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Effect of Drone Reed Material on Great Highland Bagpipe Sound

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Summary
Great highland bagpipe drones are equipped with single beating reeds. These reeds were traditionally made of cane but more and more musicians nowadays use synthetic reeds. The advantage of synthetic reed is its reduced dependance on air moisture and temperature as well as its increased stability with aging. Despite this advantage, many musicians consider that equipping their instrument with synthetic reeds would degrade its timbre and remain faithful to cane reeds. In the present study, the sound of drones equipped with cane or plastic reeds was first recorded. Expert listeners were then asked to assess these recordings with respect to the following attributes : *global quality of sound*, *clarity*, *aggressiveness*, *warmth*, *volume* and *immersion*. The reed material appeared to be without significant effect on the global quality of drone sound (and also on other perceptual attributes), when one tenor or bass drone was played alon e, and when the two tenor drones and the bass drone were played with the chanter (full set). However, independently of the material, some reeds obtained higher ratings than some other ones. *Global Quality* was correlated with *warmth*, *immersion* and *clarity* (to a lesser extent with *aggressiveness*)in full set condition. Correlations between perceptual results and signal analyses showed, about tenor drones, that listeners appreciated sounds having a fundamental frequency with a large magnitude, and less energy for higher harmonics. The analysis of the material influence on these signal properties indicated that synthetic tenor reeds should obtained higher quality ratings (even if this effect was not significant according to the statistical analysis).

PACS no. 66.008.Jh, 75.002.Cd, 75.012.Pq

1. Introduction

Among the bagpipes, the Great Highland bagpipe (GHB, see Figure 1) is the most played all over the world. It consists of a bag, a blowpipe used to blow the bag, three independent drones equipped with single beating reeds traditionally made with sections of cane, and a diatonic oboe described as "chanter", equipped with a double reed. The two "tenor" drones play a Bb3, whereas the "bass" one plays a Bb2. A drone reed can be considered as an open-closed cylinder where a vibrating blade is clamped. The GHB drones are cylindrical pipes excited by simple reeds similarly to the clarinet (which is in addition equipped with a mouthpiece).

The Great Highland Bagpipe is characterized by the feeling of immersion created by its three drones [1] and a particular attention is therefore paid to drone sound. The pipe of a woodwind instrument is usually considered as mainly responsible for the pitch and the timbre of the played note. Nevertheless, the coupling between the reed and the pipe is important and the reed resonance itself significantly contributes to the sound emitted by a clarinet [2] or a bagpipe [3].

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Some studies enabled to relate the reed functioning and the physical properties of the reed material : elasticity, density, etc. [4, 5]. The natural cane from which reeds are traditionally made is a material having a high modulus of elasticity and a low density. These properties vary considerably not only among individual reeds but also between different portions of the same reed [6]. Moreover, these properties can largely vary with the age of the reed [7] and with the moisture [8]. So non-organic reeds have been developed, the use of synthetic materials enables the reproducibility of their characteristics [6].

While synthetic reeds remain a minority among clarinettists, especially professional players, they are nowadays widespread among GHB players. Indeed, they have the reputation of a higher stability while playing: their reduced sensitivity to moisture and warmth solves tuning instability [9], a recurring problem with cane reeds. Moreover, their life-span is much longer than the one of cane reeds. Nevertheless, the latter remain still popular because their timbre is sometimes preferred by some pipers to that of synthetic ones.

The GHB scale and pitch evolution over time was studied [10], but so far no study focused on the perception of the drone sound, despite it is considered of high importance by bagpipe lovers. Such considerations led us to ask expert listeners (with strong musical background as

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Figure 1. Great Highland Bagpipe.

pipers) their opinions about the sound quality of drones equipped with synthetic or cane reeds. Three listening tests were designed to assess: i) single tenor drones, ii) single bass drones and iii) the three drones played with the chanter (full set) as done in a usual playing situation. In each of these tests, the *global quality of sound* was to assess, as well as several qualitative attributes such as *clarity*, *aggressiveness*, *warmth*, *volume* and *immersion*.

2. Material and methods

2.1. Sound recordings

Eight different reed models were under study: four were synthetic (industrial production, 4 different brands) and four were made of cane (hand-crafted production, 4 different reed makers). These brands were ones of the most used by bagpipers because of their stability, setting possibilities and timbral properties. All these reeds were new but were played for several hours before recording. Two sets were available for each reed model, each set consisting of the three reeds needed to equip the three drones. Two professional musicians played over their respective instruments (bagpipes 1 and 2) equipped with these reed sets for the need of the recordings. For each set, the following recordings were carried out: one tenor drone alone (always the same for a given instrument), the bass drone alone and finally a slow tune from Brittany played on the chanter accompanied by the three drones (full set). The sequences lasted 8 s for the drones alone and 15 s for the full set tune. To sum up, 32 (8 reed models × 2 sets × 2 musicians) sequences were recorded for each listening test (tenor drone alone, bass drone alone and full set), namely 96 sequences in all. A single microphone (DPA4006) was used for the (monophonic) recordings and was placed in front of the musician at a distance of 1.20 m and a height of 1.60 m. The microphone was placed by a sound engineer, in order to have a good balance between the chanter and the three drones (and room effect, even if the reverberation time was very short) in full set configuration.

2.2. Listening test procedure

Three listening tests were designed to assess respectively tenor drones alone, bass drones alone and the full sets. In each test, the listener was presented with the 32 respective recordings (in random order) that were reproduced over headphones (Sony CDR2000). He or she sat in an audiometric booth and was instructed to not modify the headphones position during the whole test [11]. Each test was made of two sessions. Subjects were asked to assess the *global quality of sound* in a first session, then several qualitative attributes in a second one: *clarity*, *volume*, *aggressiveness* and *warmth* for the two tests about drones alone, to which was added *immersion* for the full set test. These terms were determined on the basis of a pre-study, during which pipers were asked to give few terms (10 maximum) which could characterize the drone sound and the perceptual differences between different drones; then the most cited terms (without synonyms) were kept. When *immersion* was cited by pipers in this preliminary study, it can be thought that they referred to the sensation they experienced when playing their own instrument (with the three drones surrounding the piper's head) rather than to the one created by listening to a (monophonic) recording of a bagpipe. However, they indicated that they could be more or less immersed according to the timbre of the drone, and not only according to the spatial sensation. So it can be thought that immersion still makes sense, even in the case of a monophonic reproduction.

