Spectral features influencing perception of pipe organ sounds

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Sound recordings of twelve pipe organs from four European countries (six Baroque, two Romantic and four contemporary) were subjectively evaluated. Principal sound contexts of Principal 8' (pitches C2, C3, C4, C5, and C6) were judged by twelve organ experts on dissimilarity in timbre. Perceptual space was constructed for each of the five tested sound contexts, using the multi-dimensional scaling latent class approach. Levels of individual harmonics and levels in third of octaves were used for the interpretation of perceptual spaces. The method of embedding of these acoustic characteristics into perceptual space contributed to the discovering of the main spectral features, significantly influencing perception, and established their relations (similarity, opposition, or independence) in each context. Level of the fundamental, levels of high frequency components and levels of noise components in the band about 100 – 200 Hz proved to be the main spectral features, influencing the perception of the timbre of the organ pipe sound. Pitch dependence of their mutual relations and frequency positions are also found and discussed.

1 Introduction

The pipe organ is one of the most complicated musical instruments considering the mechanical construction, the sound creation, and radiation. Moreover, each instrument is rigidly connected to a specific place (church, concert hall, etc.) and the room acoustics there. The history of the organ reflects the evolution of European religiosity as well as aesthetics of music (from cultural periods like Baroque and Romantic up to contemporary sound taste). From the acoustic point of view, each instrument is made of many independent sound sources – pipes, combined in ranks (stops), which are further grouped into divisions (manuals, pedal). Each division has its own keyboard providing the compass (tone range). Each organ stop is designed for the specific sound timbre (solo or department contribution). An independent use of stop combinations (registration) allows the creation of the richness in sound timbres and also the instrument dynamic span.

The scale of each pipe (geometrical dimensions like diameter or mouth width and height in the flue pipe, etc.) and the voicing have a great influence on all acoustic parameters of the pipe sound. Eleven organ manufactures from nine European countries initiated the EU CRAFT project "Development of an Innovative Organ Pipe Design Method" consortium. The main task of this project is the development of a new scaling method of selected stops, mainly principals. One of the project tasks was the detection of opinions of listeners on different instrument sounds on the basis of listening tests. The listening test results are described in this article.

2 Method

Twelve pipe organs from four European countries (six Baroque, two Romantic and four contemporary) were measured *in situ*. The list of the measured instruments is presented in Table 1.

Recordings of Principal 8' (Flautado 8'), Salicional 8' (Gamba 8', Viool 8'), Flute 8' (Hohlflöte 8', Traversflöte 4', Nachthorn 4', Flöte 4') and Octave 4' (Praestant 4') were used in the listening tests. Suitable recordings according to the test requirements (similar loudness, representative timbre variations) were selected from the recordings in four microphone positions inside each church. Individual signals were manipulated to decrease the influence of transients on the perception (uniform fade in and fade out).

Listening tests of eight sound contexts were prepared and separately performed: three mixed contexts of Principal 8', Salicional 8', Flute 8' and Octave 4' sounds (pitches C3, C4, C5) and five principal sound contexts of Principal 8' (pitches C2, C3, C4, C5, C6). Dissimilarity in pairs of sounds in timbre was judged by twelve organ experts (students of organ play from University of Music and Performing Arts of Stuttgart and organ builders).

The results of the listening tests were evaluated by using the multi-dimensional scaling method [1]; the latent class approach (program CLASCAL) [2, 3, 4] was used for the construction of the perceptual space of appropriate dimensionality for each sound context. The objects of these perceptual spaces represent test stimuli (sounds), dissimilarities between pairs of sounds are transformed into Euclidean distances.

Table 1: List of measured instruments. The order of instruments corresponds to the number of sound recordings used in the listening tests.

