering a very wide range of assessed quality were studied from the collection of the 'Didjshop', a commercial enterprise located near Kuranda in North Queensland (see Smith *et al*., 2007 for more details). They were all made in the traditional manner by local indigenous workers from a termite-eaten *Eucalypt*. These didjeridus would be classed as CI 3 according to the Cultural Indications Index classification scheme suggested by the Australian Didjeridu Cultural Hub (2011). There is a higher category CI 4 assigned to instruments made by traditional custodians in the appropriate tribal regions, but such didjeridus can also carry a secret spiritual significance that cannot be disclosed to non-initiates, and are thus inappropriate for scientific studies.

A control study was made on 9 PVC tubes with the same diameter (38 mm), but different lengths, that covered the pitch range from A1 to F2. These tubes have the advantage of a known bore profile. Their acoustical properties, with the exception of the resonance frequencies, should be substantially similar. A study was also made on a set of 3 PVC tubes with different diameters (25, 38 and 50 mm) and slightly different lengths adjusted so they sounded at the same pitch – C2 (nominally 65.4 Hz). Their acoustic properties should have been substantially similar except for the characteristic impedance Z_0.

2.2 The assessors

The 'Didjshop' system of classification involves two experienced musicians who play each instrument and assess its sound quality in each of the eight categories. This involves comparison with a permanent set of reference instruments that include, for each note over the normal pitch range, several instruments with different degrees of overall quality.

The 'Players' assessment involved an additional five experienced players who volunteered to assess the sound quality of each didjeridu (without access to the reference collection). These players had an average of 11 years playing experience, in styles ranging from traditional to contemporary.

2.3 Categories used to evaluate sound quality

The classification procedure used by the Didjshop has been used for 11 years and involves assessing the sound quality of each instrument by awarding a score out of 5 in each of the seven categories listed below. Although a set of different subjective parameters have been suggested for the didjeridu (Caussé *et al*., 2004), the classification system developed by the Didjshop was used here because it was devised by very experienced players and presumably reflects the inherent qualities.

The seven categories and the descriptions provided by the Didjshop (2011) are:

backpressure. This is described as how easy it is to perform circular breathing or how little air is needed to maintain a sound.

clarity. A measure of whether the didjeridu has a bright and clear sound, or dull, muffled and flat sound. The staff who developed this evaluation opine that clarity is perhaps the most important measure of overall sound quality.

resonance is described as giving the sound its 'fullness' or measuring 'the strength of a didjeridu's vibration'. This is considered by the Didjshop staff as the second most important criterion for overall sound quality.

loudness. A measure of the sound level produced by the didjeridu.

overtones. This quality ranks the ease of producing different formants, or sets of enhanced overtones, by changing the configuration of the vocal tract.

vocals. This measures the ease with which the player can produce sounds using vocalisations, i.e. sounds that involve simultaneous vibrations of the vocal folds and of the player's lips, at different frequencies.

speed. This is a judgment of how quickly or slowly an instrument can be played. Some didjeridus, especially longer ones, are said to perform best when played slowly while others, especially short ones, are better when played quickly. Others can be played either 'slow' or 'fast'. The score in this category describes a playing characteristic of the particular didjeridu without any necessarily reflecting upon the quality of that instrument.

overall quality. This is awarded a score out of ten. The 38 instruments studied here spanned the range in quality from 2/10 to 10/10.

2.4 Measurement of acoustical parameters

The acoustic input impedance Z as a function of frequency f was measured for each instrument at 2194 equallly spaced frequencies spanning the frequency range 50 to 3000 Hz as described previously (Dickens *et al*., 2007; Smith *et al*., 2007). A number of quantitative parameters were calculated from $Z(f)$ measured for each instrument that included the following:

Z_0 – the characteristic impedance. An effective value was calculated from the geometric mean of the first maximum and first minimum in $Z(f)$. (On the semilog plot of Fig. 1, this lies halfway between the first maximum and minimum and is indicated by an arrow.)

f_1 – the frequency of the first (i.e. lowest frequency) resonance

Z_1 – the magnitude of the first resonance peak in $Z(f)$.

Q_1 – the quality factor of the first resonance peak

λ – the rate at which the maxima in $Z(f)$ decrease with increasing frequency.

Z_{MAX} – the maximum value of $Z(f)$ in the 1-2 kHz range.