After listening to a sequence, the listener had to indicate his judgment with respect to these attributes along a continuous scale ranging from 0 to 10 on a MATLAB graphical user interface (see Figure 2). The three tests were carried out consecutively but in random order by each listener. The two tests about drones alone lasted about 15 minutes each, whereas the full set test took 25 minutes. Each test was preceded by a 3-min pre-test to familiarize the listener with the stimuli, the answering interface and the different criteria. Listeners were explicitly told that only the drones' sounds were to be assessed, and not the chanter for the full set test.

2.3. Listeners

The 12 listeners involved in the study were all trained pipers with a high practice level (expert listeners). Participants were not remunerated for the test. Their hearing has not be checked by the experimenters, but listeners were

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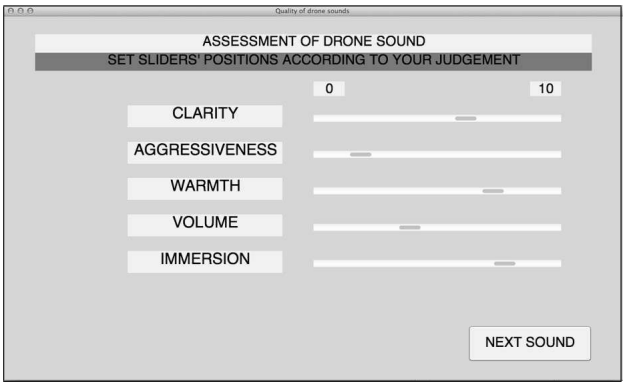


Figure 2. MATLAB graphical interface for the assessment of perceptual attributes in the full set test, which includes *immersion* (translated from french).

asked if it had been checked within the two past years and if they were free of hearing problems (they were excluded from the experiment if it was not the case).

3. Results of perceptual tests

3.1. Global quality of drones in the full set test

Each listener gave 32 scores corresponding to the 32 conditions : 8 reed models (4 synthetic reeds, and 4 cane reeds) * 2 sets for each reed * 2 instruments/players (as each musician played on his own bagpipe, the influences of the instrument and the player were merged). These assessments were analyzed using repeated measures analysis of variance with reed material (2 levels) and instrument/player (2 levels) as within-subjects factors. Reed models and reed sets were not considered as factors in this analysis (there is no relationship between the set 1 for a given reed model and the set 1 for another reed model, and also there is no relationship between the model 1 in cane and the model 1 in plastic). Thus the possible effects were only those of the reed material, the instrument/player, or their interaction.

No violation of sphericity was reported by a Mauchly's test. The analysis did not reveal any significant effect of the reed material ($F(1, 11) = 0.008$; $p = 0.93$) as can be seen on Figure 3. However, the analysis indicated a significant effect of the instrument/player ($F(1, 11) = 12.02$; $p = 0.005$): sequences obtained a better assessment for bagpipe/player 1 than for bagpipe/player 2 (see Figure 4). Moreover, an interaction between factors reed material and instrument/player was highlighted by the ANOVA ($F(1, 11) = 20.7$; $p = 0.001$): when looking at the figure 5, it seems that for the bagpipe/player 1, synthetic reeds obtained better quality ratings than cane reeds and that, on the contrary, for the bagpipe/player 2, cane reeds obtained better quality ratings than synthetic reeds. But actually, the Bonferroni post-hoc test indicated no significant difference between cane and synthetic reeds for bagpipe/player 1 ($p = 0.062$) nor for bagpipe/player 2 ($p = 0.075$). It is worth noting that using Bonferroni post-hoc test, the initial

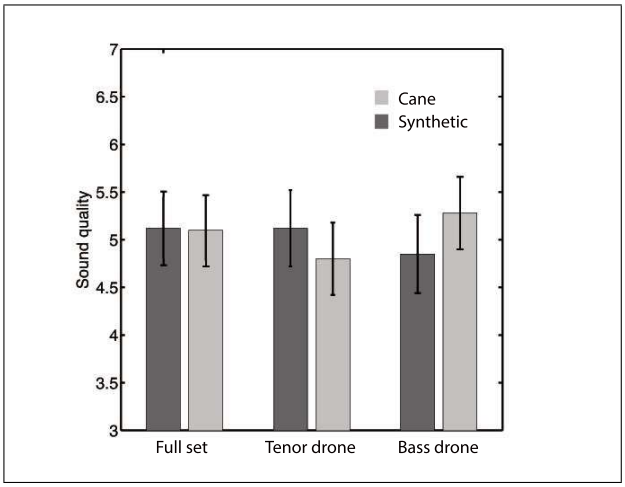


Figure 3. Mean global quality ratings (with 95% confidence intervals) as a function of the reed material for the full set test, the tenor drone only test, and the bass drone only test.

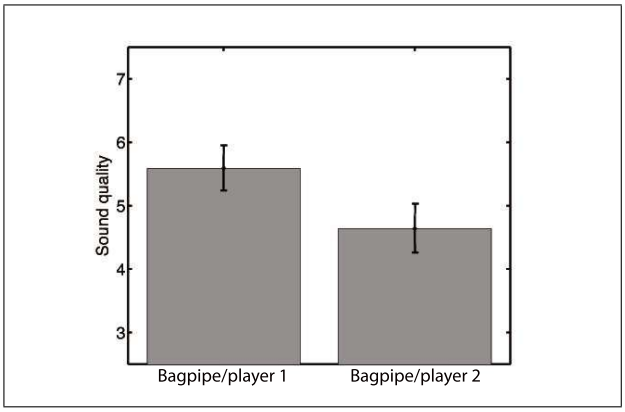


Figure 4. Mean global quality ratings (with 95% confidence intervals) as a function of the instrument/player for the full set test.

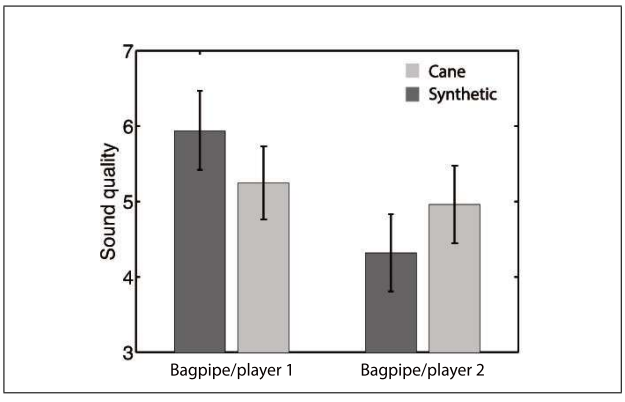


Figure 5. Mean global quality ratings (with 95% confidence intervals) as a function of the instrument/player and the reed material for the full set test.

p value is multiplied by the number of paired comparisons which tend to reduce the significance of the effect.

