# Метод звуковых матриц в мультисенсорной аналитике для анализа многомерных скалярных полей

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*В наши дни трудно представить современные научные исследования без использования инструментов визуальной аналитики. Исследователи столь же часто анализируют науные данные на базе анализа поставленных им в соответсвие графический изображений, как и в повседневной жизни люди судят о предметах в основном на базе визуальной информации о них. Однако получать и анализировать информацию о мире вокруг можно не только с помощью глаз, но также и других органов чувств. Анализ научных данных мог бы быть существенно более эффективен при подключении дополнительных органов чувств. В данной статье представлен подход мультисенсорного анализа, обсуждаются теоретические вопросы, описаны основные концепции разработанных программных приложений, реализующих подход, представлен один из возможных видов аудио-визуального мэппинга для решения задачи анализа многомерных скалярных полей, так называемые «звуковые матрицы», и приводятся практические примеры анализа многомерных скалярных полей.*

***Ключевые слова:*** *научная визуализация, многосенсорный анализ, FRep, сонификация.*

# Sound Matrices approach in multisensory analytics: for multidimensional scalar fields data analysis

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*In our day it's hard to imagine modern research in sophisticated scientific area without use of visual analytics tools. It's become so common for scientists to obtain conclusions about scientific data on base of visual information as for people in their everyday life to make judgments about things on base of what they see. However, humans are able to receive and analyze information about world around them not only through their eyes, but with help of other sensory stimuli as well. Consequently, it would be not reasonable for researches to limit themselves to only one sensory stimuli in their research. In this work we introduce multisensory analytics approach, discuss theoretical issues, introduce main concepts of software tools implementing our approach, describe one of the possible auditory-visual mappings methods for multidimensional scalar fields analyses, that we called "sound matrices" and give practical examples of multidimensional scalar fields analyses.*

***Keywords:*** *scientific visualization, multisensory analysis, FRep, sonification.*

## 1. Multisensory visualization in modern research. Related works

Visual analysis of graphical representation of data has practically become a part of modern scientific research. It should be taken into consideration that researchers, as all people of creative professions, are predisposed to spatial creative thinking, so in the process of analysis of scientific data, they usually readily refer to various spatial and graphic images. This is one of the reasons, why scientific visualization and it's successor visual analytics as a method of data analysis has proven to be a very efficient tool often used by researchers. A quite general definition of visualization is "a binding (or mapping) of data to a representation that can be perceived" [1] is used more often nowadays and thus visual analysis is extended to become multisensory analysis. Among the sensory stimuli other than visual, the usage of sound has been widely investigated since early 80-s [2], [3]. The human auditory perception is considered most quantitative because of its sensitivity to subtle changes in the sound characteristics. The technique of data representation using variable sound characteristics such as pitch, volume, note duration, rythm and others is called data sonification [4]. Let us look at sonification method characteristics more closely. Auditory perception has always been the human's early warning system, which may operate in the background mode. In [5] a small survey was made on the situations when using audio analysis may be even more effective than visual perception. The main classes of data that fall in this category are time-varying data and multidimensional data. The auditory perception brings the unique advantage to distinguish even small variations in the parameters of the single sound wave and to compare sound waves and thus can efficiently complement standard visual analyses, and help solving perceptional issues it often has to face

[6], [7]. As it was already noticed in [8] currently, it is considered that any person may be trained to develop an ear for music and ability to adequately judge on all its nuances allows one to take advantage of the most advanced extended sound analysis capabilities as well. In [9] the procedures of time-varying data representation in the graphical form using a musical accompaniment are considered. In the paper [10], there are examples of the presentation of scientific data in the form of musical fragments. This is largely a matter of sensory capabilities of a specific researcher, but in general in some cases just sound mapping and analyses can be sucessfully carried out. We will consider such possibility in this article, however, we are mostly concentrated on efficiently combining auditory and visual perception approach, that allows one to significantly enhance the ability to conduct analysis, taking advantages of two sensory organs that work differently, and to perceive the same information in different ways complementing each other. An extension of visualization through creating additional perceptual human inputs or more general a combination of several sensory stimuli for data representation is called data perceptualization [11], [12] (or data sensualization [13]). The typical combinations are between visual and auditory stimuli, visual and tactile/haptic stimuli [14], or three of these stimuli applied together [13]. As it was already mentioned in this article, we will concentrate on a visual-auditory data analysis practical case, although theoretical formalizations of establishing correspondences between the initial data and multiple sensory stimuli for multisensory analysis are assumed and were given in [15]. However, the problem of formalization of multiple sensory stimuli analysis and interpretation of analysis results in terms of initial data should be solved separately for each sensory stimuli.