Z_{HC} – the impedance associated with harmonic coincidence. This was calculated as the sum of the magnitudes of the peaks in $Z(f)$ measured around the harmonics f_n of f_1 that ocurred within the frequency range of 1 – 2 kHz.

H – The harmonicity at low frequencies was defined as the average value of $f_n/(2n\text{-}1)f_1$ for $n = 2$ to 6.

A more detailed description of these parameters can be found in Smith *et al.,* (2007).

2.5 Measurement of geometric parameters

The internal diameter at the mouth end of the instrument, d_{in}, was measured by the Didjshop prior to the application of the beeswax mouthpiece. The maximum and minimum internal diameters of the often asymmetric bore at the downstream end of the instrument were measured using calipers, and the effective output diameter, d_{out}, taken as their geometric mean.

3. RESULTS AND DISCUSSION

3.1 The acoustic impedance

Figure 1 shows an example of the measured input impedance spectrum $Z(f)$ of a traditional instrument.

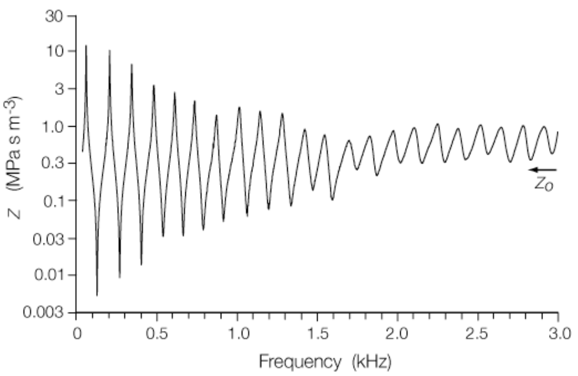

Figure 1. A semi-logarithmic plot of the measured acoustic impedance as a function of frequency for a traditional didjeridu. The arrow on the right indicates the value defined for the characteristic impedance, Z_0, at low frequencies. The rankings of this instrument in the various categories were: *backpressure* = 8, *clarity* = 3, *resonance* = 6, *loudness* = 4, *overtones* = 3, *vocals* = 5, *speed.* = 27, *overall quality* = 4. A photograph of this particular instrument is denoted as instrument D in Fig. 12 in Smith *et al*., (2007).

The impedance spectra of all the instruments studied showed the expected strong peak at the fundamental frequency that is required for maintenance of the vibration regime. However, in didjeridus of higher ranked *overall quality*, the amplitude of the higher resonance peaks decreased rapidly with increasing frequency. This produced impedance spectra with little structure and only maxima of low magnitude in the region 1 to 2 kHz – the region where formants are emphasised in performance (see Fig. 2 in Smith *et al*., 2007 or Fig. 1 in Schneider *et al.,* 2008).

3.2 Consistency of the subjective parameters

Musicians have different musical backgrounds, preferences and individual styles. Indeed one difficulty with the didjeridu for these studies might be the absence of a formal academic tuition system where players increasingly become familiar with a common terminology over many years of study. Players who have learnt from their elders in the traditional manner may indeed share a common terminology, but it would be in their particular native language and probably have no exact equivalent in English. Consequently each player might have a different concept of what is meant by each of the 8 different categories for sound quality. A player's assessment of each subjective parameter could also be influenced by its suitability to his particular style of playing.

3.2.1 Range of scores for the subjective parameters

The *overall quality* was scored out of ten, whereas the other seven parameters discussed here were scored out of five. The panel of 5 players assigned the full range of available scores for each parameter. The Didjshop allocated a reduced range of scores for some parameters; i.e., *backpressure* (3 – 5), *resonance* (2 – 5), *loudness* (3 – 5), *vocals* (2 – 5), *overtones* (2 – 5), *speed* (1 – 4), and *overall quality* (2 – 10). It was thus difficult to maintain an absolute scale for these subjective parameters, and consequently the relative rankings of each musician were usually used for analysis rather than the individual scores.

3.2.2 Ranking of instruments by the Players

To check the degree of consistency between the scores awarded by the 5 different players, the Kendall Coefficient of Concordance, W, was calculated from the individual rankings of the 8 subjective parameters by the 5 players for the 38 traditional didjeridus – see Table 1. (W is a parameter used to rank the concordance of judgements; $W = 1$ if all players ranked the instruments in exactly the same order, $W = 0$ if the rankings were essentially at random – see Kendall and Babington Smith (1939)). There was some consistency in the order of the 5 players' rankings; the probability p that such results might arise by chance were generally significant at the 1% level or better. The exceptions were *backpressure* and *overtones*, where the agreement among players was only significant at the 10% and 20% level respectively.