An other repeated measures analysis of variance was conducted replacing the reed material by the reed model as within-subjects factor (8 levels). It showed a significant

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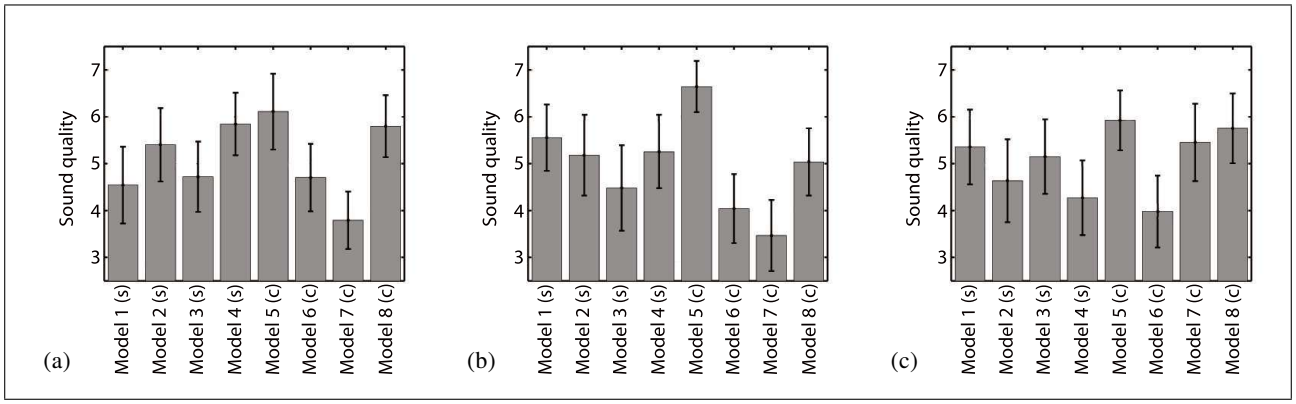


Figure 6. Global quality ratings (means and 95% confidence intervals) as a function of the reed model for the full set test (a), the tenor drone only test (b) and for the bass drone only test (c). Models 1 to 4 are synthetic (denoted s), models 5 to 8 are cane (denoted c).

model effect ($F(7, 77) = 6.8$; $p < 0.0001$): independently of the material, some reeds were preferred to some other ones (see Figure 6(a)). Although the cane and synthetic reeds were globally identically rated, the reed model 7 (made of cane) obtained significantly lower ratings than the model 4 (synthetic) ($p = 0.017$ according to Bonferroni's post-hoc test). Moreover the reed model 7 obtained also significantly lower ratings than the cane reed models 5 ($p = 0.017$) and 8 ($p = 0.005$).

3.2. Global quality of tenor and bass drones alone

Similar analyses were carried out on the quality assessments obtained from the two tests involving respectively the tenor and bass drones alone. A first ANOVA (with reed material and instrument/player as factors) did not highlight any significant effect involving the reed material (see Figure 3) or the instrument/player, whatever the drone. A second ANOVA (replacing the reed material by the reed model) indicated that the reed model had a significant effect for the tenor drones ($F(2.54, 27.89) = 5.47$; $p = 0.006$ according to the ANOVA with Greenhouse-Geisser correction, used because of the violation of sphericity reported by Mauchly's test) as can be seen on Figure 6(b). However the reed model had no significant effect for the bass drones (F(2.33,71.24)=1.79; p=0.18 according to the ANOVA with Greenhouse-Geisser correction, used because of the violation of sphericity reported by Mauchly's test) - see Figure 6(c)).

In order to observe the individual correlations between full set test and tenor drone only and bass drone only tests, the correlations were computed (for the 32 conditions: 8 reed models * 2 items * 2 instruments/player) for each of the 12 listeners. Figure 7 shows that the individual correlations between full set test and tenor only or bass only tests appeared to be always very low. Hence, the quality of the full set does not follow the quality of the tenor drone or the bass drone when played alone.

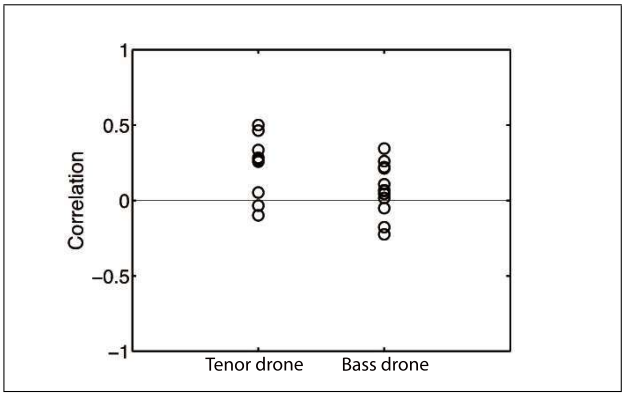


Figure 7. Individual correlations between global quality ratings from full set and tenor drone only tests, and from full set and bass drone only tests. Each circle represents the correlation for a given listener.

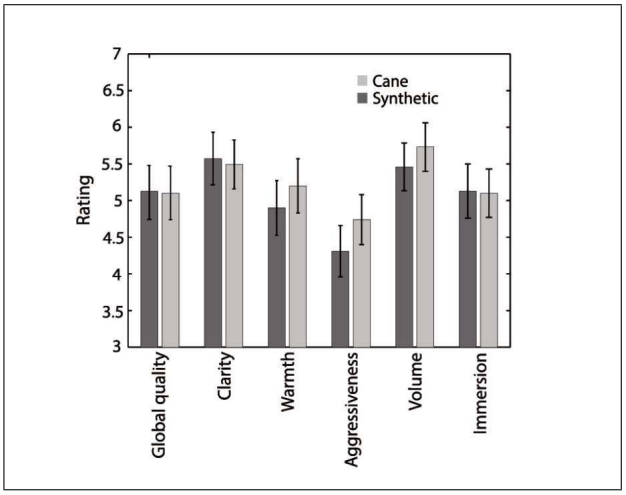


Figure 8. Mean ratings (with 95% confidence intervals) for all the perceptual attributes, as a function of the reed material for the full set test.

3.3. Other qualitative attributes

Figure 8 indicates the mean ratings (with 95% confidence intervals) for all perceptual attributes, as a function of the reed material for the full set test. As observed for the global quality, the ANOVA did not reveal any effect of the reed material, whatever the perceptual attribute.

