USING TIMBRE CHANGES IN FLUTE PLAYING TO ENHANCE THE PERCEPTION OF DYNAMICS: A PILOT STUDY

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ABSTRACT

L'étude rapportée dans cet article vise à explorer les liens entre nuances dynamiques et variations de timbre à la flûte traversière. Les nuances de timbre sont utilisées par plusieurs flûtistes afin de maximiser la perception de leurs nuances dynamiques sans compromettre leur capacité de projection sonore. Afin de comprendre ce qui se passe sur le plan acoustique, des sons de flûte correspondant aux quatre combinaisons entre les nuances dynamiques forte et piano, ainsi qu'entre deux nuances de timbre, « rond » et « brillant », ont été enregistrés et analysés grâce à l'extraction de descripteurs acoustiques du timbre avec la Timbre Toolbox (Peeters et al., 2011) [11]. Les résultats, obtenus d'abord par une analyse par composantes principales, puis par une mise en rapport de divers descripteurs acoustiques, démontrent un lien clair entre l'augmentation de la brillance et celle de la nuance dynamique, et ont permis de dégager les principales caractéristiques acoustiques de ces quatre catégories de sons, notamment en ce qui concerne les propriétés spectrales, les propriétés de l'attaque, ainsi que celles en lien avec le caractère bruité et la stabilité du son.

The study described in this paper aims to explore the links between dynamics and timbre variations in flute playing. Timbre nuances are used by many flutists to optimize the perception of the dynamics they are playing, without compromising their sound projection capacity. In order to better understand what happens in terms of acoustics, flute sounds corresponding to each of the four combinations between forte and piano dynamics, as well as between « bright » and « round » timbres, have been recorded and analyzed through the extraction of acoustic descriptors of timbre with the Timbre Toolbox (Peeters et al., 2011) [11]. The results, obtained first by a principal component analysis, and then by graphical representations linking several acoustic descriptors, have shown a clear link between the increase of brightness and dynamics, and made it possible to find out the principal acoustic characteristics of all four sound categories, including spectral properties, attack properties, noisiness, and stability of tone.

1. INTRODUCTION

The goal of the research presented in this paper is to answer questions emerging directly from the perspective of instrumental practice, using computational tools to analyze particular aspects of musical timbre. Since the end of the 19th century, there has been an increasing number of pieces written for large orchestras. Also, room acoustics has become a specialization around the beginning of the 20th century, and architects have been working with acousticians to build concert halls dedicated to symphonic music [1]. Hence, Western classical musicians often have to play in quite large spaces. Regardless of the acoustics of most concert halls that have been conceived to magnify instrumental sound and make it resonate as easily as possible, instrumentalists must put a concrete effort in providing the greatest sound projection they can, in order to be heard by the audience as far as in the last rows. Consequently, they must develop strategies to achieve this: playing with enough sound intensity, finding ways to exaggerate contrasts in dynamics, and optimizing the timbre of their instruments so that can listeners perceive them easily, all of that in spite of the blurring effects of reverberation and the sound absorption that usually occur in concert halls.

Moreover, according to Meyer (2009), the flute is not the instrument capable of the greatest maximal sound intensity, with an average of 91 dB (67-86 dB in the low register, 83-100 dB in the high register), and has a dynamic range of about only 6 dB without changing the sound color [10]. There is also a considerable difference in the perception of dynamics according to the register. As Meyer puts it, « *[w]hen one further takes into account the low sensitivity of the ear at low frequencies, then these values suggest that a low frequency ff is perceived as equally loud as a pp of the highest notes* [10]. » Consequently, flutists have to play so that the perceived sound intensity in the low register matches that of the high register, and so that *forte* and *piano* dynamics can be easily recognizable, without compromising sound projection.

Hence, several professional flutists learned how to master timbral nuances, mainly through variations in

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[1] See, for example, Thompson, E. A. *The Soundscape of Modernity: Architectural Acoustics and the Culture of Listening in America, 1900-1933*. MIT Press, Cambridge, 2004.

sound brightness, first to maintain their expressivity, but also to make changes in dynamics more easily perceptible. The aim of this research is to find out what characterizes these timbral variations, their properties, and the link between sound color changes and dynamics. For this purpose, sound samples recorded by a flutist will be analyzed through the extraction of acoustic descriptors of timbre, to start an investigation of the links between brightness and dynamics in flute playing.

