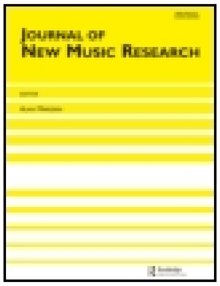

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A Comparative Study of Saxophone Multiphonics: Musical, Psychophysical and Spectral Analysis

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A Comparative Study of Saxophone Multiphonics: Musical, Psychophysical and Spectral Analysis

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Abstract

Despite a number of recent studies on the production of multiphonics in woodwinds, an exhaustive study on the perception of these sonorities is still missing. In this work we undertake a comparative study of saxophone multiphonics from the musical, perceptual and acoustical points of view. We propose four major classes based on the analysis of the musical attributes and playing techniques of a set of 118 alto saxophone multiphonics, spanning all the possible sonorities previously reported. Then, we perform a dissimilarity rating experiment for all possible pairs of a subset of fifteen representative multiphonics. This experiment provides confidence in the suggested classification, since the four classes are segregated in a Multidimensional Scaling (MDS) representation. We also find two possible acoustical correlates of the perceptual dimensions: the spectral centroid (SC) and the modulation frequency (MF). Finally, this last representation is explored through morphing trajectories, which correspond to multiphonics that change the timbre and musical interval organization with fixed fingering.

Keywords: timbre perception, saxophone multiphonics, dissimilarity ratings, acoustic features, musical notation

1. Introduction

The development of extended techniques for traditional musical instruments contributed not only to enlarge the timbre variety but also to change the musical discourse during the second half of the past century. In this context, the appearance of multiphonics in woodwinds renewed the existing repertoire for these instruments, stimulating the interest of composers and performers for this new kind of sonority (Bartolozzi, 1967).

Multiphonics consist of the production of several notes at once by otherwise monophonic instruments. Their production in woodwinds requires a specific technical study on fingerings and embouchure.

For the more restricted case of the saxophone, two of the earliest musical examples that we could find appear in *Coltrane Jazz* by John Coltrane recorded in 1959, and in the *Sonate for alto saxophone and piano* by Edison Denisov, published in 1970. Among the main works that studied the performing aspects of the saxophone multiphonic tones we can find *Les sons multiples aux saxophones* by Daniel Kientzy (1982) and *Hello Mr. Sax!* by Jean-Marie Londeix (1989). These works presented a catalogue of the possible multiphonic tones in the seven members of the saxophone family, addressing the fingering, pitch, trill possibilities, and variables of the dynamics. They have been indispensables for the development of several musical pieces and are responsible for the interest that these sonorities generated during the last 30 years. However, these studies, and a more recent one focused on playing techniques (Weiss & Netti, 2010), do not address the more problematic aspects of the multiphonic tones, such as their dynamical nature and their complex timbric attributes. Another of the common problems associated with multiphonic tones lies in their musical notation. Some recent works addressed this issue including, for example, the parameters of the modulation frequency in the notation (Gottfried, 2008).

The multiphonics tones are characterized by having more than one recognizable pitch due to the particular control of the fingering, embouchure and blowing pressure that creates new resonances within the bore. In this way they are similar to chords but with several differences

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regarding the tuning of the notes and the timbre, as they are in most cases inharmonic sounds. The bore resonances arise because of special fingerings that modify the effective length of the bore depending on the combination of open and closed holes. In turn, the tuning and timbre are controlled by means of the embouchure, the vocal tract and the blowing pressure (Chen, Smith, & Wolfe, 2011; Scavone, Lefebvre, & da Silva, 2008).

However, there are some phenomena that are common to all saxophone multiphonics. The frequencies of the oscillations induced by the resonance are subject to inter-modulation distortion due to the nonlinearity in the reed (Benade, 1990). As the blowing pressure is increased, this distortion creates new frequencies (products) and alters substantially the timbre of the sound. Finally, there are certain regimes where the acoustic system behaves chaotically (Keefe & Laden, 1991), adding more particularities to the timbre. These phenomena show that the addition of new frequencies has several effects on the quality of the sound. Moreover, many control parameters such as blowing intensity and vocal configurations could be modified continuously, giving a continuous range of multiphonics.

Compared to acoustical studies, the psychophysics of multiphonic perception has received much less attention, and a complete picture of how these multiple sonorities are organized is still missing.

In addition, multiphonics constitutes an interesting starting point for the study of musical timbre. The classical studies on timbre perception were focused on traditional instruments and traditional techniques with harmonic sounds (Caclin, McAdams, Smith, & Winsberg, 2005; Grey, 1977). The study of the perception of saxophone multiphonics could bring a new perspective on timbre organization.

In order to illustrate the diversity of these sounds we display in Figure 1 four examples of saxophone multiphonic power spectra. The main differences observed are related to the distribution of the spectral energy and the partial frequencies. The partial frequencies are organized into clusters of principal peaks and flanking side-bands. The number of clusters, their width and location depend on the fingering and the blowing intensity (Backus, 1978). The solid vertical lines in the graph indicate the two principal frequencies (the two main pitches that are actually perceived), the dotted line corresponds to the spectral centroid (SC) and the dark horizontal line measures the spacing of the sidebands.

These examples correspond to the four classes of multiphonic sounds described in the next section, where we will analyse a large set of tone samples from a musical perspective. Our aim is to advance in a possible classification scheme for the saxophone multiphonics that eventually could be extended to other woodwind instruments. For this purpose, we will also perform a dissimilarity rating psychophysical test and evaluate possible acoustical correlates of the perceptual dimensions obtained in the experiment.