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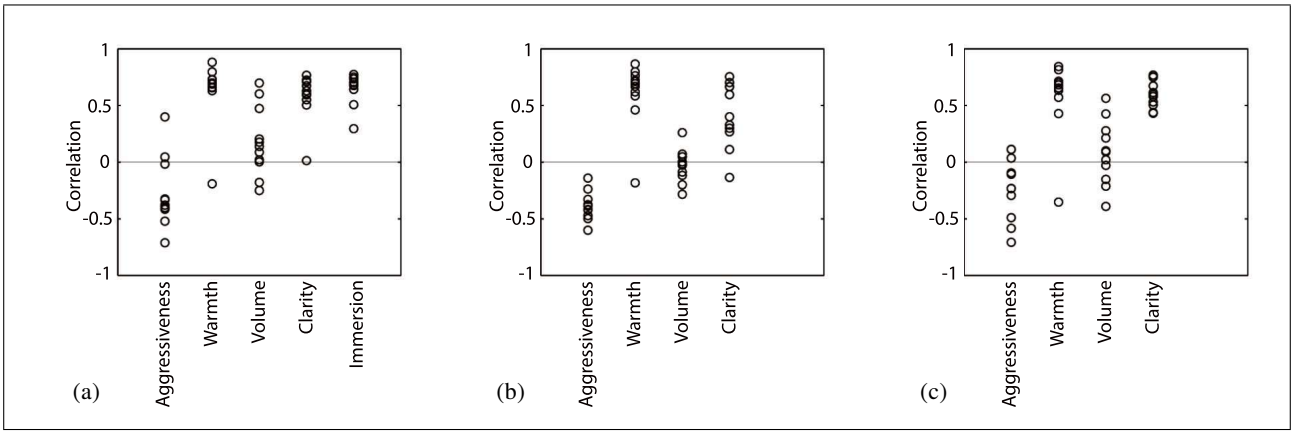


Figure 9. Individual correlations between global quality ratings and the other qualitative attributes for the full set test (a), the tenor drone only test (b) and for the bass drone only test (c). Each circle represents the correlation for a given listener.

Table I. Component matrix for the three tests. Note that the components are not necessarily identical for the three tests (PCAs were computed individually for each test).

	Full set		Tenor drone		Bass drone	
Component	1	2	1	2	1	2
Global quality	−0.97	−0.07	−0.84	−0.5	−0.75	−0.54
Aggressiveness	+0.60	−0.67	+0.92	−0.28	+0.86	−0.43
Warmth	−0.90	−0.20	−0.86	−0.41	−0.85	−0.27
Volume	+0.01	−0.94	+0.65	−0.67	+0.68	−0.63
Clarity	−0.90	−0.02	+0.08	−0.91	−0.19	−0.88
Immersion	−0.94	−0.14	/	/	/	/

In order to observe the individual correlations between the *global quality of sound* and the qualitative attributes (*clarity*, *aggressiveness*, *warmth*, *volume* and *immersion*), the correlations were computed (for the 32 conditions: 8 reed models * 2 items * 2 instruments/players) for each of the 12 listeners. Figures 9(a), 9(b) and 9(c) show these individual correlations respectively for the full set test, the tenor drone only test, and the bass drone only test. The dispersion between listeners is larger for some attributes (especially *aggressiveness* and *volume* in the full set and the bass drone only tests) than for others (especially *warmth*). Moreover some isolated points can be noticed (but these different isolated points were not caused by a single listener). Nevertheless some observations can be made:

Warmth was highly correlated with the *global quality of sound* in the three tests (tenor, bass and full set).

Clarity was correlated with the *global quality of sound* in the full set test (the correlation was sligthly lower in the bass drone test and much lower in the tenor drone tess (large dispersion between listeners).

Aggressiveness appeared negatively correlated with the *global quality of sound*, but the correlations were low (especially for the full set and the bass drone tests, which provided large dispersions).

The correlation of *volume* with the *global quality of sound* was very low, whatever the test.

Immersion (full set test only) appeared to be correlated with the *global quality of sound*. When a sound was well appreciated, it was also considered as immersive. This result confirms that the sensation of immersion is not exclusively related to spatial properties (as the recordings were monophonic).

Principal Component Analyses have been computed to highlight the multiple correlations. The PCAs were computed from matrix with 32 rows (or "individuals": 8 reed models * 2 items * 2 instruments/players) and 6 columns (or "active variables": *global quality*, *aggressiveness*, *warmth*, *volume*, *clarity* and *immersion*). The values were averaged across listeners. The PCAs were normalized. Two components were found for each of the three tests (Table I). They explained 87% of the variance in the full set test, 89.9% in the tenor drone test, and 84.6% in the bass drone test. Figure 10a indicates the different perceptual attributes on the plane of the two principal components found for the full set test. The PCA indicated that in the full set test, *global quality*, *warmth*, *clarity*, *immersion* and *aggressiveness* were well represented by the first principal component. So *global quality*, *warmth*, *clarity* and *immersion* were correlated. *Aggressiveness* was also correlated with them (to a lesser extent), but negatively. Only *volume* appeared to have no relationship with them (and was related with the second principal component). Figure 10b indicates the 32 conditions (or individuals: 8 reed models * 2 items * 2 instruments/players, numbered from 1 to 32, see Table II) on the plane of the two principal components found for the full set test. They appear well grouped, with no remarkable outlier. According to the

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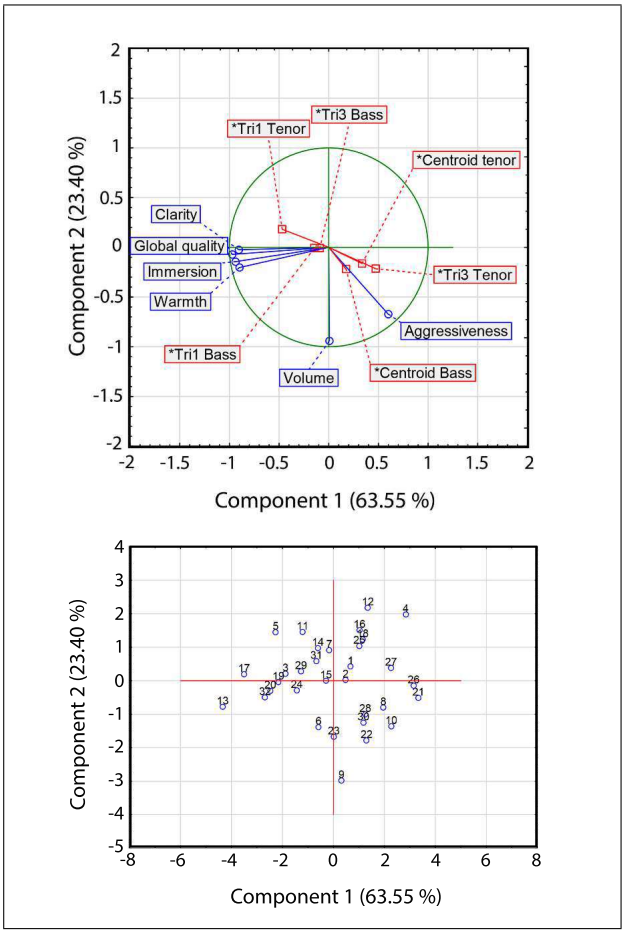