3.2.3 Comparison of Players and Didjshop rankings

The assessments made by the Didjshop involve musicians who assess instruments regularly, unlike the players who would not have been asked previously to assess formally an instrument in terms of the 8 subjective parameters. It is thus quite possible that the Didjshop ranking might differ from those made by the 5 volunteer players. However, the Spearman rank-order correlation coefficient, r_S, calculated between the ranking awarded by the Didjshop and the average ranking of the 5 players was significant at the 5% level or better for most subjective parameters: see Table 1. The exceptions were *backpressure* and *speed*, which were only significant at the 20% and 10% level respectively.

The 'combined' ranking of each subjective parameter for each instrument used for this paper was derived by averaging the Didjshop ranking for that parameter with the mean ranking of the 5 players. This produced a good distribution of rankings across the 38 instruments with at least 33 different values for each parameter (the exception was *speed* with only 29).

It thus appears that there is a useful, if not particularly large, degree of consistency in the interpretation of the 8 subjective parameters. However it is surprising that *backpressure* was the least consistent term, because this term is widely used by both didjeridu and brass players.

Table 1. The correlations between the individual rankings of the 5 players and the Didjshop for each subjective parameter for the 38 traditional didjeridus. W denotes the Kendall Coefficient of Concordance calculated for the 5 players. r_S denotes the Spearman rank-order correlation coefficient between the ranking of the Didjshop and the average ranking of the 5 players. The probability p refers to such a non-null result arising by chance.

	5 Players		Didshop and average ranking of the 5 players	
Parameter	W	p	r_S	p
backpressure	0.26	0.10	0.16	0.17
clarity	0.35	4×10^{-4}	0.35	0.02
resonance	0.39	6×10^{-5}	0.71	3×10^{-7}
loudness	0.33	9×10^{-3}	0.41	5×10^{-3}
vocals	0.37	2×10^{-4}	0.56	1×10^{-4}
overtones	0.24	0.21	0.55	2×10^{-4}
speed	0.32	0.01	0.21	0.10
overall quality	0.34	6×10^{-3}	0.51	5×10^{-4}

3.3 The independence of subjective parameters

Although the players have assessed each instrument in terms of 8 subjective parameters, it is possible that these parameters are not completely independent, i.e. they could exhibit a degree of collinearity. There could thus be varying degrees of overlap among parameters, or in some cases players may even be unaware they are assessing essentially the same subjective parameter.

The interdependence of subjective parameters was examined by calculating the degree of correlation between the rankings of each pair – see Table 2. A high degree of positive correlation is apparent between most of the parameters (*clarity*, *resonance*, *loudness*, *vocals*, *overtones* and *overall quality*) ranked by the Didjshop and the players. Two examples are given in Fig. 2. The other two parameters (*backpressure* and *speed*) are correlated with each other, although not significantly correlated with the other parameters. A further examination of the correlations between parameters using their average scores rather than their relative rankings produced the same results as Table 2, the only difference being a less significant correlation between *backpressure* and *speed.*

3.4 The contribution of the other subjective parameters towards *overall quality.*

The subjective parameter *overall quality* differs from the other 7 subjective parameters in that it refers to the overall properties of an instrument, rather than to a particular attribute. It is thus interesting to investigate the relative contributions that the other parameters might make towards the *overall quality*. The results of a multiple linear regression on the rankings of the Didjshop shown in Table 3 indicated that the parameters *clarity, backpressure* and *resonance*, all contributed significantly to the assessed *overall quality*. The results are consistent with the Didjshop statement that *clarity* and *resonance* are the two most important contributors to overall quality.

3.5 The correlations between acoustic parameters

A set of acoustic parameters previously chosen to describe different features in $Z(f)$ were found to exhibit a useful degree of correlation with the subjective parameter *overall quality* (Smith *et al.,* 2007). However, it is very likely that these acoustic parameters are not orthogonal, and could exhibit a high degree of collinearity.