2. Musical analysis: A possible classification

There are some problems that usually arise when dealing with multiphonics that were disregarded in previous studies: (a) the same fingering could produce more than one multiphonic with very different sonorities; (b) fingerings are usually not efficient in the same way for different saxophonists and saxophones; (c) the whole set of multiphonics span a wide range of different sonorities; (d) the

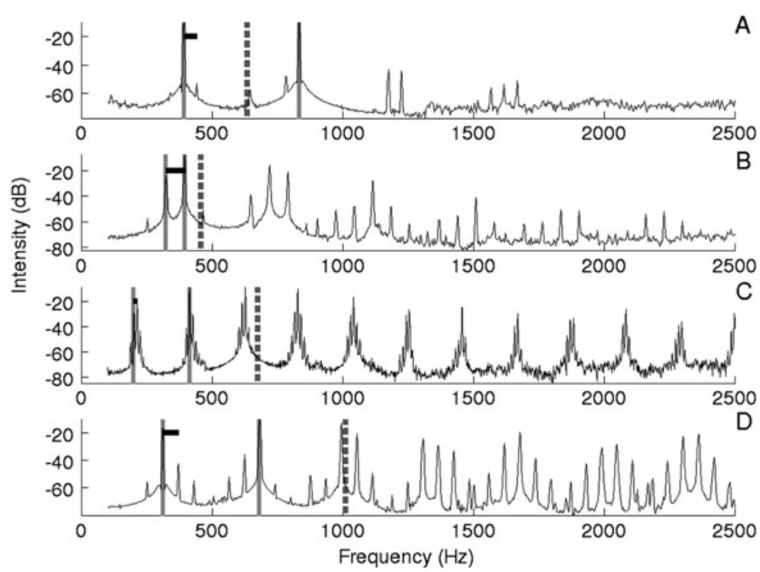

Fig. 1. Four power spectrums of alto saxophone multiphonics. The solid vertical lines indicate the two principal frequencies; the dotted line indicates the spectral centroid and the dark horizontal line corresponds to the distance between sidebands (and to the modulation frequency). Each multiphonic belongs to one of the four proposed classes: (A) *Multiharmonic*, (B) *Bichord*, (C) *Tremolo* and (D) *Complex Multiphonic*.

usual musical notation is not well adapted to multiphonics; and (e) unlike conventional saxophone tones, they behave as dynamical structures, being able to pass through different sonorities.

We propose a classification scheme for the multiphonic tones taking into account these characteristics from the musical perspective.

2.1. Procedure

Due to the vast number of possible multiphonic tones within the seven members of the saxophone family, we decided to circumscribe the study to a set of 118 tones of the alto saxophone, spanning all the possible sonorities previously reported for this family member.

To analyse these tones from a musical point of view we used two concepts introduced by Pierre Schaeffer, which are closely related: 'reduced listening' and 'sound object'. The 'reduced listening' consists of listening to the sound in a context-independent manner and for its own sake, by removing its real or supposed source, the precedence, the environment and the meaning it may convey. The concept of 'sound object refers to every sound phenomenon and event perceived as a whole, a coherent entity, and heard by means of reduced listening, which targets it for itself, independently of its origin or its meaning' (Chion, 1983).

Also, Schaeffer proposed a typology for the sound objects meant to be used in composition and analysis of electroacoustic music (Schaeffer, 1966) and based on 'morphological criteria', which are defined as the distinctive features or properties of the perceived sound objects that allows identifying them (Chion, 1983).

For our multiphonics musical analysis we select three features from Schaeffer' criteria that are intimately related: *grain, quality of surface* and *iteration*. The grain could be defined as the microstructure of the matter of sound, that can be more fine or coarse and which evokes by analogy the tactile texture of a cloth or a mineral, or the visible grain in a photograph or a surface. Schaeffer defined three types of grain characterized by the sustainment of a sound: *resonance grain,* for sounds without sustainment but that are prolonged by resonance (e.g. the rapid tingling of a resonating cymbal); *rubbing grain,* for maintained sounds, often caused by the rasping of breath of the sustaining agent (bow, or breath in a flute sound); *iteration grain* for iterative sustainment (e.g. drum roll) (Chion, 1983). Once having defined the grain type, we could define the quality of surface of a sound object as the relation within the type of the grain and its evolution, considering that the quality of surface of a sound would be smoother or rougher depending of the type of grain and its evolution. For example, we could say that the quality of surface of the sound of a soprano clarinet playing the low register is smoother than a drum roll, or that the quality of surface of the sound of the oboe is rougher than the flute. At last, the idea of iteration is closely related to the type and size of the grain of a sound object. The relation between the size and the velocity in which appears the subsequent grains is what we could perceive as 'iteration' of a certain sound object. For example: in a drum roll every hit on the drum is perceived as one grain, but in a very fast and *pp* roll we could not listen to a particularly hit even when we perceive an iteration grain; on the other side, a very slow and *ff* roll would be perceive as more 'iterative', with a slow iteration, somewhat similar to that which happens with the sound of the engine of a truck.

The type and the size of grain, which add to the different velocities of iteration, are two of the most important cues we utilized for the musical analysis. These cues added to other more frequented musical terms such as intensity, musical interval, tessitura and consonance/dissonance, made it possible to present a musical classification for saxophone multiphonics based on their sonority. This classification has been partially presented in previous works (Proscia, 2011; Proscia, Riera, & Eguía, 2011).

Complementing this approximation, we include also the concept of 'spectromorphology', developed by Denis Smalley, which is focused on the two aspects referred by the term: 'the interaction between sound spectra (spectro-) and the ways they change and are shaped through time (-morphology)' (Smalley, 1986).

2.2. Recordings

A database of 118 multiphonic tones was obtained from recordings of a Selmer Super action 80 Serie III alto saxophone tuned at A = 440 Hz, with a Selmer Serie 80 C* mouthpiece and Vandorem 3½ reeds. The recordings were made using an acoustical measurement microphone (DBX TRA-M) and a Focusrite Sapphire external soundcard at a sampling rate of 48 kHz with a resolution of 24 bits. The multiphonics were selected and performed by one of the authors (MP). The samples were recorded in a room with sound isolation and acoustic treatment (noise floor 19 dBA, teverberation time T60 @ 1 kHz 0.3 s). These recordings are available at http://www.lapso.org/multiphonics.html.

2.3. Results

The different sonorities from the database were classified into four multiphonic classes, named as: *Bichords, Complex Multiphonics, Multiharmonics, Tremolos.* In Figure 2 we display several examples for these classes using musical notation.