2. DEFINITIONS

2.1. Dynamics and brightness

From the point of view of musical acoustics, dynamics consist of changes in sound intensity and depend strongly on the amount of energy provided to initiate and to sustain the vibration. In flute playing, it is possible to change the air pressure by the action of thoracic-abdominal muscles, but to keep a stable tone, flutists usually simply change the lip opening while adjusting the supporting action of the respiratory muscles in order to keep the same air pressure, resulting in a lower or higher air flow at the embouchure.

But the concept of brightness is somewhat less easy to define, since it is a property of musical timbre, and a multidimensional parameter. According to Castellengo and Dubois (2007), timbre perception depends on two processes: identification of the sound source, and qualification. Humans are predisposed to focus on the identified sound source and to follow it over the course of time rather than to try to qualify it. One must overcome this reflex to be able to look more deeply at timbre differences in their relativity, or to assimilate them to a movement between timbral dimensions [4]. Therefore, brightness is not a parameter which perception is straightforward, and to which one will listen to in a conscious way. It is only after recognizing the flute, its pitches, and perceiving dynamics that a person will listen to the timbral properties of the sound and describe them. This is maybe why timbre does not always seem to be a priority among instrumentalists, or at least this could explain why several instrumentalists prefer to talk about sound colour as a creative and expressive tool rather than to talk about timbre as a property of the sound itself.

However, brightness seems to be often strongly correlated to high spectral centroid values, this acoustic feature being one of the most important for the distinction between instrumental tones, as shown by the results of several studies in psychoacoustics of musical timbre [3, 6, 7, 8, 9].

2.2. Labels for the description of instrumental timbre

2.2.1. *Sound color exercises by Trevor Wye*

An approach to teaching changes in flute timbre can be found in Trevor Wye's *Practice books for the flute* (1999). Providing exercises to gain more contrast and flexibility in sound color changes, Wye writes: « *The flute is capable of producing a great variety of sounds, more so than any other orchestral instrument. Musical painting is more interesting when the palette has many colours. These exercises will help you to play in 'Technicolor' instead of black and white. Play this first exercise A with a full, strong, rich, dark, 'purple' tone. Try not to turn the head of the flute inwards to do this. It is better to play this exercise loudly. [...] Now play exercise B with a hollow, open, gentle, 'yellow' tone, more like the recorder in colour. Play more softly than A. When changing from A to B try to obtain the greatest* difference *in colour. It is the* difference *in tone which is the most important* [13]. »

Wye distinguishes two sound colours (or timbres), which he associates to dynamics: it's better to play *purple* loudly, and it's better to play *yellow* softly. Consequently, one could use these two sound « colours » to enhance the perception of contrasting dynamics. This exercise series has been mastered and adopted by several orchestral flutists and teachers such as Robert Langevin, principal flutist of the New York Philharmonic Orchestra, who teaches them since years in his masterclasses, as they are very useful in orchestral playing. Numerous North American flutists have then practiced them and use them on a daily basis, and the exercises are very well known by all flutists who come from this pedagogical branch.

Figure 1. On the left, the « bright » embouchure (flatter lip aperture); on the right, the « round » embouchure (rounder lip aperture).

2.2.2. *Labels used for the timbre of other instruments*

For the purpose of this study, however, labels such as « *purple* » or « *yellow* » seemed vague and ambiguous. To find other labels to describe these two distinctive sound colours, we looked at other studies on verbal description of musical timbre. In her study on guitar timbre, Traube (2004) interviewed 22 guitarists and asked them to select the 10 best adjectives to describe the nuances produced on their instruments. The 3 preferred adjectives were « *metallic* », « *round* » and « *bright* », followed by « *thin* », « *warm* », « *velvety* », « *nasal* », and « *dry* » [12].

Later, in their study on verbal descriptions of piano timbre, Bellemare and Traube (2006) asked 8 advanced-level pianists to select and define the best 10 adjectives for piano timbre description. The 15 terms that were the most often selected were « *round* », « *clear* », « *warm* », « *harsh* », « *full-bodied* », « *velvety* », « *sparkling* », « *rich* », « *soft* », « *bright* », « *resonant* », « *brassy* », « *transparent* », « *shimmering* », and « *metallic* » [1, 2].