Figure 10. (a) Perceptual attributes (active variables: circle markers) and signal parameters (additional variables: square markers) on the plane of the two principal components found for the full set test. (b) Conditions (or individuals: 8 reed models * 2 items * 2 instruments/players, numbered from 1 to 32 - see Table II) on the plane of the two principal components found for the full set test.

PCA for tenor drone test and bass drone test (Table I), *global quality*, *warmth* and *aggressiveness* remained well represented by the first principal component (one should note that principal components were not necessarily identical for the three tests). So *global quality*, *warmth* and *aggressiveness* remained correlated with each other (still negatively for *aggressiveness*), but *clarity* appeared to be not correlated with them (alike *volume*).

To summarize about perceptual attributes:

- None of the perceptual attributes appeared significantly dependent on the reed material (whatever the test).
- *Global quality*, *warmth*, *immersion*, *clarity* and *aggressiveness* were correlated with each other in the full set test (to a lesser extent for *aggressiveness*).
- *Volume* was neither correlated with *global quality* nor with the other attributes (whatever the test), and *clarity* was neither correlated with *global quality* nor with the other attributes in the tenor drone and the bass drone tests.

Table II. PCA conditions (or individuals, see Figure 10(b)).

Condition	Reed model	Material	Item	Bagpipe /Player
1	1	Synthetic	1	1
2	1	Synthetic	1	2
3	1	Synthetic	2	1
4	1	Synthetic	2	2
5	2	Synthetic	1	1
6	2	Synthetic	1	2
7	2	Synthetic	2	1
8	2	Synthetic	2	2
9	3	Synthetic	1	1
10	3	Synthetic	1	2
11	3	Synthetic	2	1
12	3	Synthetic	2	2
13	4	Synthetic	1	1
14	4	Synthetic	1	2
15	4	Synthetic	2	1
16	4	Synthetic	2	2
17	5	Cane	1	1
18	5	Cane	1	2
19	5	Cane	2	1
20	5	Cane	2	2
21	6	Cane	1	1
22	6	Cane	1	2
23	6	Cane	2	1
24	6	Cane	2	2
25	7	Cane	1	1
26	7	Cane	1	2
27	7	Cane	2	1
28	7	Cane	2	2
29	8	Cane	1	1
30	8	Cane	1	2
31	8	Cane	2	1
32	8	Cane	2	2

4. Signal analysis

Several parameters were calculated (using MATLAB) on the basis of the drone recordings (tenor and bass alone): sound pressure level, fundamental frequency (mean and temporal evolution), several odd/even harmonic balance indexes, spectral centroid (mean and temporal evolution), spectral dispersion cue (degree of energy constancy between consecutive spectral bands), skewness (degree of asymmetry of the spectral distribution), kurtosis (degree of "peakedness" of the spectral distribution), Tristimulus 1 index (Power Spectral Density of the fundamental frequency divided by PSD of all harmonics), Tristimulus 2 index (PSD of the 2nd to 4th harmonics divided by PSD of all harmonics), and Tristimulus 3 index (PSD of the harmonics beyond the 4th one divided by PSD of all harmonics) [12, 13].

The different parameters were analyzed separately for tenor and bass drones, using two multiple analyses of variance (denoted Multiple ANOVA 1 and 2) with respectively i) reed material (2 levels) and instrument/player (2 levels) as within-subjects factors and ii) reed model (8 levels) and instrument/player (2 levels) as within-subjects factors.

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Table III. Parameters affected by the reed material and the instrument/player for tenor and bass drones (Multiple ANOVA 1).

		Tenor drone		Bass drone	
		F	p	F	p
Spectral Centroid	reed material	$F(1,28) = 7.89$	0.009	$F(1,28) = 18.74$	< 0.0001
	instrument/player	$F(1,28) = 9.09$	0.005	$F(1,28) = 0.89$	0.35
	material*instrument/player	$F(1,28) = 0.18$	0.67	$F(1,28) = 0.95$	0.34
Tristimulus 1	reed material	$F(1,28) = 12.05$	0.002	$F(1,28) = 1.41$	0.24
	instrument/player	$F(1,28) = 0.001$	0.97	$F(1,28) = 11.55$	0.002
	material*instrument/player	$F(1,28) = 7.75$	0.01	$F(1,28) = 4.2$	0.05
Tristimulus 3	reed material	$F(1,28) = 5.55$	0.026	$F(1,28) = 9.67$	0.004
	instrument/player	$F(1,28) = 0.007$	0.93	$F(1,28) = 0.74$	0.39
	material*instrument/player	$F(1,28) = 2.82$	0.1	$F(1,28) = 0.08$	0.78

Table IV. Parameters affected by the reed model and the instrument/player for tenor and bass drones (Multiple ANOVA 2).

		Tenor drone		Bass drone	
		F	p	F	p
Spectral Centroid	reed model	$F(7,16) = 7.72$	< 0.0001	$F(7,16) = 7.16$	0.001
	instrument/player	$F(1,16) = 18.93$	< 0.0001	$F(1,16) = 1.33$	0.26
	model*instrument/player	$F(7,16) = 0.72$	0.66	$F(7,16) = 0.79$	0.61
Tristimulus 1	reed model	$F(7,16) = 4.25$	0.008	$F(7,16) = 5.23$	0.003
	instrument/player	$F(1,16) = 0.001$	0.97	$F(1,16) = 21.06$	< 0.0001
	model*instrument/player	$F(7,16) = 2.49$	0.06	$F(7,16) = 1.24$	0.34
Tristimulus 3	reed model	$F(7,16) = 2.796$	0.042	$F(7,16) = 4.67$	0.005
	instrument/player	$F(1,16) = 0.008$	0.930	$F(1,16) = 1$	0.332
	model*instrument/player	$F(7,16) = 0.987$	0.474	$F(7,16) = 0.276$	0.954

These analyses revealed significant effects of the reed material, the instrument/player and the reed model for the spectral centroid, and for the Tristimulus 1 and 3 indexes. Table III indicates the results for Multiple ANOVA 1 with reed material and instrument/player as factors. Table IV indicates the results for Multiple ANOVA 2 with reed model and instrument/player as factors.