A summary of the main characteristics for each class is displayed in Table 1. A more detailed description follows.

Bichords. The most prominent feature of this class is the first musical interval, which could be a major, minor or a diminished third (as it is shown in Figure 2(a)), perfectly distinguishable due to their very stable sonority. Regarding the performance characteristics, the intonation required for the production of the *Bichords* is quite similar to the

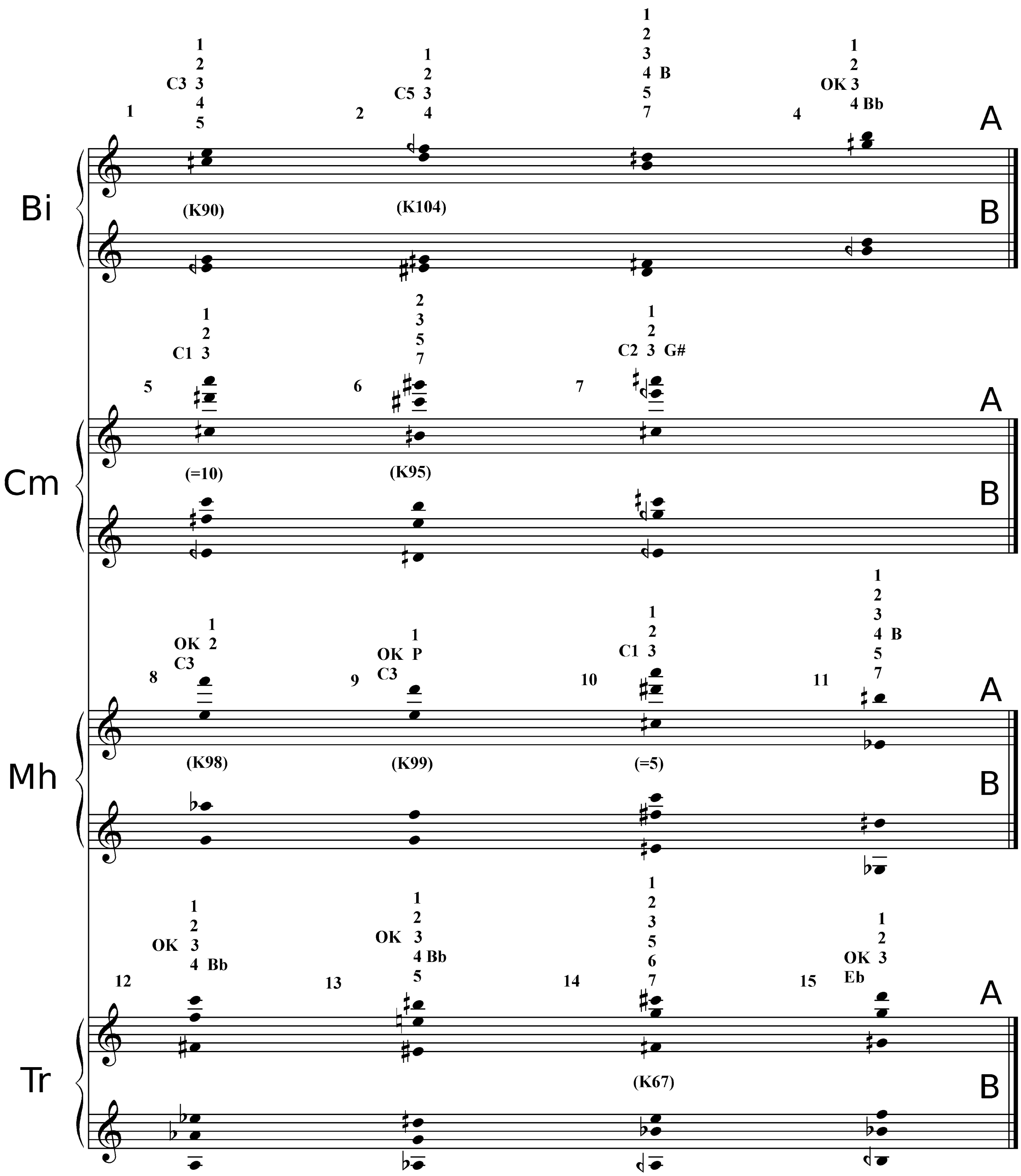

Fig. 2. Musical notation for examples of the four proposed multiphonic classes, one row for each class: (Bi) four multiphonics with a Bichords sonority, (Mh) four multiphonics with a Multiharmonic sonority, (Cm) three multiphonics with a Complex Multiphonics sonority, and (Tr) four multiphonics with a Tremolo sonority. Staff A: Alto saxophone in Eb. Staff B: Concert C. The multiphonics that are indicated with (K*) refer to the number of the corresponding fingering in Kientzy's catalogue (Kientzy, 1982). Multiphonics 5 and 10 are produced with the same fingering.

simple tones. The possible dynamics are between ***pp*** and ***mf***. This sonority resists a wide range of different articulations preferably not too aggressive, with a highlight on the possibility of make almost perfect *legatos* with simple or multiphonic tones. Their quality of surface is mostly velvety.

Table 1. Summary of the main characteristics of the four classes proposed from the musical point of view, as a possible classification of multiphonic tones of the alto saxophone: bichords, complex multiphonics, multiharmonics, and tremolos.

	Bichords	**Complex multiphonics**	**Multiharmonics**	**Tremolos**
Sound production	stable	relatively stable	unstable	relatively unstable production
Possibilities of evolution:	moderate	moderate	moderate - low	moderate—high
Harmonics emphasis	middle harmonics	high harmonics	lower harmonics, no high harmonics	equally distributed
Dynamics	***pp* < *mf***	***mf* < *ff***	***ppp* < *mp***	***mp* < *f***
First musical interval	3rd	9th	7th	8th (slightly detuned) and 9th
Tessitura aprox. (in C concert)	D4 - D5	D4 - C6	Gb3 - D6	Ab3 - F5
Consonance / dissonance	consonant	dissonant	consonant	relatively consonant
Quality of surface	velvety	rough, iterative and compact mechanical grain	smooth surface, the first harmonics are clearly heard	beats, velocity related to the tuning of the 8th

Complex multiphonics. The principal attribute of the *Complex multiphonics* is that they present a strongly inharmonic spectrum with a strident sonority and a complex intervallic construction. Their production is relatively stable, yet with almost no possibilities of evolution. Their dynamical range extends between ***mf*** and ***ff*** and they do not resist soft articulations, responding very well with *staccato, slap* and other aggressive articulation. This group presents a rough quality of surface, with and iterative and compact mechanical grain.