Table 2. The correlations between the combined rankings of the Didjshop and the 5 players for the subjective parameter of the 38 traditional didjeridus. Only terms that are significant at the 1% confidence level are shown.

	backpressure	*speed*	*clarity*	*resonance*	*loudness*	*vocals*	*overtones*	*quality*
backpressure	1							
speed	0.44	1						
clarity	.	.	1					
resonance	.	.	0.78	1				
loudness	.	.	0.65	0.72	1			
vocals	.	.	0.83	0.89	0.66	1		
overtones	.	.	0.81	0.81	0.75	0.86	1	
quality	.	.	0.82	0.90	0.83	0.88	0.86	1

Table 3. The relative contributions of subjective parameters towards the combined parameter *overall quality*. Values shown are the results of a multiple linear regression. Only terms that are significant at the 1% confidence level are shown.

	Didjshop	Players	Combined
clarity	52%	41%	67%
resonance	16%	11%	17%
backpressure	20%	13%	–
loudness	–	–	5%

Table 4. The correlations between parameters involving the magnitude of $Z(f)$.

	Z_0	Z_1	Z_{HC}	Z_{MAX}
Z_0	1			
Z_1	0.90	1		
Z_{HC}	0.59	0.58	1	
Z_{MAX}	0.75	0.73	0.81	1

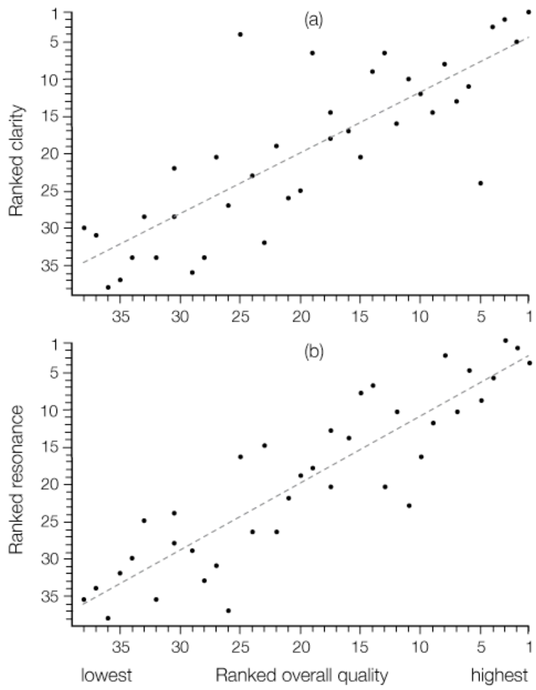

Figure 2. Two examples of relationships between the combined rankings of subjective parameters for the 38 traditional instruments. Fig. 2(a) shows the relationship between the ranked *clarity* and ranked *overall quality*. Fig 2(b) shows the relationship between ranked *resonance* and ranked *overall quality*. The parameters *clarity* and *resonance* are judged by the Didjshop to be the most important in determining *overall quality*. The dashed lines indicate the lines of best fit with $r^2 = 0.67$ (*clarity*) and $r^2 = 0.80$ (*resonance*).

Table 4 indicates that all the parameters that involve the magnitude of the impedance are strongly correlated. However the other parameters studied here (f_1, Q_1, λ and H) are not significantly correlated at the 1% level.

3.6 The relationships among subjective parameters and the measured impedance spectra of didjeridus

It now remains to investigate the relationships among the subjective parameters and the measured acoustic and geometric parameters. The problem is complicated by the collinearity in both the subjective and acoustic parameters, and differences between the rankings of the Didjshop and the Players. Here the presented results for each subjective parameter are the result of a multiple linear regression on the rankings of that parameter with the 8 physical acoustic parameters listed above. Only parameters that were significant at the 1% level or contributed more than 5% to the total variance (given in brackets) are presented.

3.6.1 *speed*

Didjshop $+f_1$ (22%) $-Z_0$ (16%)

Players $+f_1$ (28%) $+Z_0$ (25%)

Combined $+f_1$ (37%)

The parameter *speed* appears to reflect how rapidly an instrument can respond when generating the distinct rhythmic patterns. The only acoustic parameter in $Z(f)$ positively correlated with the ranked parameter *speed* by both the Players and the Didjshop was the fundamental resonance frequency f_1 - see Fig. 3.