## 2. An approach to multisensory data analysis pipeline. Visual-auditory analysis case

To obtain a multisensory representation we need to create a spatial scene [8], which is an assembly of spatial objects with their geometric, optical, sound and others descriptions. Then corresponding visual, sound and other stimuli can be generated using some specialized rendering procedures for further multicensory analysis. Based on the visual analytics process as presented in [16] and the idea of an intermediate multidimensional geometric representation of initial data [17], we proposed [8] the following interpretation of the basic multisensory analysis process 1.

In the diagram 1 perceptualization process is presented as a transformation (mapping) M: D -> I from initial data D to insight I, which is the goal of the entire process. The mapping M is a superposition of mappings from one set to another in the diagram. Thus, the initial data undergo geometric interpretation and are mapped to the set G of multidimensional geometric models. The next step is to generate several sensory stimuli SS for human perception. The mappings from G to SS are facilitated by the introduction of a spatial scene, which is an assembly of spatial objects with their geometric, optical, auditory, tactile and other properties (multimedia objects). Note that the geometric objects in the spatial scene can have their dimensionality reduced to 2D and 3D using geometric cross-sections and projections, which allows for applying well-known graphical rendering algorithms. When such a spatial scene is constructed, various sensory stimuli can be generated using corresponding rendering procedures: visual stimuli V (graphical images), auditory stimuli A (sounds), tactile and haptic stimuli T, and others. Te final insight I can be either directly obtained from the generated sensory stimuli through human perception and analysis, or it is obtained in a combination with generating a hypothesis H and its analysis including automated methods. Note that the hypothesis H can be also represented with visual and other sensory stimuli, which can help to refine or redefine it in the process of analysis. The entire process has iterative character, which is shown by the feedback loop in the diagram. The user may tune or redefine not only the parameters of the data input, but also the introduced geometric models, the hypothesis, the selection of sensory stimuli and the type and parameters of rendering procedures. Applying the presented general approach the process of data analysis involving both human vision and hearing, we need to do the following:

1. To obtain a mapping of the given data onto its representation in the form of images and sound. To obtain a necessary model of a spatial scene, its geometric and optical models need to be extended by a sound model. Such a spatial scene augmented with sonification needs to be put in correspondence to the given data and then sound rendering can be applied with output to speakers or some other sound output device for further analysis.
2. To analyze the rendered images and sound and to interpret the results of this analysis in terms of the initial data.

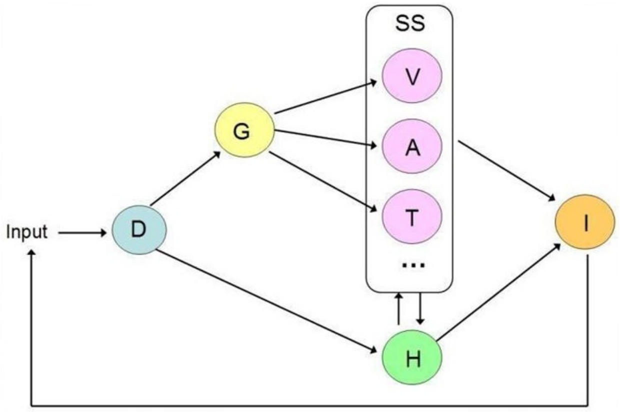
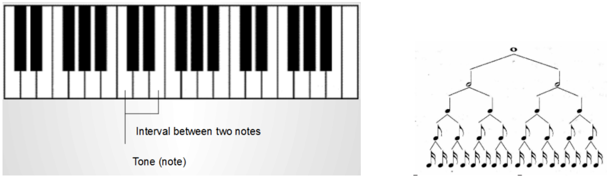


**Fig. 1.** Multisensory analysis process.

The definition of corresponding sound mappings that can be concretely analysed and easily interpreted by researchers is also a question that should be studied. Here we suggest that a researcher in common case should be trained to interpret some not quite evident sound mappings similar to musicians training their ears for further music analysis in modern practice . In our work, we take advantage of musicians' approach adopting well-known concepts of music analysis and writing used by musicians from simple properties of sound analysis (pitch, volume, duration, etc.) to "music" properties analysis (tone, interval between tones, etc.). These concepts are taken as the base of sound mapping and accordingly of sound analysis. 2 presents some musical (sound) characteristics that musicians may distinguish auditory and describe quantitatively: tone, note duration, interval between two notes are most often used ones.



