ENVIRONMENTAL NOISE CONTROL
The 2005 Congress and Exposition on Noise Control Engineering
07-10 August 2005 - Rio de Janeiro - Brazil

Interpretation and comparison of perceptual spaces

Jan Štěpánek

Musical Acoustics Research Centre, Faculty of Music, Academy of Performing Arts in Prague, Malostranské nám. 13, 11800 Praha 1, Czech Republic

stepanek@hamu.cz

Abstract Low-dimensional multidimensional perceptual space of objects is obtained as a result of the evaluation of some psychoacoustic experiments (e.g. proximity ratings evaluated using multidimensional scaling). Various methods for perceptual space external interpretation and perceptual spaces comparison are discussed. The method of 'embedding' of variable external to given N-dimensional perceptual space in the case of correlated orthogonal dimensions is described. The main idea of the embedding is optimally fitting external scale; this means the search for such direction in perceptual space, when object projections on this direction have maximal correlation with embedded external scale. Only event of embedding with significant correlation is taken into account for perceptual space interpretation. It is known that in the case of uncorrelated orthogonal dimensions the embedding is given by multiple regression of these dimensions. Described solution uses numerical computation which is independent according to correlation of dimensions. Two examples of embedding use are given: 1) interpretation of perceptual space of violin timbre using acoustic characteristics and verbal descriptions of violin tones, 2) comparison of perceptual spaces of verbal attributes used for timbre description and obtained as a result of the test with different groups of musicians. Results of embedding in both examples are discussed and compared with other usually used interpretation methods: 1) correlation of external scales with dimension coordinates, 2) Procrustean similarity transformation.

1. INTRODUCTION

Our sense organs enables us to perceive the reality or individual real objects in various aspects using sense of sight, hearing, touch, smell and taste. When we perceive specific real object, we are able to describe its geometry, colour, etc. From our experience we build in mind an abstract representation of objects and their relations – categories of patterns (two- or three-dimensional figures, colours, sound timbres, etc.). This abstract representation of objects and their relations we will call abstract or **common perceptual space** whilst we assume its multidimensionality. Every human being is constructing its **individual perceptual space** depending on his/hers disposals and experiences.

The goal of many psychological experiments is to search for the perceptual space corresponding to the specific class of objects (context of objects: colours, musical instrument sounds, etc.) and shared by the group of subjects (context of subjects: with normal eyes and colour blind, musicians and music listeners, etc.). Perceptual space corresponding to the specific context of objects and subjects we will call **context-dependent perceptual space**. In some sense the context-dependent perceptual space is a part of common perceptual space, which is usually deformed by the focus on the most pronounced features of the given context. Usually the goal of the context-dependent perceptual space interpretation is the search for the main perceptual features of studied context and for physical sources of these features. Further in this article we will speak simply about perceptual space instead of context-dependent perceptual space. Another task can be to compare two perceptual spaces of the same objects (test – retest stability, perceptual models of different groups of subjects, etc.).

Implementation of the method of optimal fitting of external scale (embedding) into the perceptual space [1] will be described. Possibilities of the use of embedding will be illustrated on examples of perceptual space interpretation and perceptual spaces comparison. Facilities of embedding will be compared with other methods of interpretation and comparison.

2. EMBEDDING

Suppose we have N-dimensional Euclidean space of M objects of any kind. An object O_i (i = 1, 2, ..., M) in this space is described by N coordinates O_{i1}, O_{i2}, ..., O_{iN}. Coordinate of dimension j (O_{1j}, O_{2j}, ..., O_{Mj}) is also called internal scale j (j = 1, 2, ..., N), see [1], p. 63. Let we have variable V describing objects of the space, values V_1, V_2, ..., V_M of variable V (obtained independently on the coordinates) we call **external scale**.

2.1 Definition of Embedding

An **embedding** of external scale into the space is given by optimal fitting of external scale and is given by such a direction in the space, which gives maximum correlation between the external variable values and the projection coordinates of the space objects onto this direction. But only **successful embedding**, it means the embedding with significant value of correlation (significance of $\alpha = 5\%$ will be used), will be taken into account.