No.	Organ builder, town, year of manufacturing	Country	Style
1	Mühleisen, Neckarweihingen, 2003	Germany	contemporary
2	Mühleisen, Stetten, 1990	Germany	contemporary
3	Mühleisen, Waiblingen, 1991	Germany	contemporary
4	Ludwig Hartig, Straupitz, 1853	Germany	Early Romantic of middle Germany
5	Gottfried Silbermann, Reinhardtsgrimma, 1731	Germany	Baroque of middle Germany
6	Hendricus Hermanus Hess, Rotterdam Charlois, 1784	Holland	Northern Baroque
7	Boogard, Capelle a ďIjsell, 1995	Holland	contemporary
8	Cavaille-Coll, Epernay, 1869	France	French Romantic
9	Manuel Sa Couto, Gueifaes de Maia, 1810	Portugal	Portuguese / Iberian Baroque
10	?, Porto, 1785	Portugal	Portuguese / Iberian Baroque
11	?, Dornes, 1760	Portugal	Portuguese / Iberian Baroque
12	Cavaille-Coll, Lamas, 1901	Portugal	French Romantic

The acoustic characteristics of sounds were calculated from the spectra of the quasi stationary parts of the tested signals and used for the external interpretation of perceptual spaces. The following characteristics were calculated:

- 1. Levels of individual harmonics [dB] denoted here as L_{Hi}, i = 1, 2, ...,
- 2. Levels in third of octaves [dB], which are denoted here as L_{Ti}, i = 1, 2, ..., frequency boundaries are given for example in [5], page 242, but we will use the lengthened sequence of thirds starting from the band T1 with boundaries f_{T1} Є <18,22.4> Hz, and continuing through T2 f_{T2} Є <22,4.28> Hz, then f_{T3} Є <28,35.5> Hz, f_{T4} Є <35,5.45> Hz, etc.

An external interpretation of the perceptual spaces was made, using the method of optimal fitting of the external scales [1], applied to acoustic characteristics. This method will be referred to in the context as **embedding** (improperly named immersion in [6, 7]). The embedding of any external variable (meaning the variable describing objects of perceptual space, but obtained independently of the listening test) is defined as a direction in the perceptual space, causing a maximum correlation between the external variable values and the projection coordinates of perceptual space objects onto this direction. But only successful embedding, meaning the embedding with a significant value of correlation, are taken into account for the perceptual space interpretation, only successfully embedded acoustic characteristics or features can be important for the decision of the judges on the (dis)similarity of sounds. The vector of embedding in the perceptual space is defined by the direction of (successful) embedding; the vector orientation is given so that the projection values are growing in the direction from the origin of the vector. The origin of the embedding vector will be placed in the origin of the perceptual space coordinates for drawing.

The angles between the embedding vectors were calculated and the relations between the embedded acoustic characteristics were qualified according to the contained angles as follows:

- a) small angles between embeddings ($\alpha \leq 20^{o}$) => similar influence on perception,
- b) nearly orthogonal embeddings ($70^{o} \leq \alpha \leq 110^{o}$) => independent influence on perception,
- c) nearly opposite embeddings ($\alpha \geq 160^{o}$) => opposite influence on perception.

The aim of the interpretation was to search for a system of embedded acoustic characteristics, which completely describes the perceptual space and constitutes a system of nearly orthogonal embeddings; the ideal situation would be that the number of characteristics in the system is equal to the number of space dimensions.

3 Results

Only the results of the listening tests of Principal 8' sound contexts of tones C2, C3, C4, C5 and C6 will be described here. In all these contexts, the three-dimensional solution was selected to be appropriate for interpretation. The perceptual space interpretation will be demonstrated on the embedding results of tone C2. Successfully embedded acoustic characteristics are indicated in Table 2, the contained angles of the selected acoustic characteristics are stated in Table 3.

Table 2: The correlation coefficient r and the direction cosines of the selected and successfully embedded acoustic characteristics for tone C2 Principal 8' (for eleven objects the Pearson correlation coefficient r = 0.85 is significant on the level 0.1%, r = 0.74 on 1%).

Harmonic / Third octave	Frequency (Hz)	r	cos(Dim1)	cos(Dim2)	cos(Dim3)
H1	65.4	0.90	0.018	0.579	-0.815
H2	130.8	0.90	-0.021	-0.816	0.578
H3	196.2	0.78	-0.110	0.505	0.856
H4	261.6	0.91	-0.455	-0.240	0.858
H5	327	0.88	-0.559	0.752	0.350
H6	392.4	0.77	-0.729	0.187	0.658
T15	450 – 560	0.93	-0.853	0.416	0.315
T16	560 – 710	0.91	-0.897	0.255	0.361

Table 3: The angles contained in the selected embeddings for tone C2 Principal 8'. The representative system of acoustic characteristics is bold.