**(a)** Aurally measure interval between two notes and determine tone (note itself). For this a musical scale used in musical composition should be defined first of all (minor, major, based on C,D,F note and etc.).

**(b)** Measure note duration. The basic rhythm parameters in musical composition should be defined first of all.

**Fig. 2.** Musical sound characteristics musicians may distinguish aurally.

In this article, only simple cases of sound analysis, cases that for advanced analysis require some musical training (e.g., to determine interval and note) will be considered. From authors point of view, a camera, a sound receiver, a haptic cursor and other similar elements need to be explicitly placed in the spatial scene as spatial models of the human organs of perception. Thus, a spatial scene includes spatial objects representing data as well as other spatial objects representing their influence on human senses. Rendering of the spatial scene generates information for output devices provided for consideration by humans, namely a screen, speakers, a haptic device and others.

## 3. Multimedia coordinates based approach for visual-auditory analyses

Although some efforts have been made on the development of data perceptualization, a formal framework for establishing correspondences between data and multiple sensory stimuli has not been yet proposed. In [15] we introduced a framework based on the concept of multimedia coordinates introduced previously in [18] and applied in multidimensional shape modeling. The approach is formalization of mapping from a multidimensional geometric model to a multimedia object that can be treated as a multidimensional object with Cartesian, visual, audio, haptic and other types of multimedia coordinates. To operate with multimedia coordinates, one can introduce a system of normalized numerical coordinates (a unit cube) and its one-to-one correspondence to the multimedia space. By selecting a real normalized value, one can use the corresponding value of the multimedia coordinate [15]. Each geometric coordinate variable takes values within a given interval and multimedia coordinates also have their own variation intervals as well. So to define the mapping, one has to establish a correspondence between these intervals through the normalized numerical coordinates. Thus a space mapping between geometric coordinates and multimedia coordinates establishes correspondence between the multidimensional shape and the multimedia object. In this way, a correspondence can be also established between the given scientific data and a multimedia object, because introducing a multidimensional geometric model is one of the steps in the visualization pipeline presented previously. As for multidimensional geometric model involved in multisensory visualization we used approach based on a constructive method to the creation of function evaluation procedures for geometric shapes, called the Function Representation (FRep) [19] and it's extension HyperVolume [20], where the object is represented not by a single function, but by a vector-function with one component responsible for the object geometry and other components serving as point attribute functions representing such object properties as material, color, transparency, sound characteristics and others.

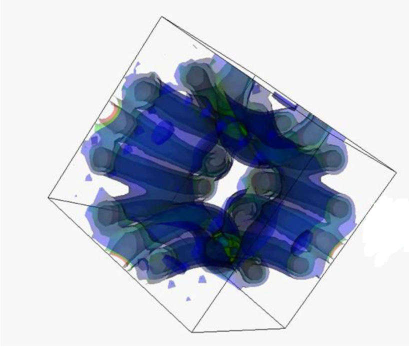
Thus both multimedia coordinates and hypervolume model for describing multimedia object are quite interconnected within presented approach used. To visualize a multidimensional geometry (or scalar field) special methods and geometric modelling techniques controlled quite well within multimedia coordinates concept are used. Usually they are:

1. Use of several semitransparent colored isusurfaces (see example (3(a)) in case when dimensionality of geometric object is not greater then 4D.
2. Projections on a subspace [PAS*96].
3. Cross-sections (see example 3(c)).

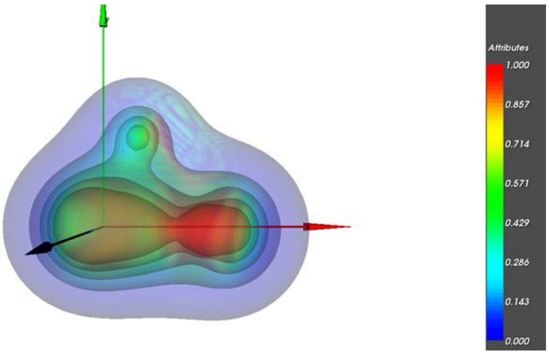
For more effective analysis these geometric operations may be defined interactively, through providing some specialized interactive widgets (plane, hypercube widgets to define cross-section and etc.). Also some special types of spatial scene may be introduced to provide special graphical representations called "matrices of cross-sections" or spreadsheats. An according type of multimedia coordinates was introduced in [18] and is called "spreadsheet coordinates". This type of coordinates allows for spreadsheet-like spatial organization of elementary images or shapes in the regularly or irregularly placed 1D, 2D or 3D nodes. In this work we will consider the case of a 1D node. Let us consider a simple case of 1D spreadsheet on Fig.3 (c) with the specific types of multimedia coordinates:

1. "x", "y" and "z" types correspond to world coordinates in the Cartesian coordinate system. They are used to describe a set of 3D isosurfaces f(x,y,z)=c
2. "c" type corresponds to a photometric coordinate, namely the color.