2.2 Correlation and Geometry of Embedding

Squared correlation of embedding is equal to squared multiple correlation (sum of squared correlations of external scale with internal scales) in the case of uncorrelated dimensions of the space [1]. Multiple regression weights of the linear regression of external scale on internal scales (dimensions) can be used for the calculation of direction cosines of embedding (direction cosines are weights normalized by the square root of the sum of weight squares). The vector of embedding in the space is defined by the direction of embedding; the vector orientation is given so that projection values are growing in the direction going from the origin of the vector. For drawing the origin of the embedding vector will be placed in the origin of the space coordinates.

2.3 Implemented Algorithm of Embedding

For the possibility to use embedding also for correlated dimensions the numerical calculation of external scale fitting was implemented in STATISTICA software [2]. The main idea of the algorithm is the generation of suitable number of vectors (their number is given as input parameter) filling the space in different directions (like in 3D ray tracing algorithm used in the room acoustic simulations [3]), calculation of correlation between the external variable values and the projection coordinates of the space objects, and search for the correlation maximum. Some optimizations of the vector generation were also introduced to lower the number of generated vectors (and the time necessary for the calculation) without any loss of the precision of the solution.

In addition to the maximum correlation of embedding also direction cosines, angles contained between embedding and individual dimensions, and object projection coordinates are calculated. When the embedding of several external scales is searched also the angles contained between pairs of embeddings are calculated.

3. EMBEDDING APPLICATION EXAMPLES

The examples of the application of embedding to perceptual space of sound timbre will be given in the following paragraphs. There are many possible ways how to construct perceptual space: it is possible to get proximity ratings directly from the psychoacoustic experiment, or calculate them from any collection of data, and then use appropriate model of multidimensional scaling. Also factor analysis solution above perceptual variables can be regarded as perceptual space. We will give the examples of perceptual spaces constructed from pair dissimilarity test results using multidimensional scaling, latent class approach [4].

3.1 Interpretation of Perceptual Space

Perceptual space of stationary violin timbre was obtained based on dissimilarity pair test of violin sound of tones B3, F#4, C5, G5 and D6 [5]. Acoustic characteristics of listened sounds (levels of individual harmonics, levels in critical bands, and spectral centre of gravity) were calculated and used as external scales for the perceptual space interpretation [6]. Only successfully embedded acoustic characteristics or features can be important for judge's decision about (dis)similarity of sounds. The perceptual space interpretation will be demonstrated on the results of embedding for tone G5 with two-dimensional perceptual space.

The angles contained between the embedded vectors were calculated and the relations between the embedded acoustic characteristics were qualified according to the contained angles in following way:
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 goal of the interpretation was to search for a system of embedded acoustic characteristics which fully describes the perceptual space and constitutes a system of nearly orthogonal embeddings; in an ideal situation the number of characteristics in the system should be equal to the number of space dimensions.

Successfully embedded acoustic characteristics into perceptual space of timbre of violin tone G5 are indicated in Table 1, together with the angles contained among them.

Table 1: Successfully embedded acoustic characteristics of violin tone G5. Levels of individual harmonics [dB] are denoted as L_{Hi}, levels in critical bands [dB] as L_{Bi}, spectral centre of gravity as f_{cg}. The correlation coefficients are denoted as R_E (Embedding) and R_{Di} (with Dimension i).The correlations significant on 1% are bold. The angles between embeddings satisfying conditions of similarity, orthogonality or opposition are bold.