	H1	**H2**	**H3**	H4	H5	H6	**T15**	**T16**
H1	–							
H2	**158**	–						
H3	**117**	**84**	–					
H4	144	43	52	–				
H5	83	110	43	67	–			
H6	106	82	47	40	31	–		
T15	**91**	**95**	**56**	54	26	16	–	
T16	**98**	**86**	**59**	47	35	13	**10**	–

Thus the thirds T15 and T16 have similar influence on perception ($\alpha = 10^o$) and they are further represented by one "mean" or "common" embedding, H1 and H2 have "weak nearly" opposite influence, H1 & H2 and T15 & T16 nearly orthogonal, H2 and H3 nearly orthogonal influence. The embeddings of the representative system of the acoustic characteristics are described in Figure 1.

Similar selections were made for other sound contexts. Table 4 includes the representative systems of the acoustic characteristics for all studied tones of Principal 8' sounds; Figure 2 summarizes the frequency positions of the acoustic characteristics mainly influencing perception.

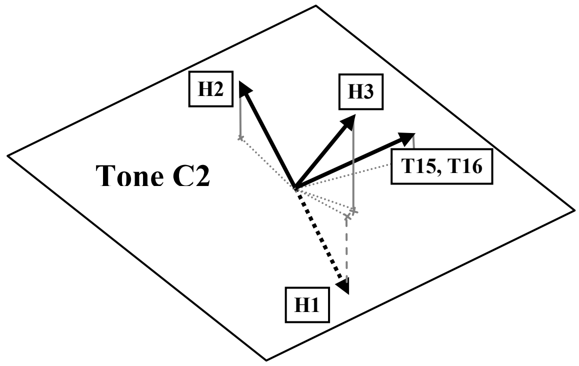

Figure 1: The representative system of the embeddings of the acoustic characteristics into the perceptual space of tone C2, Principal 8'.

Table 4: The angles contained between the embeddings of the acoustic characteristics generating representative systems of the main timbre perception impact for tones C2, C3, C4, C5 and C6 of Principal 8'.

Tone C6	T10-T14	H1	Frequency [Hz]
T10-T14	–		140 – 450
H1	75	–	1046.5
T27, T28	108	108	7100 – 11200

Tone C5	T11	H2	Frequency [Hz]
T11	–		180 – 224
H2	75	–	1046.5
T22, T23	73	104	2240 – 3550

Tone C4	T7-T10	H1	H4	Frequency [Hz]
T7-T10	–			71 – 180
H1	169	–		261.6
H4	58	119	–	1040.0
T22-T26	93	92	60	2240 – 7100

Tone C3	H1	T10	H2	Frequency [Hz]
H1	–			130.8
T10	62	–		140 – 180
H2	159	132	–	261.6
T20-T24	82	80	87	1400 – 4500

Tone C2	H1	H2	H3	Frequency [Hz]
H1	–			65.4
H2	158	–		130.8
H3	117	84	–	196.2
T15, T16	94	91	58	450 – 710