4.1. Spectral centroid

The spectral centroid was defined as:

$$SC = \frac{\sum_{i=1}^{n/2} f_i \cdot S(i)}{\sum_{i=1}^{n/2} S(i)}, \quad (1)$$

where $S(i)$ is the FFT magnitude (computed over the whole 8 s signal: a B flat played by a tenor or a bass drone) of bin number i, f_i is the center frequency of the bin i and n is the number of FFT bins (n corresponding to the sampling frequency).

The spectral centroid was significantly higher with drones equipped with cane reeds than with drones equipped with synthetic reeds, both for tenor and bass drones (see Figure 11).

The Multiple ANOVA 1 indicated that the spectral centroid was significantly higher with the tenor drone of bagpipe/player 2 than with the tenor drone of bagpipe/player 1 (see Figure 12). On the contrary, the statistical analysis did not reveal any significant effect of the instrument/player for bass drones. Moreover, no interaction between reed material and the instrument/player was observed.

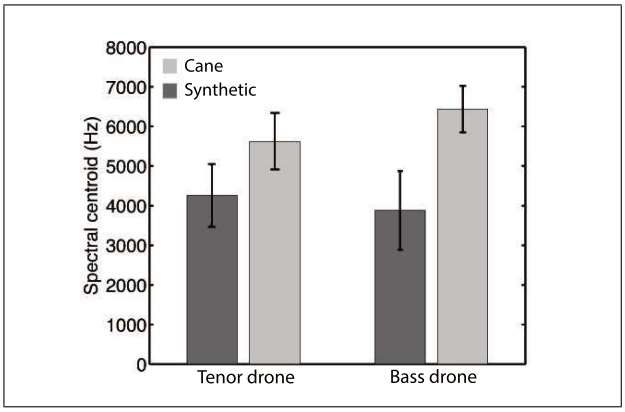


Figure 11. Spectral centroid (means and 95% confidence intervals) as a function of the reed material for tenor and bass drones.

The Multiple ANOVA 2 (with reed model and instrument/player as factors) showed a significant effect of the reed model on the spectral centroid (see Figure 13), but the spectral centroid of a given synthetic reed model was never higher than the one of a given cane reed model (both for tenor and bass drones). This observation is in agreement the material effect.

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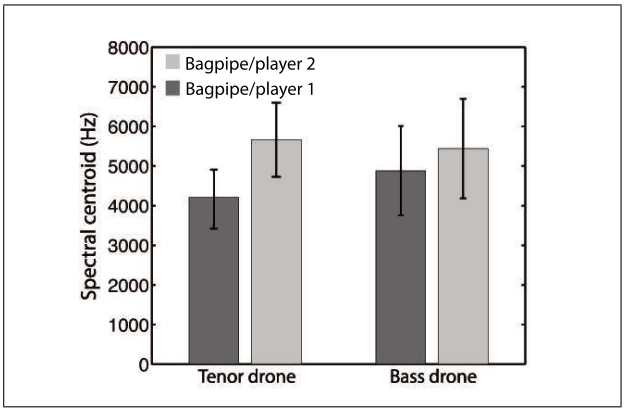


Figure 12. Spectral centroid (means and 95% confidence intervals) as a function of the instrument/player for tenor and bass drones.

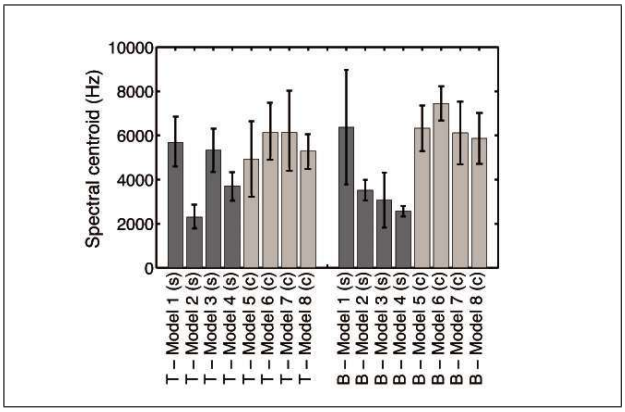


Figure 13. Spectral centroid (means and 95% confidence intervals) as a function of the reed model for tenor (T) and bass (B) drones. Models 1 to 4 are synthetic (s), models 5 to 8 are cane (c).

The effect of the instrument/player for the tenor drone highlighted in Multiple ANOVA 1 were confirmed in Multiple ANOVA 2. Moreover, no interaction between the reed model and the instrument/player was observed.

4.2. Tristimulus 1

The Tristimulus 1 index was defined as:

$$TRI1 = \frac{A(1)}{\sum_{h=1}^{H} A(h)}, \tag{2}$$

where $A(h)$ is the Power Spectral Density (PSD) of harmonic number h (computed over the whole 8 s signal: a B flat played by a tenor or a bass drone), H is the total number of harmonics and $A(1)$ is the PSD of the fundamental frequency. Thus, Tristimulus 1 indicates the importance of the fundamental frequency.

The Multiple ANOVA 1 indicated that this index was significantly higher for synthetic reeds than for cane reeds, only for tenor drones (see Figure 14). On the contrary, the statistical analysis did not reveal any significant effect of material for bass drones.

The Tristimulus 1 index was significantly higher with bass drone of bagpipe/player 2 than with bass drone of bagpipe/player 1 (see Figure 15). On the contrary, the statistical analysis did not reveal any significant effect of the instrument/player for tenor drones.

Moreover, an interaction between the reed material and the instrument/player was observed (see Figure 16): about the tenor drone, the Tristimulus 1 index was significantly larger for synthetic reeds than for cane reeds for the bagpipe/player 1 ($p < 0.0001$ according to Bonferroni's post-hoc test) but not for the bagpipe/player 2 ($p = 0.63$). About the bass drone, the Tristimulus 1 index was significantly larger for cane reeds than for synthetic reeds for the bagpipe/player 2 ($p = 0.03$ according to Bonferroni's post-hoc test) but not for the bagpipe/player 1 ($p = 0.078$).