R_E	R_{D1}	R_{D2}	Embedding angles [°]	L_{H1}	L_{H2}	L_{B23}	L_{B24}
0.95	**-0.94**	-0.13	L_{H1}	–			
0.74	0.23	-0.70	L_{H2}	**93**	–		
0.76	-0.32	-0.70	L_{B23}	65	28	–	
0.77	-0.46	-0.62	L_{B24}	55	38	**10**	–
0.84	**0.84**	0.01	f_{cg}	**169**	**76**	**104**	114

In the next listening tests the listeners described spontaneously the timbre dissimilarities using verbal attributes. Frequencies of occurrence of verbal attributes were used as external scales and embedded into the perceptual space. Criteria for attribute selection were frequency of use, embedding correlation significance and embedding angles (similarity, orthogonality and opposition). The selection of successfully embedded verbal attributes is assigned in Table 2. The embedded vectors of selected systems of acoustic characteristics and verbal attributes are in Figure 1.

Table 2: The selection of successfully embedded verbal attributes of violin tone G5. The correlation coefficients are denoted as R_E (Embedding) and R_{Di} (with Dimension i).The correlations significant on 1% are bold. Rank means rank according to frequency of the attribute use. The angles between embeddings satisfying conditions of similarity, orthogonality or opposition are bold.

R_E	R_{D1}	R_{D2}	Rank	Embedding angles [°]	sharp	narrow	clear	voiced	round	soft
0.61	0.53	-0.29	1	sharp	–					
0.87	**0.80**	0.36	2	narrow	**75**	–				
0.63	-0.28	-0.57	3	clear	66	141	–			
0.68	-0.37	-0.58	5	voiced	**71**	146	**5**	–		
0.84	**-0.76**	0.35	7	round	**177**	**108**	111	**106**	–	
0.93	-0.60	0.69	8	soft	**160**	**85**	134	129	23	–
0.70	0.68	-0.13	9	metallic	21	54	**87**	**92**	**162**	139

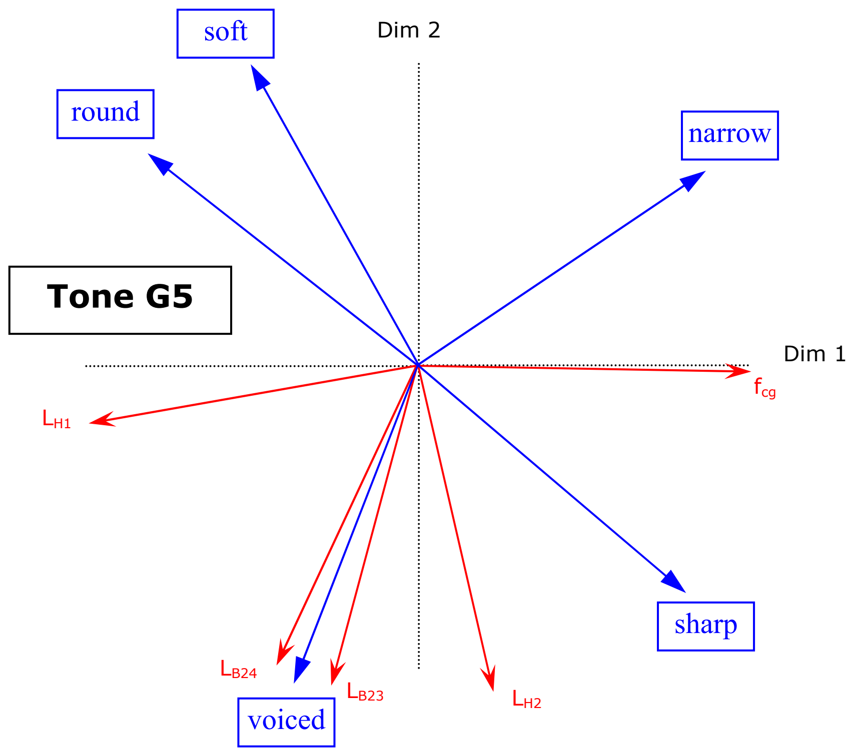

Figure 1: The most successfully embedded acoustic characteristics and verbal attributes into perceptual space of timbre of violin tone G5.