This result agrees with the observation of Amir (2004) that 'fast' instruments often have a higher pitch. As expected, f_1, and thus the ranked speed, is negatively correlated with the length of each instrument. Because f_1 is (inversely) related to the time taken for sound to travel between the ends of the instrument, it seems reasonable that this would also determine how quickly the instrument responds. It is interesting that the Didjshop found Z_0 to be negatively correlated with *speed* (as is the case for most other parameters) whereas the players' assessment was the opposite for this particular subjective parameter.

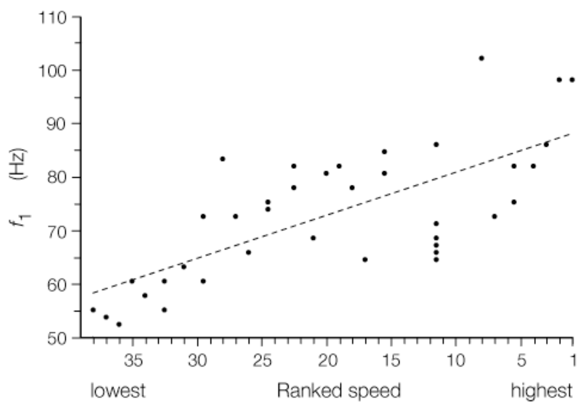

Figure 3. The relationship between f_1, the frequency of the first impedance maximum, and the combined ranked parameter *speed* for the 38 traditional instruments. The dashed line indicates the correlation ($r^2 = 0.51$).

3.6.2 *backpressure*

Didjshop + Z_0 (29%) + Z_{MAX} (21%)

Players no significant relationships

Combined no significant relationships

The ranked Didjshop parameter *backpressure* was positively correlated with the characteristic impedance Z_0, as well as Z_{MAX}, the maximum impedance in the range 1 to 2 kHz. This was in complete contrast with the Didjshop assessment of the other subjective parameters (except *clarity*) that were all negatively correlated with Z_0

The parameter *backpressure* appears to be generally associated with the mean DC flow of air through an instrument; e.g. 'how little air is needed to maintain a sound' (Didjshop, 2011) or 'A high backpressure … requires a smaller degree of mean flow' (Amir, 2004). *backpressure* also appears to correspond qualitatively to the RCA (air column resistance) used by Caussé et al. (2004). Z_0 of these didjeridus has been shown previously to vary with d_{in}^{-2} (and is inversely proportional to d_{in}^{2} for a cylinder) – see Smith *et al*., 2007. The observed correlation between backpressure and Z_0 is therefore expected. (The correlation between flow and cross-sectional area may not be the trivial one due to DC resistance, because the chief limit to flow through the didjeridu is the opening of the lips. It is possible that this small area gives rise to high acoustic impedance at the operating frequency, which in turn might lead to lip vibrations with lower average amplitude, and therefore lower DC flow.)

A high backpressure will require a smaller mean flow of air through the instrument and thus allow a longer period of playing for a single breath. During cyclic breathing it would also allow the air stored in the cheeks to maintain the sound for longer whilst fresh air is inhaled through the nose. Because the contrast between the inhalatory and exhalatory phases of cyclic breathing is an essential part of the didjeridu sound, it might be expected that a high backpressure would be a desirable feature and thus be correlated with *overall quality*. However, this was not the case with our data. This might be because instruments with a large diameter (and thus low backpressure) generally produce the desirable smaller values of the parameters Z_0, Z_1, Z_{HC}, and Z_{MAX}.

3.6.3 *resonance*

Didjshop – Z_0 (59%)

Players – Z_0 (48%) – H (9%) – Z_{HC} (7%)

Combined – Z_0 (60%) – H (8%) – Z_{HC} (7%) + Q_1 (7%)

The parameter *resonance* has a strong negative correlation with Z_0, perhaps because lower overall impedances are associated with a wider diameter and the reduced wall losses can then produce a stronger resonance, although this might be expected to favour also a positive correlation with Z_1. The small positive correlation with Q_1 is consistent with this.

The negative correlation of the players' rankings with H, the harmonicity of the low frequency resonances, and also Z_{HC}, an indicator of harmonic coincidence, suggest that players preferred a dominant fundamental in the sound and weak second and other low harmonics. Weak low harmonics would lead to greater subjective prominence of the harmonics in the varying formants produced by the player's changing vocal tract.