Multiharmonics. A common characteristic in the two previous sonorities is that they present different types and velocities of iteration, with different timbres and sizes of internal grain. The *Multiharmonics,* in turn, present a considerably smooth surface without stridencies. Their dynamics extend between ***ppp*** and ***mp***. This sonority is quite similar to those which result of playing harmonics on string instruments. Regarding the performance characteristics this is the most difficult and unstable sonority. They do not resist large dynamic variations or aggressive articulations. *Multiharmonics* usually present two simultaneous notes that are perceived as if they were produced by two saxophones simultaneously. The most significant timbric change occurs with the appearance of a third pitch, which can be produced in some case as a result of increasing the pressure of the blow. Even when there is a change in the global pitch and the musical interval, a substantial modification of the surface (to a less smooth quality) is also apparent.

Tremolos. The most outstanding characteristic of the *Tremolos* is the beating integrated to the sound. This iteration–quite similar to the *frullato* in the woodwinds or *tremolo* in the strings—is related to the mistuning of the 8th, which is the first interval. The velocity and even the timbre of the internal grain could be easily modified by changing the intonation and the velocity of the air in the vocal tract, which turns the *Tremolos* into the most flexible sonority from those which we present here. Their production is quite simple and they resist dynamics from ***mp*** to ***f***.

From the musical perspective of the analysis, we may release some topics related to this preliminary classification. First, concerning the notes and dynamical range, each group we propose is delimited to a specific note range of the saxophone, presents a characteristic musical interval arrangement, and is circumscribed to a certain dynamic range. From the point of view of the performer, they also present a distinctive intonation, position of the vocal tract and embouchure. Regarding the timbre, each class presents a particular quality of surface, which is determined by the size and type of the internal grain of the sound. Hence, we could say that each of the sonorities proposed here is well characterized and clearly delimited from each other. This let us propose the four classes (*Bichords*, *Complex Multiphonics*, *Multiharmonics* and *Tremolos*) as a possible classification for the alto saxophone multiphonic tones.

The full set of 118 multiphonics was then divided into 21 Bichords, 39 Complex Multiphonics, 34 Multiharmonics and 24 Tremolos. It is worth noting that, despite the fact that the four classes are well defined, there is a small number of multiphonics that does not fit perfectly into any group. These ‘hybrid’ sonorities could be considered lying in the borderline between classes.

3. Pair comparison psychoacoustic experiment

We will now continue our study by centring just on the timbre of multiphonics, and making some quantitative analysis. Timbre is a complex attribute of sound, which is naturally multidimensional (Donnadieu, 2007). For the case of multiphonics, timbre is similar to those of inharmonic tones, but with the constraints given by the instrument and the playing techniques. In this section, we explore the timbre of stationary multiphonics sounds through a psychophysical experiment.

A psychoacoustic experiment was designed in order to evaluate a possible organization of the multiphonic tones, and eventually build confidence on the classification scheme detailed in the previous section.

This experiment was done adopting a pairwise comparison protocol for similarity/dissimilarity rating, in a similar fashion to Grey (1977). In this experiment subjects were asked to judge the timbric similarity/dissimilarity between a pair of sounds using a numeric scale. These results were analysed using multidimensional scaling (MDS), which serves to represent the dissimilarity (perceptual distance) with a geometric configuration.

3.1. Experiment details

Stimuli. We selected 15 samples out from the set of 118 recorded multiphonic tones. They were representative of the four classes proposed and they were selected to show different nuances and fundamental frequencies (four *Bichords*, four *Multiharmonics*, four *Tremolos* and three *Complex* tones). The samples were edited selecting an interval of three seconds of duration as stationary as possible. Their intensity was not normalized because different tones had different noise components and we wanted to preserve the characteristics of a realistic listening as much as possible. Nevertheless, the level was adjusted to restrict the range of intensities from 62 to 71 dBA SPL (at the listeners' ears). This intensity issue was taken into account inserting some catch trials that will be detailed later.

Participants. Five subjects participated in the experiment, aged between 25 and 35 years old. All of them were recruited on a volunteer basis from the career of Electroacoustic Composition at the University of Quilmes and gave written consent for participating in the experiment. Subjects were not aware of the classification proposed, self-reported that they had no hearing disorder and have training in the field of contemporary electroacoustic music.

Procedure. As a warm-up, subjects were first presented with the 15 stimuli in order to get a glimpse of the variety of sounds. Next, they were presented with six training pairs (that were discarded later) and then with the whole shuffled set of 225 pairs, plus 23 catch trials. The similarity between sounds was evaluated with a 5 point scale in Spanish: 1 'nada similares', 2 'poco similares', 3 'algo similares', 4 'muy similares', 5 'practicamente iguales' (possible translation 1 'not similar', 2 'barely similar', 3 'some similarity', 4 'pretty similar', 5 'almost equal'). As the recordings were not normalized in intensity we include some catch trials with different intensities to test if the listener was influenced by this cue (8% of all trials).

The experiment was carried out with MATLAB using the playrec library, on a Mac Mini and a Focusrite Saffire as interface. The stimuli were delivered through calibrated open headphones (Sennheiser HD 600) in the same room used for the recordings.