A significant effect of the reed model on the Tristimulus 1 index was revealed (both for tenor and bass drones) by the Multiple ANOVA 2, but no significant difference could be observed when reed models were compared by pairs by using Bonferroni's post-hoc test (see Figure 17). The effect of instrument/player given by the Multiple ANOVA 1 for the tenor drone was confirmed by the Multiple ANOVA 2. An interaction between the reed model and the instrument/player was highlighted for the tenor drone by the Multiple ANOVA 2, but no significant difference could be observed when conditions were compared by pairs by using Bonferroni's post-hoc test.

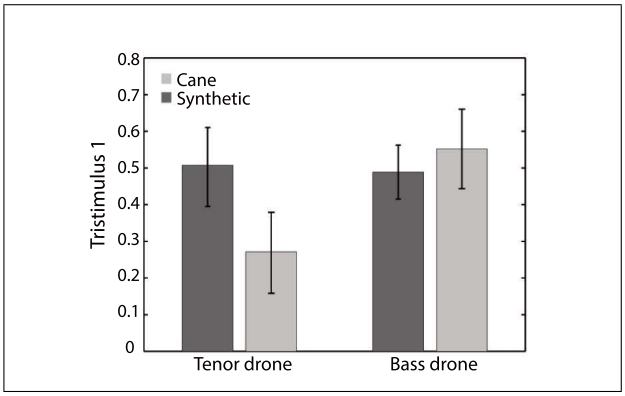


Figure 14. Tristimulus 1 (means and 95% confidence intervals) as a function of the reed material for tenor and bass drones.

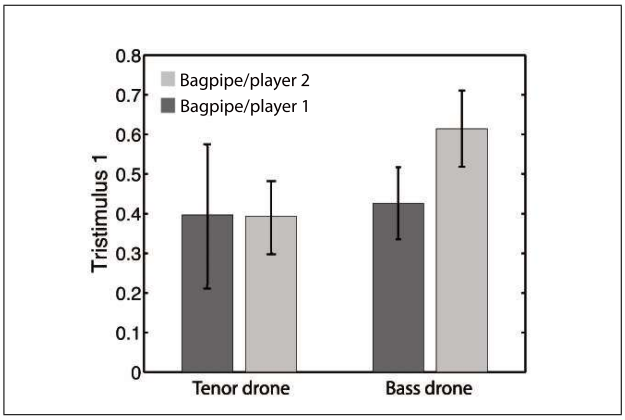


Figure 15. Tristimulus 1 (means and 95% confidence intervals) as a function of the instrument/player for tenor and bass drones.

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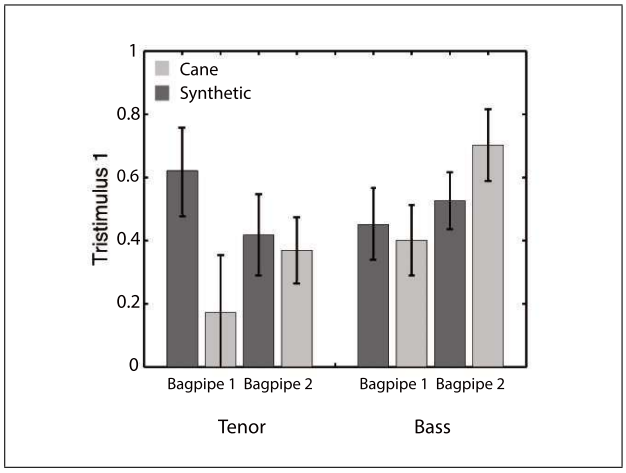


Figure 16. Tristimulus 1 (means and 95% confidence intervals) as a function of the reed material and the instrument/player for tenor and bass drones.

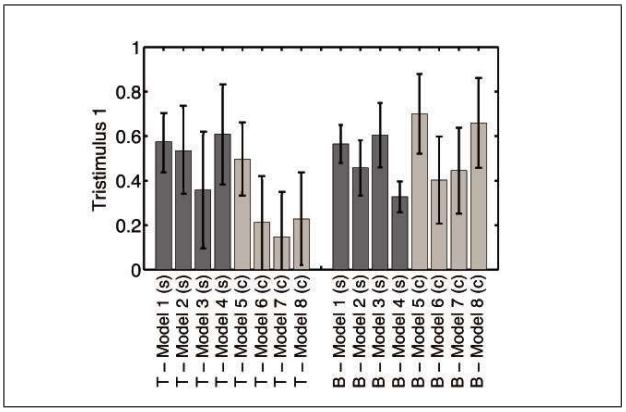


Figure 17. Tristimulus 1 (means and 95% confidence intervals) as a function of the reed model for tenor (T) and bass (B) drones. Models 1 to 4 are synthetic (s), models 5 to 8 are cane (c).

4.3. Tristimulus 3

The Tristimulus 3 index was defined as

$$TRI3 = \frac{\sum_{h=5}^{H} A(h)}{\sum_{h=1}^{H} A(h)}, \quad (3)$$

where $A(h)$ is the Power Spectral Density (PSD) of harmonic number h (computed over the whole 8 s signal: a B flat played by a tenor or a bass drone) and H is the total number of harmonics. Thus, Tristimulus 3 indicates the importance of the higher-order ($h \geq 5$) harmonics.

The Multiple ANOVA 1 indicated that for tenor drones, this index was significantly higher for cane reeds than for synthetic reeds. On the contrary, for bass drones, the Tristimulus 3 index was significantly higher for synthetic reeds than for cane reeds (see Figure 18).

A significant effect of the reed model on the Tristimulus 3 index was revealed (both for tenor and bass drones) by the Multiple ANOVA 2. However, about the tenor drone, no significant difference could be observed when reed models were compared by pairs by using Bonferroni's post-hoc test (see Figure 19). About the bass drone, the Tristimulus 3 index of reed model 4 was significantly higher than the ones of models 2, 3, 5, 6, 7 and 8 ($p = 0.032$ for the least significant case according to Bonferonni's post-hoc test).

No effect nor interaction with instrument/player was given by Multiple ANOVA 1 and 2.