3.2 Comparison of Perceptual Spaces

Perceptual space of verbal attributes used by musicians for the description of musical sound timbre was obtained based on dissimilarity pair test applied on 25 selected Czech verbal attributes [7]. The test was performed for several groups of musicians (string instrument players, wind instrument players, piano players, composers and conductors, and sound designers). One of the goals of the study was to compare the group models of timbre. Perceptual spaces of verbal attributes were compared using embedding of dimensions of one space (external scales) into second space and vice versa.

The comparison will be demonstrated on perceptual space of wind instrument players and piano players (both are two-dimensional), and composers and conductors (three-dimensional), see Table 3. Embeddings of both dimensions into both spaces are successful (significant) and nearly orthogonal (according to orthogonality criterion postulated in paragraph 3.1).

Table 3: The embedding of dimensions of perceptual space of wind instrument players into perceptual spaces of piano players (Piano) and composers and conductors (ComCon). The correlation coefficients are denoted as R_E (Embedding) and R_{Di} (with Dimension i of Piano or ComCon space). The angles between embedding of dimensions are in degrees.

R_E	R_{D1}	R_{D2}	**Piano**	Dim 1
0.98	0.85	0.49	Dim 1	–
0.91	-0.49	0.76	Dim 2	**78**

R_E	R_{D1}	R_{D2}	R_{D3}	**ComCon**	Dim 1
0.99	0.98	0.10	-0.06	Dim 1	–
0.97	-0.14	0.94	-0.16	Dim 2	**88**

The embedding of dimensions of perceptual space of wind instrument players into the space of piano players is illustrated in Figure 2. The deviations of individual verbal attribute coordinates due to embedding are in Figure 3. Mainly the deviation of verbal attributes *cool*, *lucid* and *harsh* decrease correlation of embedding in the second dimension ($R_E = 0.91$).

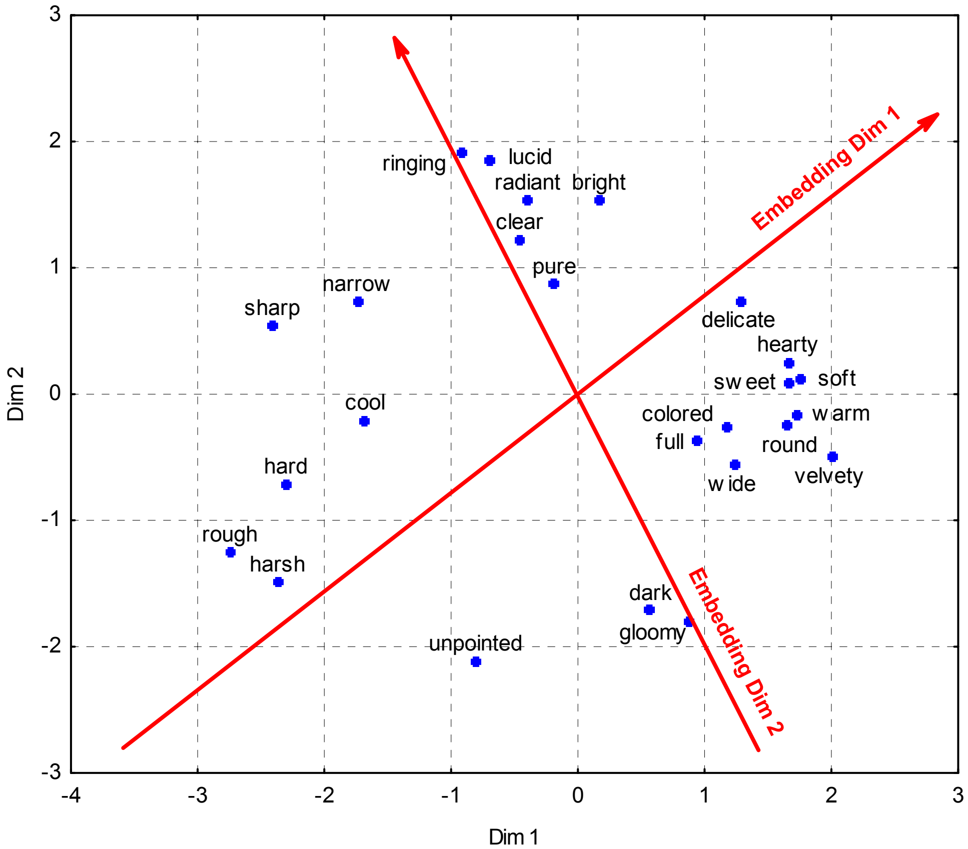

Figure 2: The comparison of perceptual spaces of verbal attributes used for the description of timbre. The embedding of dimensions of wind instrument players into the space of piano players is marked by arrows.