3.2. Results

Starting from the recorded answers, a dissimilarity matrix was built for each subject, and some statistical tests were performed (Grey, 1977). First, as only five subjects participated in the experiment, we tested whether the responses correlate with each other in order to ensure that meaningful results could be obtained from means across subjects. This was the case, as the smaller correlation coefficient obtained was 0.77. Next, we analysed the catch trials and found no significant deviations from the zero mean (t-test, p = 0.606), indicating that the answers were not affected substantially by changes in the intensity. To see whether if the answers were influenced by the order of presentation of the stimulus we computed a t-test across all subjects for the presentation order as a possible source of systematic bias. We find significant biases ($p < 0.05$) for only in four pairs out of 225. A further analysis of these four cases showed that these correspond to tones that are more easily concatenated in one direction than the reverse, due to the dynamical features of the multiphonics involved. In the following, we disregard these particular cases of asymmetry and performed a symmetrization in the presentation order as a previous step to the multidimensional scaling analysis. In order to use MDS with matrices coming from answers given by different subjects we adopted an individual difference scaling method, INDSCAL (Carroll & Chang, 1970). This tool allows an arbitrary number of dimensions for representing the data. We computed two- and three-dimensional representations of MDS (2D configuration stress = 0.186, 3D configuration stress = 0.129). In the present work we will mainly focus on the 2D

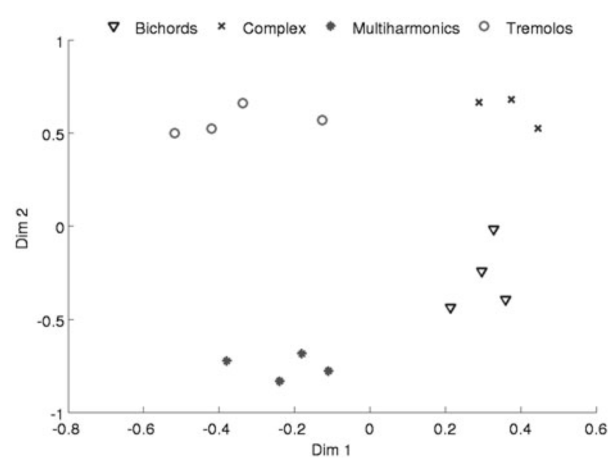

Fig. 3. The INDSCAL configuration obtained for the fifteen multiphonic tones used in the experiment. Markers indicate the multpihonic class: triangles are used for the *Bichords*, stars for *Multiharmonics*, circles for *Tremolos* and crosses for *Complex Multiphonics*. Each group remains clustered in a 2D representation of perceptual dissimilarities.

representation since this is informative enough for segregating the different classes proposed. Henceforth, each multiphonic sample was assigned to a point in a two-dimensional space with a metric that tries to satisfy the perceptual distances judged by the subjects. The results are displayed in Figure 3, using a different marker for each multiphonic class: triangles for the *Bichords*, stars for *Multiharmonics*, circles for *Tremolos* and crosses for *Complex Multiphonics*. The first thing to note is that the grouping of the classes is well preserved. This could indicate that the subjects judged more similar the tones that belonged to the same class. At the same time, the spatial arrangement of the points shows possible interrelations between classes. We can see, for example, that the *Bichords* class lies in between the *Multiharmonics* and the *Complex* class, and that this group is aligned horizontally with the *Tremolos* group.

4. Exploring the multiphonics spectra

One major drawback of the results provided by the MDS analysis of the previous section is the lack of an acoustical interpretation. In this section we will explore the spectral characteristics that are more related to the parameters involved in the multiphonic production. In this way we would be able to give a more complete description of the proposed classification and establish possible correspondences with the perceptual space.

Our choice of spectral characteristics is not mean to be general (or universal) nor exhaustive. We choose the features that could be related to the multiphonic production through a simplified model based on FM tones.

From the multiphonic spectra displayed in Figure 1, it could be noted that the organization of the frequency components is very similar to that found in frequency modulated (FM) synthetic tones. In fact, by means of FM synthesis it is possible to obtain inharmonic tones and modulations very similar to those performed by saxophone players. This frequency organization shows clusters of partials bearing some principal frequencies and side-bands (that are the product of the nonlinear inter-modulation). Regarding the playing techniques, the principal frequency components are related to the bore-vocal tract resonances and its harmonics; and therefore controlled by the fingering and the vocal tract configuration. In turn, the intensity of the side-bands or the inter-modulations depth is related to the blowing pressure. Concerning the perception of timbre, the principal frequencies could be associated with the perceived pitches and musical intervals, while the side-bands' organization could contribute both to the brightness of the sound and the temporal modulations (beating frequency or the size of the internal grain).

We therefore selected four spectral features motivated by the simplified FM modelling, timbric attributes and the playing techniques described before:

(1) Spectral centroid (SC)
(2) Modulation frequencies (MF)
(3) Principal frequencies F1 and F2
(4) Musical interval (MI) in semitones between F1 and F2.

(1) The spectral centroid (SC) (Beauchamp, 1982; Schubert & Wolfe, 2006) is a magnitude related to the brightness of a sound and it is often used as a key parameter for timbre classification. It was computed as the normalized mean of the power spectrum $SC = \sum_n f_n P_n / \sum_n P_n$, where f_n is the frequency of the signal and P_n its power spectrum. (2) The modulation frequency (MF) is a relevant attribute since it corresponds, if slow enough, to the beating frequency and, in a more general perspective, to the size of the internal grain of the sound. This MF was measured as the frequency distance between side-band components, computing the autocorrelation of the power spectrum and finding the highest peak. (3) The frequencies F1 and F2 were selected to correspond as much as possible to the notes perceived in the multiphonic. The F1 was selected by taking the lowest frequency from a set of the highest spectral peaks. Then, the F2 was selected by taking the next peak in height and frequency that was neither a harmonic of F1 nor a side-band of F1. (4) The musical interval was computed through: $MI = 12\log_2(F_2/F_1)$.

Figure 4 shows the summary of these magnitudes for the whole set of 118 multiphonics, and for the four classes proposed. The box plots show that some parameters can be used to segregate some classes. For example the MI is well suited to discriminate the *Bichords,* as the MF does for the *Tremolos*.