According to the adjectives to be found in the results of both studies on guitar and piano timbre, and since they made sense to the flutist who recorded the excerpts [2] to be analyzed, we decided to replace the label « *purple* » by « bright », and « *yellow* » by « round ».

3. METHODOLOGY

3.1. Overview

The experiment described here is a pilot study, meant to explore the acoustic characteristics of different dynamics and timbre nuances by analyzing samples from the sound palette of one flutist who learned and mastered the technique described earlier. For the sounds used in this experiment, the aim was to keep dynamics (*piano* and *forte*) and timbre nuances (bright and round) as stable as possible. Consequently, for a given dynamic, the air flow and velocity stay the same; a *forte* dynamic will usually necessitate a greater air volume than a *piano* dynamic. Then, we tried to separate timbre nuances from dynamics in terms of sound intensity. The technical aspects that changed between round and bright are the vowel (or the shape of the mouth), and the shape of lip aperture. Basically, to produce a round sound, the flutist used a rounder lip aperture and a vowel closer to « *uuh* », and for a bright sound, they used a flatter lip aperture and a vowel closer to « *aah* » (see Figure 1), while adjusting the size of the lip aperture according to the chosen dynamic, without changing the other parameters.

3.2. Recordings and computational analysis

All sounds have been recorded at the Performance Measurement and Recording Laboratory [3] in Montreal, on a Powell Conservatory flute in 9K aurumite. A cardioid DPA 4011-T1 microphone, placed at a distance of 50 cm and an angle of 40°, a Fireface 800 interface and Reaper (version 4.591) have been used to record the sounds with a sampling rate of 48,000 Hz and a 32-bit bit depth resolution. The excerpts have been downsampled to 44,100 Hz [4], and edited to be analyzed individually.

In all cases, the sounds were 3 seconds long and played on the low C$\#_4$ (278,44 Hz). To reduce the possible amount of data for this first pilot study, we chose only one note in the lower part of the low register, where almost all tone holes are closed. The reason for this was to aim for the greatest number of minima in the impedance spectrum (corresponding to the frequencies of overtones in flute-like instruments), resulting in the greatest possible variations of intensity in the overtones, thus increasing the range of possible timbral variations. That said, even if it is part of the very low register, C$\#_4$ is still easier to attack and play than the lowest notes on the flute (B_3 and C_4).

Four categories of sounds have been recorded: Bright and *piano*, bright and *forte*; round and *piano*, and round and *forte*. Each type of sound has been recorded in at least 3 instances for 5 different attack consonants: « *D* », « *F* », « *K* », « *P* », and « *T* », to take in account the role of attack transients in timbre variations.

Then, 47 acoustic descriptors were extracted from each soundfile, using the Timbre Toolbox in MATLAB (version 2015a) [11]. Several types of descriptors have been considered: Temporal, spectral, spectro-temporal, and harmonic descriptors. For spectral descriptors, we used the Short-Term Fourier Transform with power scaling version (*STFTpow* in the Timbre Toolbox). Before analyzing the obtained data, all descriptors values have been normalized with the *zscore* function in MATLAB, so that descriptors could be compared on similar scales, to facilitate the visualization of results.

4. RESULTS

4.1. Principal component analysis (PCA)

The first step to obtain an overview of the relative importance of the extracted timbre descriptors and of the principal characteristics of both recorded timbre nuances (bright and round), of *piano* and *forte* dynamics, and of their interactions, we first performed a principal component analysis (PCA) [5]. In the resulting timbre spaces where all soundfiles are represented along dimensions corresponding to a linear combination of the most significant descriptors, two sound instances that are similar will be placed next to each other, as two very different ones will be placed far away from each other.

4.1.1. Dimensions

With the first 3 dimensions of the principal component analysis, we were able to explain up to 77,467 % of the variance; with 4 dimensions, up to 82,318 %. For each dimension, the relative importance of all descriptors was rated with a coefficient; Table 1 shows the 4 most important descriptors according to the absolute value of their coefficients in descending order for the extremes of each of the first 4 dimensions. Dimension 1, explaining 54,896 % of the variance, is defined by high PCA coefficients for median autocorrelation coefficients (6,7,5,8) at the minimal end, and by high coefficients for descriptors related to brightness at the maximal end. Dimension 2 explains 15,003 % of the variance and groups descriptors related to noisiness and attack transients (minimum end), and to the RMS value and spectral energy (maximum end). Then, dimension 3 explains 7,568 % of the variance and groups various spectral descriptors (minimum) and various temporal descriptors (maximum). Lastly, dimension 4 explains 4,851 % of the variance and

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[2] The flutist who recorded the excerpts is also the author of this paper.