To summarize:

- The spectral centroid appeared to be higher for drones equipped with cane reeds than for drones equipped with synthetic reeds, both for tenor and bass drones. The differences between reed models were in agreement with this statement.
- The effects on the Tristimulus 1 index (relative to the importance of the fondamental frequency) were different depending on the drone and the instrument/player: about the tenor drone, this index was higher for synthetic reeds than for cane reeds, but only for bagpipe/player 1. On the contrary, about the bass drone, this index was higher for cane reeds than for synthetic reeds, but only for bagpipe/player 2.
- The effects on the Tristimulus 3 index (relative to the importance of the 5^{th} and higher harmonics) were different depending on the drone: about tenor drones, this

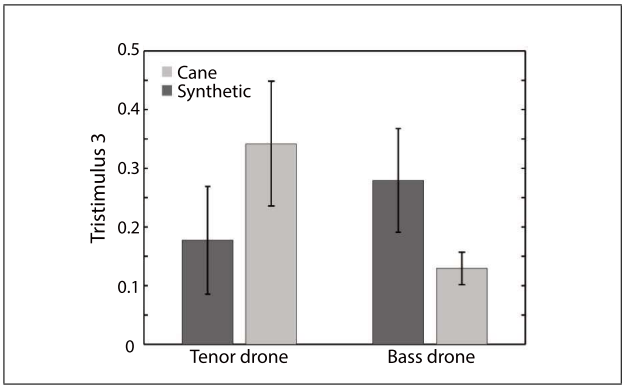


Figure 18. Tristimulus 3 (means and 95% confidence intervals) as a function of the reed material for tenor and bass drones.

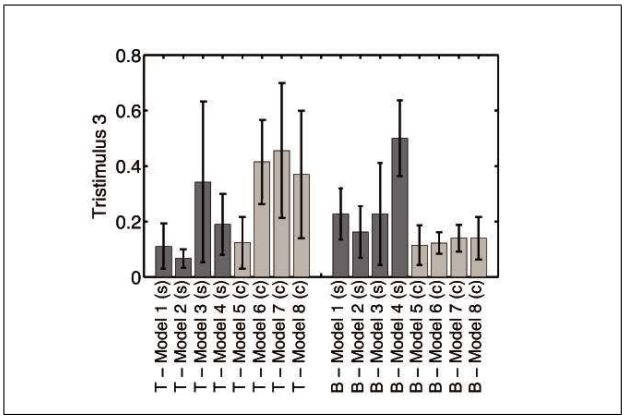


Figure 19. Tristimulus 3 (means and 95% confidence intervals) as a function of the reed model for tenor (T) and bass (B) drones. Models 1 to 4 are synthetic (s), models 5 to 8 are cane (c).

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index was higher for cane reeds than for synthetic reeds. On the contrary, about bass drones, this index was higher for synthetic reeds than for cane reeds.

For tenor drones, these three parameters are in agreement and show that the cane reeds globally provide more energy in high frequency than synthetic reeds. For the bass drones, the agreement between spectral centroid and Tristimulus indexes is less obvious. The differences observed in the material effects between tenor and bass drones for Tristimulus 1 and 3 indexes indicates that the acoustic behavior as a function of the reed is not identical between the two drones. The dimensions of the bass drone are larger than the ones of the tenor drone, the dimensions of tenor and bass reeds are also different, and so the mechanical effect of reed material cannot be generalized.

5. Correlation between perceptual results and signal parameters

The correlations between *global quality* and signal parameters (respectively for tenor and bass drones) were observed. For tenor drone, the global quality was correlated with Tristimulus 1 ($r(32) = 0.72$) and inversely correlated with Tristimulus 3 ($r(32) = -0.81$). The correlation with other parameters was inferior to 0.7. No correlation superior to 0.7 was observed between *global quality* and signal parameters for bass drone. Correlations between *global quality* obtained in the full set test and signal analyses for tenor and bass drones were also computed but were always inferior to 0.7. The representation of spectral centroid, Tristimulus 1 and 3 as additional variables on the plane of the two principal components found for the full set test (Figure 10a) confirms the very low correlation between these parameters and the perceptual attributes in the full set test.

To summarize:

- Correlations showed, about tenor drones, that listeners appreciated sounds having a fundamental frequency with a large magnitude, and less energy for higher harmonics. The analysis of the material influence on these parameters (respectively Tristimulus 1 and 3) indicates that synthetic reeds should be preferred by listeners. This can indeed be observed on Figure 3 even though no significant effect was revealed by the ANOVA.
- The spectral centroid appeared to be dependent on the material (for both tenor and bass drones), but its influence on sound quality seemed low.

6. Conclusion

The reed material appeared to be without significant effect on the *global quality* of drone sound, when the tenor drone was played alone (tenor drone test), when the bass drone was played alone (bass drone test), and when the two tenor drones and the bass drone were played with the chanter (full set test). However, independently of the material, some reeds were preferred to some other ones, both in the full set test and in the tenor drone test.

The reed material appeared also to be without significant effect on the other assessed perceptual attributes (*warmth*, *clarity*, *aggressiveness*, *volume* and *immersion*). *Global quality* was well correlated with *warmth* and *immersion* and to a lesser extent with *aggressiveness* (negatively). *Global quality* was also correlated with *Clarity*, but mainly in the full set test.

The spectral centroid was significantly higher for drones equipped with cane reeds than for drones equipped with synthetic reeds, both for tenor and bass drones. However its influence on perceived sound quality seemed low.

For tenor drones, cane reeds led to more energy for higher harmonics (Tristimulus 3) than synthetic reeds. For bass drones, the opposite effect was observed. Moreover, for tenor drone only, cane reeds led to a less energetic fundamental frequency (Tristimulus 1) than synthetic reeds. The only correlation between subjective quality and signal parameters was obtained for tenor drone: listeners appreciated drone sounds with a fundamental frequency with large magnitude, and less energy for higher harmonics.

The perceptual effect of the reed material (even about other instruments) was not investigated by previous studies. According to reed manufacturers, the reduced sensitivity to moisture and warmth of synthetic reeds solves tuning instability. About the players' opinions, some of them choose the synthetic reeds because of the tuning stability and longevity, and some other ones prefer the cane reeds because of the timbre they provide (the timbre quality is generally reported as being related to *warmth*, *clarity*, *immersion*, *volume* and *aggressiveness*). But according to the results of this study, *volume* is not consistent with the *global quality* and *aggressiveness* is only slightly correlated. Moreover, the reed material appeared without significant effect on all these perceptual attributes (so the cane reeds would not provide warmer or more immersive sounds as was claimed by some bagpipers). According to the perceptual results, the reed model is more influential that the material itself, however this statement was not confirmed by signal analyses on single drone recordings. The correlations between single drones and full set appreciations was very low. The sound quality of the drones in full set condition was possibly given by a combination of the drones and chanter sounds rather than to the drones themselves (even if listeners were explicitly told that only the drones sounds had to be assessed and not the chanter).

In this study the reeds were new (only played for several hours). It could be interesting to reproduce the perceptual tests and signal analyses with more aged reeds, in order to confirm the degradation of the timbral properties of cane reeds over time. It could also be of interest to study the relationship between the perceived quality and the mechanical characteristics (density, elasticity, etc.) of different reed models.

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