In order to determine which parameters discriminate between which classes we perform a one-way ANOVA test with a post hoc Tukey HSD multi-comparison procedure. The null hypothesis was rejected for all parameters with a highly significant ($p < 0.01$) value for SC, MF and MI. For SC the post hoc test showed that *Complex Multiphonics* and *Tremolos* are significantly different from each other and form the other two classes. However *Bichords* and *Multiharmonics* cannot be segregated using this parameter. *Bichords* are significantly different from the other three classes along the MI parameter. For the MF parameter the only class that displays significant differences with the others is the *Tremolo*.

In the following figures, we display the set of multiphonics in two-dimensional plots using the different features that we selected as coordinates. *Bichords*, *Complex Multiphonics*, *Multiharmonics* and *Tremolos* are represented by triangles, crosses, stars and circles respectively. From these two-dimensional representations we can evaluate possible acoustical correlates of the sensory dimensions of Figure 3.

In Figure 5 we display SC versus MI. We can observe that within this representation some of the classes proposed are segregated. This is an expected result for the *Bichords*

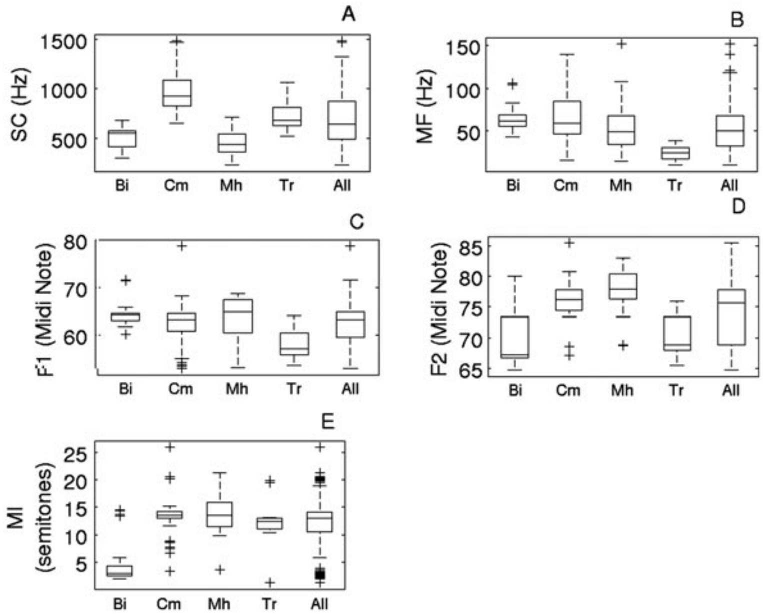

Fig. 4. Boxplots of the selected spectral multiphonic features for each class (Bi=Bichord, Cm=Complex multiphonics, Mh=Multiharmonics, Tr=Tremolos) and the whole set (All). A) spectral centroid (SC); B) Modulation Frequency MF; C) First principal frequency F1; D) Second principal frequency F2; E) Musical interval MI between F1 and F2.

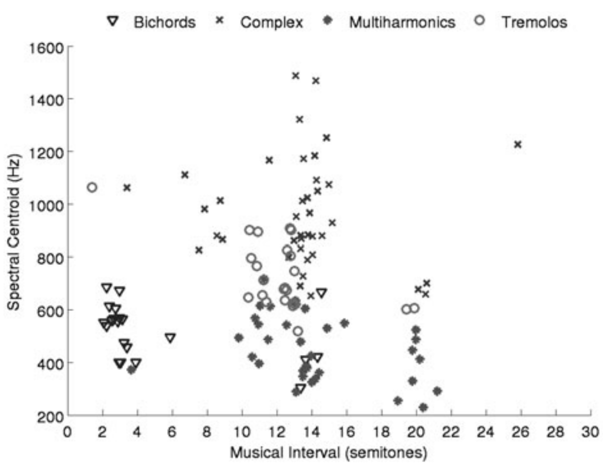

Fig. 5. Spectral centroid (SC) versus Musical Interval (MI). This representation shows that these features serve to segregate the *Bichords* class, as there are mainly major or minor thirds. SC segregates Complex, Multiharmonics and Tremolos.

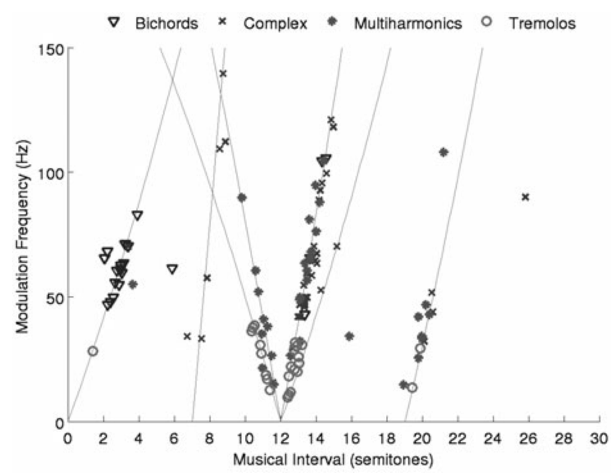

Fig. 6. Modulation Frequency versus Musical Interval. This representation shows that there is a strong ordering related to the intermodulation between the frequencies in the multiphonic.

(triangles), since they were defined with the musical interval in mind. Also note that most of *Tremolos* (circles) show a MI of a mistuned octave, in accordance with their slow-beating characteristic.

In Figure 6 we show a plot of MF versus MI, where an organization related to the interaction between MF and MI can be clearly seen. For example, if a multiphonic is made from a mistuned octave it will show slow beats, and if this mistuning is enlarged the beat frequency will rise up, giving origin to 'V' patterns. These patterns were adjusted using the expression MF = $mF_1 + nF_2$ (with F_1 constant, F_2 variable and n and m small integers, for example the leftmost line in this figure correspond to the MF = F_2—F_1 curve, for a representative F_1 of 337 Hz and F_2 starting at F_1).