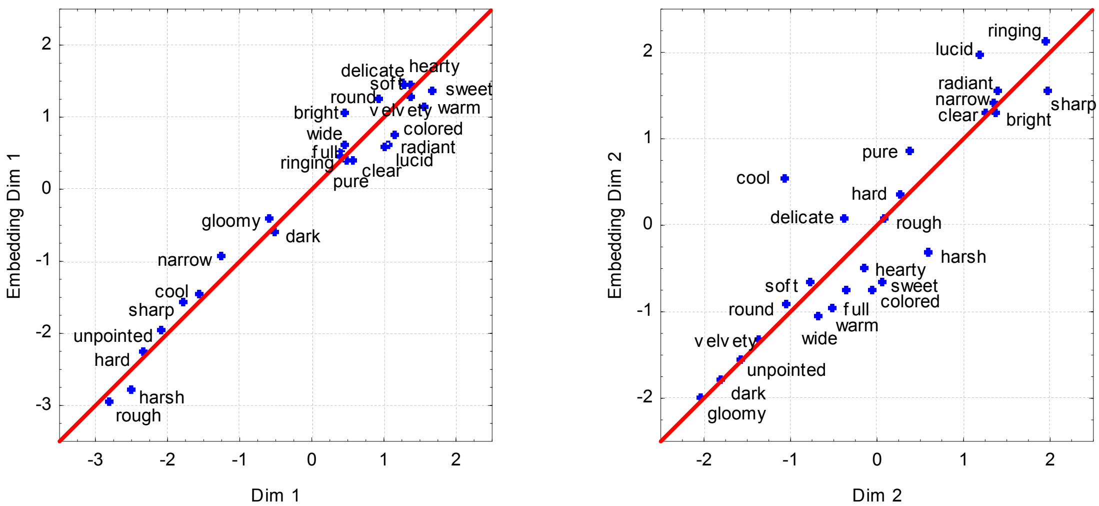

Figure 3: The embedding of dimensions of wind instrument players into the space of piano players. The deviations of coordinates of individual verbal attributes due to embedding for both dimensions.

The embedding of dimensions of perceptual space of wind instrument players into three-dimensional space of composers and conductors is illustrated in Figure 4. Dimension embeddings are nearly orthogonal. It is evident from correlations R_E but also R_{D1} and R_{D2} (Table 3) that the first two dimensions of both spaces are very similar, this is also visible in Figure 4 where dimension embeddings determine plane close to the plane of the first two dimensions.