[3] Centre for Interdisciplinary Research on Music and Media Technology (CIRMMT), Montreal (Qc, Canada).

[4] This seems to have been one of the non-official technical requirements of the Timbre Toolbox in its 2011 original version.

[5] The scripts used in this MATLAB implementation are an adaptation of Manon Moulin's scripts for her work on piano timbre acoustics at the Laboratoire d'Informatique et d'Acoustique Musicale (LIAM), with the help of Sébastien Bel, Ph.D. candidate in Musicology at the Faculté de musique, Université de Montréal, Canada.

focuses on attack and decay properties (minimum), and various temporal descriptors (maximum).

PCA Dimensions — Brightness vs Dynamics (Total explained variance: 82,318 %)				
Dimension	**Explained Variance**	**Coefficients**	**Dimensions Overview**	**Descriptors** *(In order of importance, according to the absolute value of their coefficients)*
1	54.896 %	Max : 0.19695	*+ Brightness*	Spectral Slope, Spectral Centroid, Tristimulus 2, Spectral Flux
		Min : -0.19635	*- Stability, Regularity*	Autocorrelation Coefficients 6, 7, 5, 8
2	15.003 %	Max : 0.34955	*+ RMS Value / Spectral Energy*	RMS Value, Harmonic, Noise, and Spectral Energies
		Min : -0.23177	*- Noisiness / Attack Transients*	Noisiness, Attack Slope, Decay Slope
3	7.568 %	Max : 0.43486	*+ Temporal Descriptors*	Temporal Centroid, Decrease Time, Effective Duration, Attack Time
		Min : -0.35845	*- Spectral Descriptors*	Fundamental Frequency, Spectral Irregularity, Frequency of Modulation, Flatness
4	4.851 %	Max : 0.40438	*+ Various Temporal Descriptors*	Logarithm of Attack Time, Effective Duration, Release Time, Temporal Centroid
		Min : -0.32041	*- Attack & Decay Properties*	Attack Slope, Attack Time, Decay Slope, Tristimulus 3

Table 1. First 4 dimensions of the principal component analysis, with maximal and minimal coefficients, and the most important descriptors for each dimension, according to the absolute value of their coefficients.

4.1.2. Observations

Figure 2 shows the first two dimensions of the PCA. Along the first PCA dimension, 3 groups are distinguishable: round *piano* sounds and bright *forte* sounds at the extremes, and bright *piano* and round *forte* sounds forming a third group in the middle. Round *piano* sounds generated high values for the autocorrelation coefficients, as bright *forte* sounds generated high values for descriptors related to brightness, such as spectral slope and spectral centroid. Along dimension 2, round *piano* and bright *forte* sounds also generated higher RMS values and harmonic energies. The middle group (bright *piano* and round *forte* sounds) shows higher noisiness values and attack times. Therefore, to not combine louder dynamics with an increased brightness may lead to more instability and noisiness in tone.

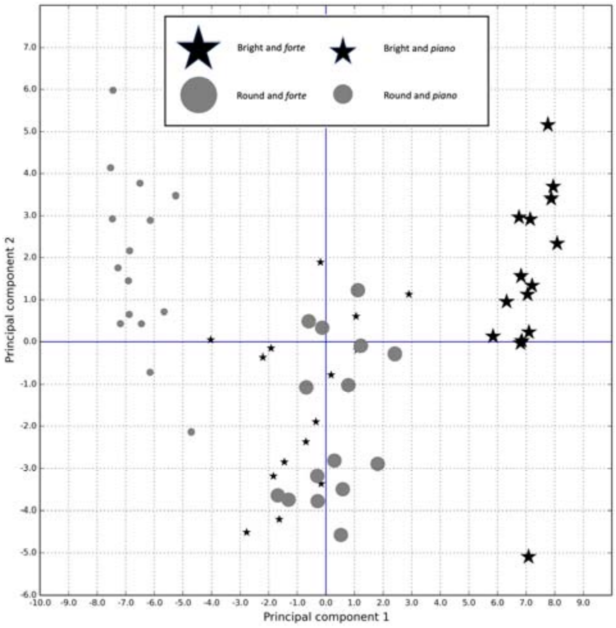

Figure 2. PCA dimensions 1 and 2.