In Figure 7 we show the results for SC versus MF. The main result of this representation is that the four classes are spatially segregated, occupying different locations. The SC is the feature that is more discriminatory between classes, and is related to the intensity of the blowing and to the

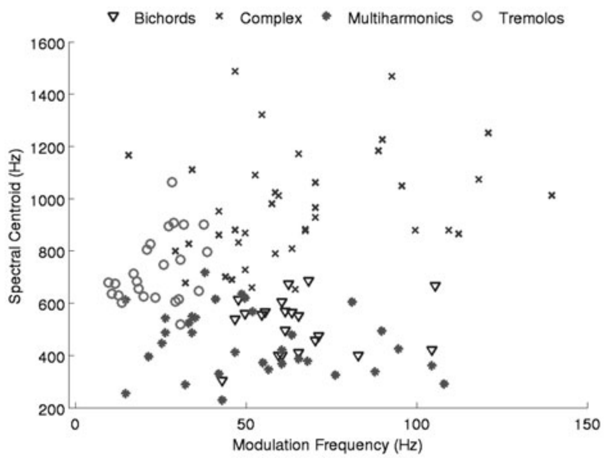

Fig. 7. Spectral centroid versus Modulation Frequency. Using this representation it is possible to assign distinct regions to each class of multiphonics. It also correlates with the results of the multidimensional scaling configuration from the psychoacoustics experiment (Figure 2).

level of distortion present. Along this dimension it can be observed that the *Multiharmonics* are the softer sounds, the *Bichords* occupy an intermediary region and that the *Complex Multiphonics* and the *Tremolos* are the brightest tones, requiring more blowing intensity. The other coordinate, MF, segregates the multiphonics based on their beat frequencies and periodic fluctuations. This last magnitude allows discrimination between *Complex Multiphonics* and *Bichords* on one side and *Tremolos* on the other.

This last representation seems to be the most suitable for comparing with the obtained MDS configuration (see Figure 3). Also, it will be useful to evaluate possible timbric transitions using the same fingering, by means of varying modulation frequency and brightness, as will be discussed in the next section.

From the last representation in terms of spectral feature coordinates SC and MF (see Figure 7) we may re-interpret the results of the MDS analysis of the psychoacoustic test. The experimental results showed that there are at least two perceptual dimensions that could have been used by the subjects for evaluating the dissimilarity between multiphonics. Even when the coordinates given by the MDS method have no intrinsic meaning, in some cases it is possible to assign some acoustical correlate to these dimensions. In order to investigate probable correspondences, we computed the correlation between the MDS coordinates and the acoustical features.

In Table 2 we display the obtained correlation coefficients for the two- and three-dimensional cases. The significant correlations ($p < 0.05$) are marked with a star. We first analyse the 2D case. The correlation coefficient between the MF and the first dimension of MDS (dim 1) was 0.664, and between the SC and the second dimension of MDS (dim 2) was 0.685. This suggests that both MF and SC could be relevant parameters to perform a

Table 2. Correlation coefficients between the INDSCAL dimensions of the multiphonics used in the experiment and the spectral attributes: (FM) frequency of modulation, (SC) spectral centroid, (F_1) first principal frequency (F_2), second principal frequency and (MI) musical interval between the principal frequencies. Significant correlations with tolerance of 0.05 are marked with a star.

	2D Dim1	2D Dim2	3D Dim1	3D Dim2	3D Dim3
FM	0.664 *	−0.351	0.775*	−0.203	−0.082
SC	0.382	0.685 *	−0.019	0.720*	0.543 *
F_1	0.622 *	−0.457	0.775 *	−0.285	−0.257
F_2	0.133	−0.253	0.530 *	−0.226	0.633 *
MI	−0.513	0.179	−0.260	0.036	0.896 *

multiphonic timbre classification and also good candidates for assigning a physical meaning to MDS dimensions. Also F_1 has high correlation with the first dimension because it also correlates with MF, maybe because the multiphonic production is constrained to some saxophone keys and embouchure configuration. For the 3D MDS there is still a prevalence of the first two dimensions, with the same correspondences as observed in the 2D case, and slightly higher correlation values. The third dimension appears to be more related to the MI and can be useful to allow a better segregation of the *Bichords* multiphonics.

5. Discussion

Having a space defined by acoustical parameters might be useful for several purposes. From the point of view of the classification scheme proposed, it assigns each group to a region that can be used *a posteriori* to classify other multiphonic tones. In Figure 8 we display the same data as in Figure 7, but adding shaded regions that cover the whole space. These regions were obtained using a naive Bayes

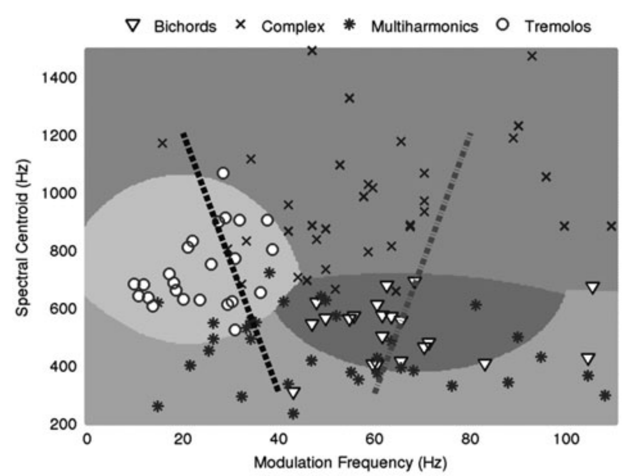

Fig. 8. Spectral centroid vs. Modulation Frequency. Figure 7 was used to train an automatic classification system that serves to represent the extent of the classes regions. Dotted lines dark and grey represent multiphonic trajectories in this timbric space.

classification, with the assumption of Gaussian distributed samples (MATLAB 'classify' function).