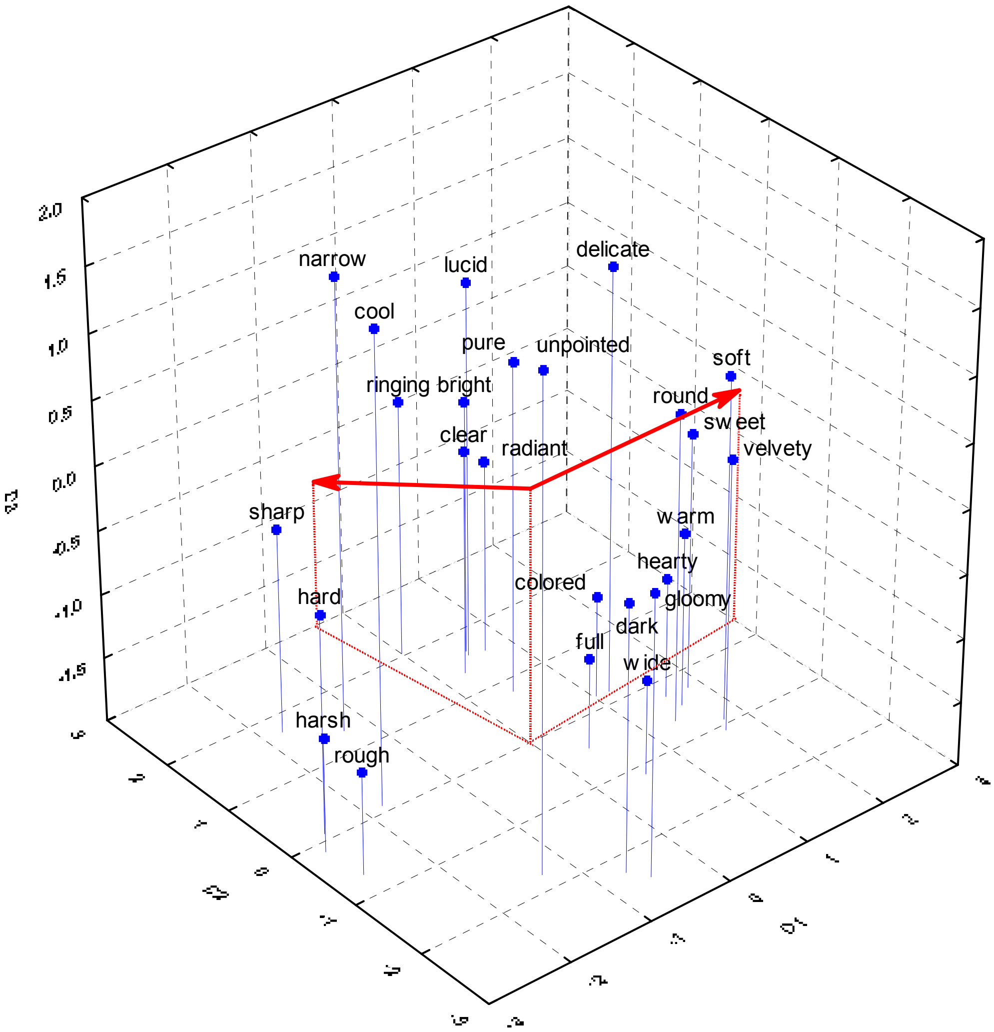

Figure 4: The comparison of perceptual spaces with unequal number of dimensions. The embedding of dimensions of wind instrument players into the space of composers and conductors is marked by arrows.

4. DISCUSSION

We will discuss not only the results of embedding, but we will also compare the potentiality of embedding with other commonly used methods of perceptual space(s) interpretation and comparison.

4.1 Embedding and Other Methods of Interpretation

The system of embedded external scales describing perceptual space in two-dimensional case may be created with only two nearly orthogonal embeddings. In the perceptual space of violin timbre of tone G5 this system can be created by two acoustic characteristics, for example first and second harmonic (Table 1) but it is interesting to take into account also embedding of spectral centre of gravity as an alternative (nearly opposite) to the first harmonic. In the embedding of verbal attributes we have also more possibilities: *Sharp* (*soft*, *round*) and *narrow* (*voiced*?). This system actually offers new dimensions of perceptual space (rotation), which is seen in Figure 1. Also view of mutual positions of directions between acoustic characteristics and verbal descriptions can be inspiring for the better understanding of perceptual space (*sharp* "between" f_{cg} and B23&B24, *voiced* "between" B23&B24).

Commonly used method of perceptual space interpretation using correlation of external scale with dimension coordinates (shown also in Tables 1 and 2) gives similar results only in the case of small angle contained between some of the dimensions and embedding. This is for example valid for f_{cg} and H1 and the first dimension (see Table 1 and Figure 1), but for very successfully embedded *soft* attribute we even did not get significant correlation with any dimension.