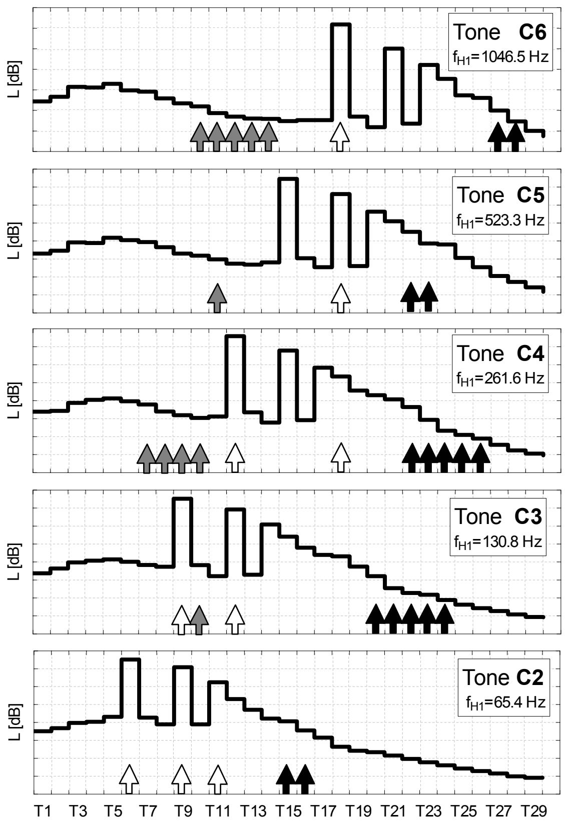

Figure 2: Frequency positions of the acoustic characteristics mainly influencing perception in Principal 8' tones C2, C3, C4, C5 and C6. Drawings of mean third octave spectra over the tested set of sounds were used. The arrows have the following meaning: ⇧ H1(H2|H3|H4), ⬆higher harmonics, ⬆ noise.

4 Discussion and conclusions

The method of embedding of acoustic characteristics into the perceptual space contributed to the detection of the main spectral features significantly influencing the perception of timbre of Principal 8' sounds and established their relations (similarity, opposition, or independence) in each studied context of sounds. The ideal representative system of acoustic characteristics was not found in all pitches (see for example tones C2, C3 and C4, where one or two angles slightly break our criteria for orthogonality – Table 4).

Nearly orthogonal systems in individual pitches are constituted by the following triplets of acoustic characteristics:

Tone C2: H1 or H2; high frequency components (T15, T16); H3 – not exactly.

Tone C3: H1 or H2; high frequency components (T20 – T24); noise components (T10) – not exactly.

Tone C4: H1 or noise components (T7 – T10); high frequency components (T22 – T26); H4 – not exactly.

Tone C5: H2; high frequency components (T22, T23); noise components (T11).

Tone C6: H1; high frequency components (T27, T28); noise components (T10 – T14).

Comparing the results of the five studied sound contexts, we may conclude:

- 1. There are three main perceptual features for timbre dissimilarity judgments based on the acoustic characteristics, which substantially influence the perception of the organ sound: level of the fundamental, levels of high frequency components, levels of noise (non-stationary) components in the band about 100 – 200 Hz. The second, third and fourth harmonic levels influence perception only in some pitches.
- 2. The frequency position of high frequency components is increasing with an increasing pitch and changes from the band 450 – 710 Hz (pitch C2) to 7100 – 11200 Hz (C6).
- 3. The frequency position of noise components is relatively stable or increases slightly (with the exception of tone C2, where it is probably masked by H2 and H3).
- 4. The relations (opposition or independence) between the main spectral features are dependent on the tested sound context and pitch.

The relations of three acoustic characteristics with substantial influence on the perception are stated in Table 5.

Table 5: The relations of the acoustic characteristics with the substantial influence on the perception in individual pitches; ⊥ is for nearly independent (orthogonal) influence, ↕ is for nearly opposite influence.

Tone	H1 (H2 in C5) and high freq. components	H1 (H2 in C5) and noise components	high freq. components and noise components
C6	⊥	⊥	⊥
C5	⊥	⊥	⊥
C4	⊥	↕	⊥
C3	⊥		⊥
C2	⊥		

Acknowledgement

Research was supported by the EU CRAFT project G1ST-CT-2002-50267–DEMORGPIPE: "Development of an Innovative Organ Pipe Design Method".

The support of the following organ builder firms is also acknowledged: Werkstätte für Orgelbau Mühleisen GmbH, Leonberg, Germany (Project co-ordinator), Manufacture d'orgues Muhleisen, Strasbourg, France, Christian Scheffler Orgelwerkstatt, Sieversdorf (Frankfurt/Oder), Germany, Orgelbau Schumacher, Baelen, Belgium, Blancafort, Orgueners de Montserrat S. L., Collbato, Spain, Oficina e Escola de Organaria, Ltd., Esmoriz (Porto), Portugal, Fratelli Ruffatti Pipe Organ Builders, Padova, Italy, Marc Garnier Orgues, Les Fins, France, Pécsi Orgonaépitö Manufaktura KFT, Pécs, Hungary, Mander Organs, London, U.K., Orgelmakerij Boogaard, Rijssen, Netherlands.

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