This partition of the SCG-MF space could be useful to gain some insight on the organization of the multiphonic tones and the allowed transitions between them. In fact, it implies the existence of intermediate regions between certain classes, and the possibility of producing 'hybrids' multiphonics, sharing some characteristics from the two neighbouring classes. Another remarkable consequence that arises from this partition is that some dynamical transitions between multiphonics are more easily achieved than others. For example, increasing the brightness of a *Multiharmonic* tone with high MF will lead to a transition to a *Complex Multiphonic*. This could be produced without changing the fingering but increasing the blow strength from *pp* to *ff* with a little relaxing of the embouchure pressure. As another example, a morphing between a *Multiharmonic* and a *Tremolo* would require slowing the modulation as the brightness is increased. In this case, it is necessary to slightly lower the tune of the low note and increase the velocity of the blowing. These dynamical transitions are of utmost importance from the musical point of view, since each multiphonic is considered as a dynamical structure capable of going through different sound stages, morphing its timbre and its intervallic structure with a fixed fingering. These multiphonic transitions can be produced by a saxophone player who has enough experience with multiphonics.

In order to illustrate the transitions between multiphonic classes, we present two morphing trajectories as examples. These trajectories are indicated by the dotted lines in Figure 8 and musically notated in Figures 9 and 10. (Recordings of these examples are available on http://www.lapso.org/multiphonics.html).

A remark on the musical notation of the saxophone multiphonic is in order at this point. Usually these sonorities are represented in the same way as a piano chord, denoting the intervallic structure of the multiphonic, the dynamics and the fingering for its production (Kientzy, 1982; Londeix, 1989). In a few cases some additional information is added, as comments about the position of the embouchure (Weiss & Netti, 2010) or even the carrier-modulator ratios (Gottfried, 2008).

When dealing with morphings between multiphonics it is useful to extend the notation with some additional complements. For example in Figure 9, we present a possible musical notation for the dark dotted line trajectory of figure 8, which represents a morphing between a *Multiharmonic* and a *Tremolo* (number 14 in Figure 2). We add a solid *crescendo* indication between the stages, in an attempt to address not only the increment in the dynamic but also the change in the quality of surface and the consonance. In terms of the axis of Figure 8, we may read it as increasing the distortion and the brightness as we move up, and slowing the modulation beats as we move to the left. This can be done without changing the fingering.

The second example (Figure 10) corresponds to a morphing between a *Multiharmonic* and a *Complex Multiphonic* (number 10 and 5 respectively from Figure 2). We start again from the lower region of Figure 8 but now we move up and right. This makes the modulation frequency higher, provoking a more compact sonority, and also raises the SC, making the sound harsher.

It is worth noting that the representation of Figure 8 is a projection of a higher dimensional timbric space. For example, since we are not including the MI dimension, the morphing between a *Multiharmonic* and a *Complex Multiphonic* move across a region of SC-MF space that is timbrically similar to that of the *Bichords*, even when there are no intervals of thirds in this transition. A more precise description of these trajectories in principle could be made

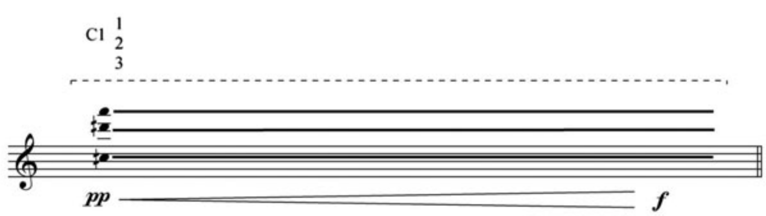

Fig. 9. Musical notation corresponding to a morphing between *Multiharmonics* and *Tremolos.* (Black dotted line in Figure 8.)

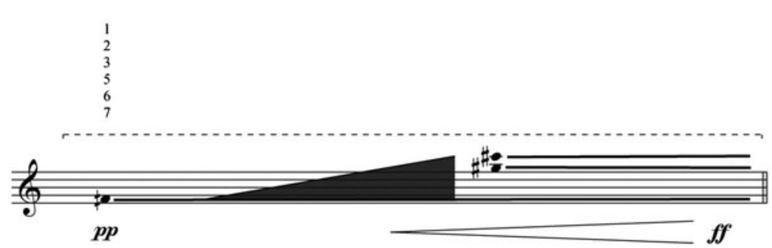

Fig. 10. Musical notation corresponding to a morphing between *Multiharmonics* and *Complex Multiphonics* (grey dotted line in Figure 8).

in a three-dimensional representation, but this also would make more difficult their visualization.

5. Summary and conclusions

Multiphonics are complex sound objects that might be described and studied from different disciplines or methodologies. In this work, we explored a large set of multiphonics of the alto saxophone from the musical, psychophysical and acoustical points of view. This allowed us to advance in a possible classification scheme for the multiphonics, taking into account their sound qualities, musical attributes and some of their acoustical characteristics.

The classification was initially proposed from the musical point of view, dividing the multiphonics into four classes according to their timbre, intensity, performing and modulation possibilities. This categorization was contrasted with a paired-comparison experiment, where the participants, who were not aware of the proposed classification, were asked to judge similarity/dissimilarity among multiphonic tones.

To complete the study we analysed the spectra of the multiphonics and found some acoustical features that were correlated with the proposed classification. We could observe that, due to the distortion present in the multiphonics when the pressure intensity is raised, the spectral centroid (SC) is modified and this consistently influences the timbre perception. Another relevant factor observed was the modulation frequency (MF). This parameter was useful to explain the heterogeneous sonorities of the multiphonics, regarding the internal grain of the sound. Finally these parameters were used to reinterpret the psychoacoustic results, as there is a significant correlation between them and the perceptual dimensions obtained from a MDS representation.

One last result that is valuable from the musical point of view is the possibility to represent morphings between different sonorities within the SC-MF acoustical parameter space. This opens a broad field of study on multiphonics, considered as dynamical structures, with numerous applications in musical composition.

As a final remark we would like to mention the possibility of extending the methodology presented in this work to the study of multiphonics for the other members of the saxophone family, or even for other woodwind instruments. The more restrictive aspect of our method probably is the choice of the spectral features, that was made based on a simplified FM model that fitted the set of alto saxophone multiphonics studied in this work. Therefore the first step for extending this study would be to broaden the set of spectral features. Nevertheless, the research methodology presented here, combining musical analysis, a psyhcoacoustical experiment and the correlation with spectral features, could be of great value in the study of the complex sonorities for other musical instruments.

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