Figure 3 shows a display of PCA dimensions 1 and 3. Here, bright *piano* and round *forte* sounds can be separated in two distinct groups, where round *forte* sounds generate higher values for fundamental frequency, harmonic deviation, frequency of modulation in the signal, and spectral flatness. Roughly, round *forte* sounds seem to be farther away from a standard harmonic spectrum with a smooth envelope than bright *piano* sounds. Furthermore, bright *piano* sounds generate higher values for several temporal descriptors, which confirms the fact that it may take more time to let all overtones speak while playing *piano*. Therefore, to play bright and *piano* or round and *forte* seems to not correspond to the natural tendencies of the instrument, and can be more challenging for the flute player.

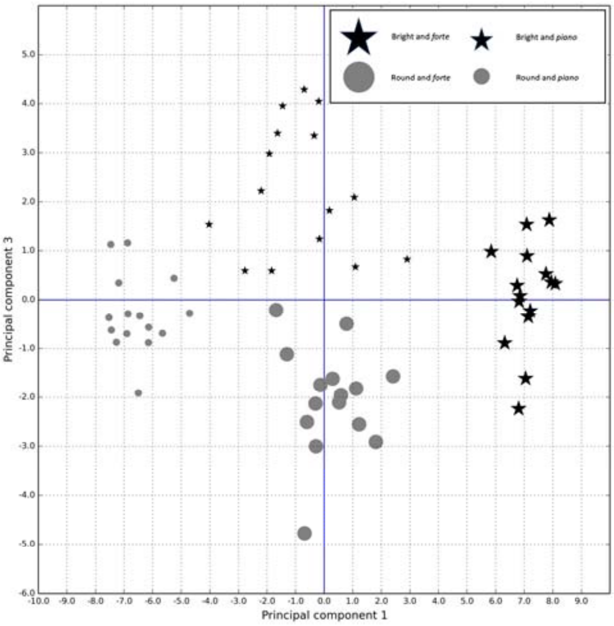

Figure 3. PCA dimensions 1 and 3.

4.2. Overview of individual descriptors

Starting from the results obtained from the principal component analysis, the data from individual descriptors was analyzed to get a closer look at characteristics such as noisiness, harmonic deviation, and spectral distribution of energy.

4.2.1. Noisiness and Harmonic Deviation

On Figure 4, zero-crossing rate values are quite consistent for all groups except for round *forte* sounds [6]. Mean values tend to be slightly higher for bright sounds, which means that there seems to be more periodicity in round sounds than in bright sounds. But sound instances of round *forte* sounds are way more randomly distributed for this descriptor, and also generate the highest values for the noisiness descriptor (which is the ratio between noise and harmonic energies). Therefore, in comparison to the harmonic content, the noise content of round *forte* sounds is proportionally higher than for the other groups.

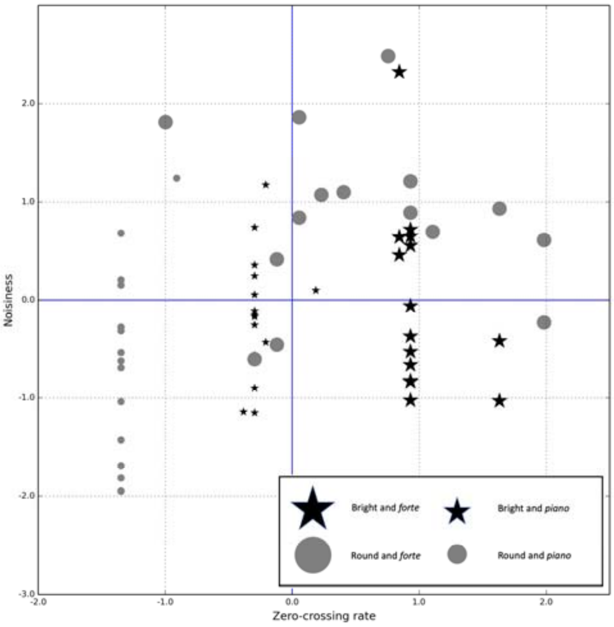

Figure 4. Zero-crossing rate and noisiness.