3.6.4 *vocals*

Didjshop – Z_0 (64%) – f_1 (7%)

Players – Z_0 (19%)

Combined – Z_0 (46%) – f_1 (13%) – H (6%) – Z_{HC} (5%)

The parameter *vocals* has a strong negative correlation with Z_0, and also a small negative correlation with f_1. The latter might arise because a low pitch would help reduce the contribution of lip harmonics in the frequency range where vocalisations occur. This is supported by the small negative correlations with harmonicity indicators.

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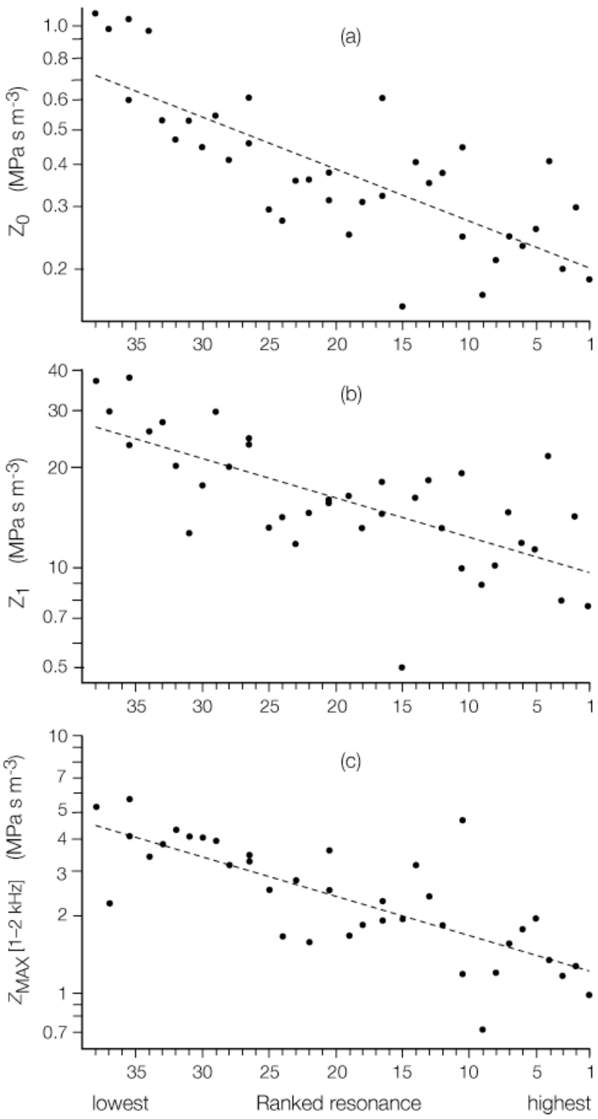

Figure 4. Semi-logarithmic plots of relationships between the measured acoustic impedance and the ranked *resonance* of the 38 traditional instruments. Figure (a) shows Z_0, the characteristic impedance at low frequencies. Figure (b) shows Z_1, the value of the first impedance maximum. Figure (c) shows Z_{MAX}, the maximum value of the impedance in the range 1 – 2 kHz. The dashed lines indicate the correlations (r^2 = 0.60, 0.48, 0.38 respectively) with probabilities $p = 1 \times 10^{-8}$, 2×10^{-6} and 2×10^{-8} that the correlation might occur by chance.

3.6.5 *loudness*

Didjshop – Z_0 (33%) – Z_{HC} (16%)

Players – Z_{HC} (23%)

Combined – Z_0 (28%) – Z_{HC} (24%)

The negative correlation of *loudness* with harmonic coincidence is not immediately obvious: in many modern musical instruments, one would expect more harmonic resonances to contribute to the loudness. In the didjeridu, however, higher harmonics of the note played do not in general coincide with resonances of the bore, so this term is less important. Further, some of the instruments with the highest harmonicity may be those that are closest to cylindrical shape, while highly flared instruments are usually louder

3.6.6 *clarity*

Didjshop – Z_0 (42%)

Players – H (19%) – Z_1 (12%)

Combined + Z_0 (21%) – H (13%)

The negative correlation of *clarity* with harmonicity could be explained in terms of the desirability of a 'hole' in the sound spectrum (Amir, 2003, 2004): inharmonic peaks in $Z(f)$ mean that the first few harmonics above the fundamental are weak.