The embedding may fail in the situation of "central" property which decreases in all directions from the centre of perceptual space but in this case fails the correlation too. A suitable solution can be the use of regional interpretation of perceptual space [1, 8].

4.2 Embedding and Other Methods of Comparison

The implemented method of embedding is possible to use in many situations of comparison of perceptual spaces. The dimensions of one space can be embedded into the second one in case of test results like test – retest, separate evaluation of different listener groups (see example in the paragraph 3.2). The only conditions for it use are the same objects of both perceptual spaces and orthogonality of dimensions (uncorrelation is not necessary). Compared perceptual spaces may have different number of dimensions. The method of embedding of dimensions is a local comparison of perceptual spaces, each dimension is embedded independently and thus it can show only partial (dis)agreement of compared perceptual spaces.

In presented examples we can see successful agreement of perceptual spaces of wind instrument and piano players (both dimensions were successfully embedded) even if with dimensions rotation (Figure 2), whereas embedding of perceptual space of wind instrument players into space of composers and conductors was successful including position (contained angles) of corresponding dimensions (Figure 4).

When we compare only corresponding dimensions using correlation (R_{Di} in Table 3), it significance can be decreased in the case of rotated embeddings (left part of Table 3). The Procrustean similarity transformation (minimizing the sum of squares of distances between corresponding space objects using rotation, reflection, dilation and translation of one space to target space) [1] provides global comparison of spaces and can be used directly only for the comparison of spaces of equal dimensionality. Also the existence of "outlier" objects or dissimilarity of some specific dimension (or space direction) may distort the results of the transformation of "similar" objects or dimensions between spaces. Common configurational similarity measure does not exist and up to now proposed measures can led even to the misinterpretation [1].

5. CONCLUSIONS

The embedding method described in this article is suitable for both interpretation and comparison of perceptual spaces. This method is an improvement of correlation analysis, adjusts more precisely to data, and implemented algorithm enables its use also for perceptual space with correlated dimensions. In the combination with the regional interpretation is powerful in interpreting perceptual space. Even if it gives only local or partial description of similarity between perceptual spaces, in the case of successful embedding of all dimensions the results are comparable with Procrustean rotation. The "outliers" are identifiable for proper treatment. Moreover it can be simply used for the comparison of spaces with unequal number of dimensions.

ACKNOWLEDGEMENTS

The research was supported by the Ministry of Education and Youth of the Czech Republic, Project No. 1M6138498401.

REFERENCES

[1] Borg, I., Groenen, P., *Modern Multidimensional Scaling, Theory and Applications*, Springer-Verlag, New York, 1997.

[2] StatSoft, Inc., *STATISTICA (data analysis software system)*, version 6.1, www.statsoft.com, 2003.

[3] Vorländer, M., 'Ein Strahlverfolgungsverfahren zur Berechnung von Schallfeldern in Räumen', *Acustica* 65, 138-148,1988

[4] Winsberg, S., De Soete, G., 'A latent class approach to fitting the weighted Euclidean model, CLASCAL', *Psychometrika,* 58: 315-330, 1993.

[5] Štěpánek, J., Otčenášek, Z., Listener common and group perceptual dimensions in violin timbre, *Proc. of the Stockholm Music Acoustics Conference (SMAC 03)*, Stockholm, 663-666, 2003.

[6] Štěpánek, J., Otčenášek, Z., 'Acoustical correlates of the main features of violin timbre perception', *Proc. CIM05 Montréal*, Québec, Canada, electronic proceedings, file: STEPANEK_J_CIM05_01.pdf, 2005.

[7] Štěpánek, J., Moravec, O., Verbal description of musical sound timbre in Czech language and its relation to musicians profession and performance quality, *Proc. of CIM05 Montréal*, Québec, Canada, Electronic proceedings, file: STEPANEK_J_CIM05_02.pdf, 2005.

[8] Štěpánek, J., 'Relations between perceptual space and verbal description in violin timbre', *Proc. acústica 2004*, Guimarães, Portugal, CD ROM, AFP 077-S, 2004.