Figure 5 shows that harmonic deviation values are highly variable for round *forte* sounds as well, and tend to be slightly higher for round sounds in comparison to bright sounds. In other words, there is more jaggedness in the harmonic spectrum of round sounds than of bright sounds.

4.2.2. Spectral distribution: Tristimulus coefficients

As expected, Figure 6 shows with a 3D display of all 3 tristimulus coefficients that bright sounds have more energy in higher frequency ranges than round sounds. Also, there is more energy in higher frequency ranges if we increase the dynamics. Therefore, the distribution of spectral energy evolves in the same direction when increasing either the brightness or the dynamics. However, dynamics seem to have a stronger effect on spectral energy distribution than timbre changes between round and bright.

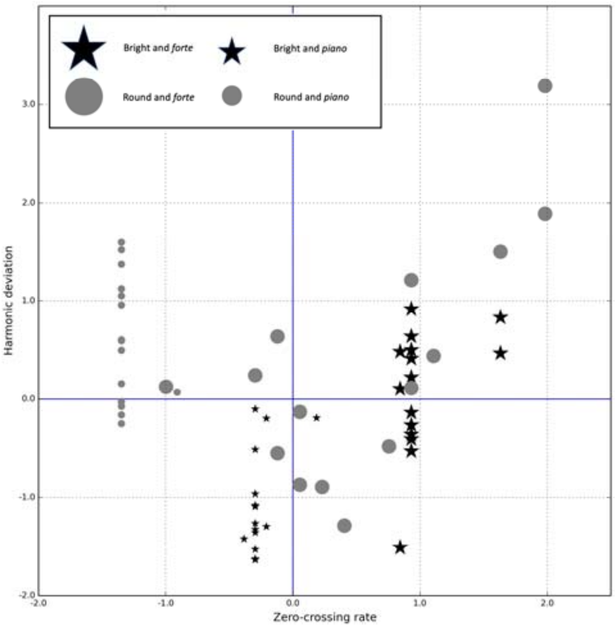

Figure 5. Zero-crossing rate and harmonic deviation

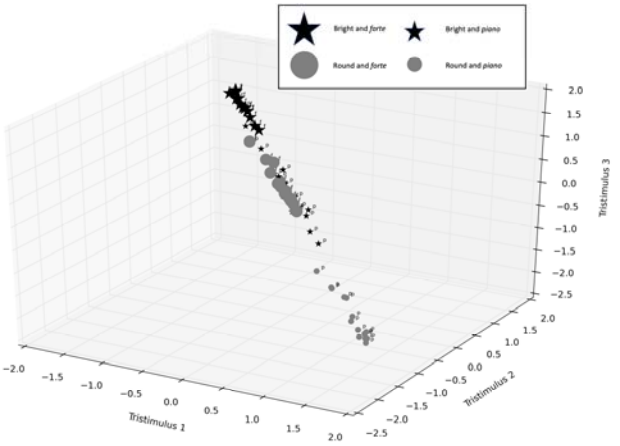

Figure 6. Tristimulus coefficients 1-2-3.

4.2.3. Spectral descriptors

Figure 7 shows a positive correlation between spectral centroid and spectral flux; the sound instances appear in the same groupings as with the first two PCA dimensions (see Figure 3). The values of both descriptors get higher if we increase dynamics and/or brightness.

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[6] According to Peeters et al. (2011), to compute the zero-crossing rate, the algorithm of the Timbre Toolbox first subtracts the local DC of each frame of the signal, then normalizes the obtained zero-crossing rate value by the window length (23.2 ms) [11]. In addition, as explained, a further normalization step has been performed with the *zscore* function in MATLAB in order to facilitate the Principal Component Analysis. The normalized values have been kept for the overview of individual descriptors for more convenience. This may explain why vertical stripes appear on the graphs of figures 4 and 5 along the *x*-axis.