3.6.7 *overtones*

Didjshop – Z_0 (63%)

Players no significant relationships

Combined – Z_0 (36%)

The parameter *overtones* exhibits a strong negative correlation with Z_0. This would allow the vocal tract to dominate in the formant range.

3.7 The subjective parameters of PVC pipes

The 11 PVC pipes were assessed by 5 players. They can be considered in 2 distinct groups.

3.7.1 Pipes of same diameter, but different length

The ranking of the scores awarded by the players to the 9 PVC pipes of the same diameter, but different lengths, were not very consistent. This is presumably because the players were being asked to rank the acoustic properties of instruments that were essentially identical, except for the variation of the fundamental resonance frequency with length. The average assessed *overall quality* of these pipes was very low – only 3/10. The most consistently ranked parameter was *speed*, with W = 0.32 and a confidence level around 10%. Indeed there was a positive correlation between *speed* and the pitch frequency, with $r^2 = 0.30$, similar to that found for traditional instruments.

3.7.2 Pipes of different diameter, but same pitch.

The acoustic properties of the PVC pipes of 3 different diameters will be different (see Schneider *et al.*, 2008), and this is reflected in more consistent rankings than when the length was varied. The agreement in rankings was only significant at around the 1% level for the parameters *vocals* and *overall quality*.

There existed strong negative correlations between the inverse of the cross-sectional area of these pipes and the following parameters; *overall quality*, *vocals*, *resonance*, *loudness*, and *overtones* with r^2 = 0.92, 0.93, 0.59, 0.63 and 0.69 respectively. This agrees with the observed negative correlations of these subjective parameters with the Z_0 of traditional ddijeridus.

3.8 The relationships among subjective parameters and measured geometry of didjeridus

Table 5 shows the correlations between the subjective parameters and the measured diameters of the traditional instruments. In general there was a positive correlation with both d_{in}, the input diameter, and with d_{out}, the effective ouput diameter. This is consistent with the general preference for instruments with low impedance. One exception was *backpressure*, where the correlation was negative and consistent with a preference for higher values of Z_0. Another exception was *speed*, where a small negative correlation was only present for the players' ranking for d_{in}.

4 CONCLUSIONS

There was a useful, if not particularly large, degree of consistency in the interpretation of the 8 subjective parameters by the Didjshop and the 5 players. However it was surprising that *backpressure* was the least consistent term, because this term is widely used by both didjeridu and brass players.

A high degree of positive correlation existed between most of the parameters (*clarity*, *resonance*, *loudness*, *vocals*, *overtones* and *overall quality*). The other two parameters (*backpressure* and *speed*) were correlated with each other, although not significantly correlated with the other parameters.

The parameters *clarity*, *resonance* and *backpressure* made the most important contributions to the *overall quality* of an instrument.

In general there was a strong negative correlation with the charateristic impedance Z_0 of the instrument for *overtones*, *vocals*, *resonance*, *loudness* and *overall quality*. However the assesments of the Didjshop and the players had opposite signs for *clarity and speed*. *backpressure* was the only parameter where the Didjshop assessment was positively correlated with Z_0.

The parameter *speed* was found to be positively correlated with f_1, the frequency of the first (or lowest) frequency resonance.

The assessments of different PVC pipes were consistent with the rankings of Z_0 for traditional instruments.

The overwhelming preference of the assesors was for instruments with a low magnitude of Z(f) across the spectrum, so that the impedance peaks of the vocal tract can have a larger effect on the output sound.

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Table 5. The correlations between the measured diameters and the subjective parameters. The parameter d_{in} denotes the internal diameter at the mouth end of the instrument and d_{out} the effective output diameter. D refers to the Didjshop, P to players and C the combined rankings from Didjshop and players. Values are presented as the r^2 when significant at the 1% level, with the sign indicating the sign of the correlation.

	d_{in}			d_{out}		
	D	P	C	D	P	C
backpressure	–0.36		–0.22			
clarity					+0.32	+0.30
resonance	+0.49	+0.36	+0.50	+0.30	+0.34	+0.37
loudness	+0.24		+0.19	+0.22	+0.34	+0.39
vocals	+0.48		+0.39	+0.18	+0.39	+0.33
overtones	+0.37		+0.20	+0.27	+0.31	+0.36
speed		–0.28				
quality	+0.45		+0.35	+0.31	+0.43	+0.44

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