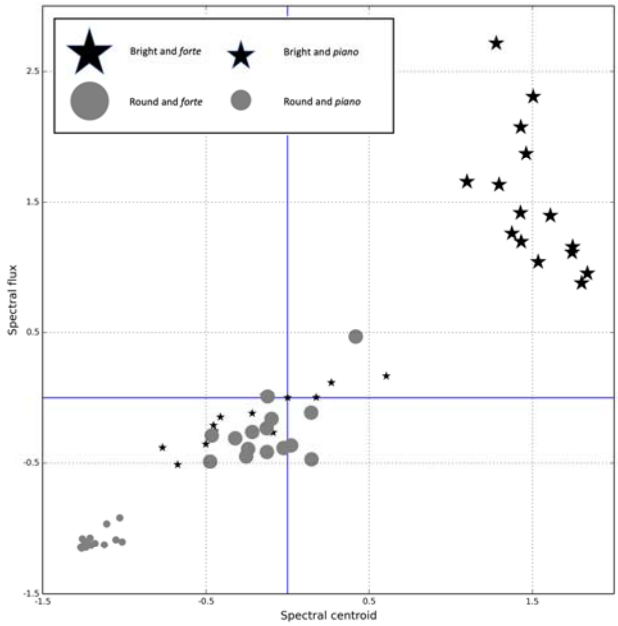

Figure 7. Spectral centroid and spectral flux.

Spectral skewness and kurtosis are also positively correlated (Figure 8). Here again, the same 3 groups as with PCA dimensions 1-2 (round-*piano*, bright-*forte*, and round-*forte* and bright-*piano* together) are observable, but in the reverse order. At one extreme, bright *forte* sounds generate the lowest values for spectral kurtosis and skewness; at the other end, round *piano* sounds generate the highest values for those two descriptors.

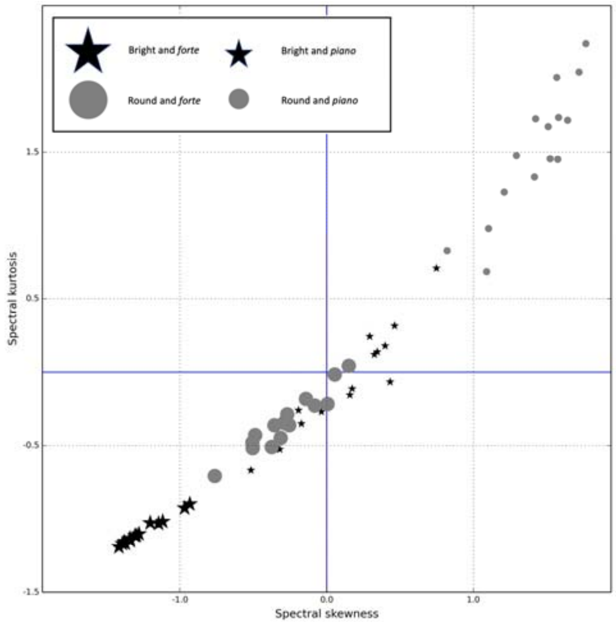

Figure 8. Spectral skewness and spectral kurtosis.

Lastly, Figure 9 shows that the values generated for spectral roll-off tend to follow the same tendency as other flute-brightness descriptors such as spectral centroid and flux, except that in that case, round *piano* sounds generated values way lower than the other groups for this descriptor. However, it gets interesting when looking at the spectral flatness dimension (on the x axis): It is the descriptor that clearly distinguishes bright *piano* from round *forte* sounds. Higher flatness values were generated for round *forte* sounds than for bright *piano* sounds. There is more jaggedness in the spectral curve when playing *forte* than *piano*, and a considerable difference is also observable between round and bright *forte* sounds.

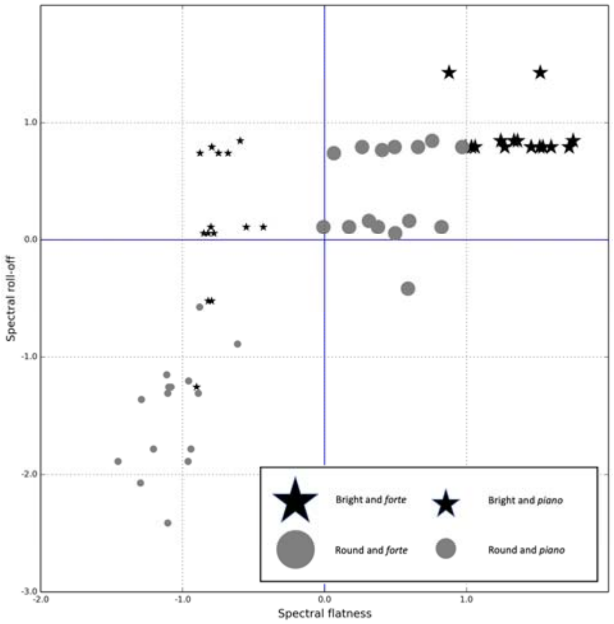

Figure 9. Spectral flatness and spectral roll-off.

5. DISCUSSION

5.1. Links between brightness and dynamics

According to these results, there is in fact a clear link between dynamics and brightness in flute playing, as it is also the case for other instruments such as the brass family. Going against this tendency leads to the obtention of a spectrum farther away from a standard harmonic spectrum (both in terms of harmonicity and harmonic deviation or jaggedness), as well as to higher noisiness and attack time values. Also, dynamics have more effect on spectral energy distribution than changes between the round and bright timbres.

Then, according to our results, the distinction between bright *piano* and round *forte* sounds consist mainly in differences in spectral flatness and harmonic deviation. The values for those two descriptors are generally higher for round *forte* sounds than for bright *piano* sounds.

5.2. About brightness and roundness

These results can also lead us to a better definition of brightness and roundness in flute playing. Brightness is related to high values for spectral centroid, spectral slope, spectral flatness, spectral roll-off, and spectral flux. Longer attack times are also necessary to get all overtones speak and get to the sustain part of bright sounds. On the other hand, roundness cannot be defined in opposition to brightness, but has rather its own characteristics. Roundness is mainly related to high values for spectral kurtosis and spectral skewness, but also to higher values for harmonic deviation and noisiness in *forte* sounds. There is a possible explanation for this, regarding instrumental technique: the combination of a particular shape of lip aperture and a higher air velocity leads to more turbulences at the embouchure, thus to more noise content in the sound. According to De la Cuadra (2005), this noise content is characteristic of the flute tone, especially for sounds played with a higher air velocity (or in other words, *forte* sounds) [5].

5.3. Limitations of the experiment

In the context of this pilot study, the analyzed sample is still very reduced, consisting of sounds recorded by only one person and limited to a very particular part of the flute register. This experience would need to be replicated on the whole low register of the flute (B_3-$C\#_5$, where notes correspond to the first resonance of the tube for each fingering), and with several flutists. In that case, it will be important to combine the recordings with an interview where performers describe their instrumental technique, their understanding of the technical aspects, and the labels they personally use to describe the different timbres or sound colors they produce. Also, in the present experiment, the results concerning the attack types (D, F, K, P, T) were not consistent enough to see if the attack consonant has a great influence on timbre variation in flute playing. This may be due to a lack of consistency in this particular aspect of flute playing during the recordings, or to the fact that the attack properties are less relevant when analyzing the variations in timbre and dynamics in this context. Finally, results were obtained with the Timbre Toolbox, but it would be relevant to compare them with those obtained with other toolboxes made for instrumental timbre analysis.

6. CONCLUSION

At the beginning of this study, the hypothesis was that flutists use timbre changes to enhance contrasts in dynamics. In fact, there is a natural tendency for brightness and dynamics to be associated in flute playing. To go against this tendency tends to distort the harmonic spectrum to a certain point, and to add noise and instability in tone production. However, this experiment shows that with proper training and some practice, it is also possible to achieve different timbre shades or sound colors independently from the chosen dynamic range, and to use them to facilitate the perception of inflexions and dynamics in the listener.

In fact, using the round timbre quality while playing with a high air velocity seems to add noise content in the sound while refraining from making too many harmonic partials resonate in the tube. Hence, a round *forte* sound would roughly contain fewer harmonic overtones (just as a standard, timbre-neutral *piano* tone), but more noise in the middle-high frequency range where the ear is very sensitive, making the flute sound easier to be heard. In the context of playing in a very large concert hall or in the orchestra, this could help the flutist to produce a kind of « fake » *piano* sound, easily heard from far away but with a distinctive color, imitating softer dynamics.

We are looking forward to replicating this experiment with several flutists, and to extend it to a broader register on the flute. Further work is needed to see if the results of this pilot study can be replicated and confirmed by the analysis of a greater dataset.

7. ACKNOWLEDGMENT

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