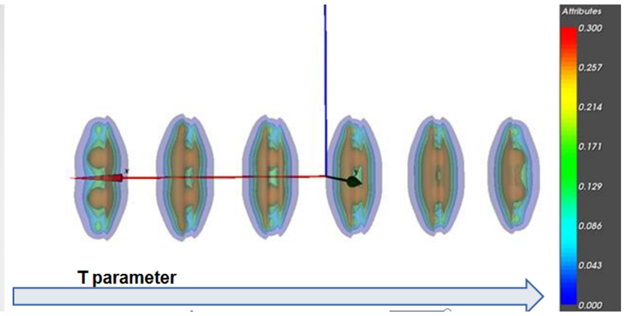
3. ”v” type correspond to 1D spreadsheet coordinates. By assigning its discrete values we construct a horizontal 1D spreadsheet. Each section in Fig. 3 represents a 4D geometric object, displayed with 3D isosurfaces f(x,y,z)=c, where c is as well mapped to a photometric coordinate.



**(a)** Visualization of scalar order-parameter field distribution.



**(b)** Visualization of electron dencity and electrostatic potential field of NCH molecule.



**(c)** Visualization of dynamic electron dencity field of C2H2 molecule with use of spreadsheet technique.

**Fig. 3.** Examples of static and dynamic scalar fields visualization.

It should be noted that we have to reduce dimensionality not only to obtain graphical representation, but as well to map our data into sound and other type of sensory stimuli. So we have to introduce other type on spreadsheet coordinates, that will be called multisensory spreadsheet coordinates in general case. In[8] we demonstrated basic interactive techniques, when sound with predefined by data characteristics is produced in selected point. In this article we are concentrating on more extended approach that we called Sound Matrices that in general may be used by researches without preliminary theoretical knowledge in music analyses, although these knowledge will make analyses more efficient and extended, and on base of them analyses may be carried out even without visual information. We'll give detailed examples and explain analyses process in details. As previously[8], we propose some generalizations on base multimedia coordinates approaches for specific type of multidimensional data multisensory analysis - scalar fields, bringing together some most well known interactive, photometric and geometrical techniques and demonstrating how they can be extended by other multisensory techniques on the example of sound.

## 4. Framework main features, cases examples

The presented below results of visual-auditory analyses were obtained with developed framework, based on HyperVolume object that influences various sensory stimuli (visual and sound in particular case) conception as base for computer scene model in multisensory analyses pipeline. The framework is designed on base of OpenSource projects VTK [23], Hyperfun [22] and OpenAL [24] in a form of API for writing standalone applications using C++ and scripting languages Hyperfun and Python. To summarize, we've tried two approaches to scalar fields data mapping to sound characteristics:

1. Direct sound characteristics mapping (frequency, volume) and generating wave with specified parameters. This an approach we've tried in our earlier works that helped us to make basic judgements on changes on specific mapped value (it's growing or falling and etc.) [15].
2. Mapping to abstract “musical terms” and operating them in entire analyses process. Notes, intervals, musical scale, musical instrument used, etc. As it will be demonstrated below this approach provides possibilities for more extended analyses.

As it was noted previously, in multimedia coordinates concept multimedia coordinates also have their own variation intervals, for example, color varies inside the color space (RGB cube). It's a well known that to judge about geometric value mapped into color an according color scale is used. Similarly, in music theory, there is an approach to judge about notes on base of their position on a specified scale (Cmaj for example), in other words, relative to the tonic, the first and main note of the scale from which each octave is assumed to begin. So in music terminology, that we adapt each note has a scale degree, that is it's position on scale. Example of C-major scale with according scale degrees C–D–E–F–G–A–B, in which C is the tonic). Usually such degrees are quite easy to learn to distinguish aurally after some special tuning for specified scale (a basic exercise in musical training). It is possible to assign a scale degree to the 12-tone chromatic scale, but this distinguishing such degrees and intervals variety is more difficult and demands training. In our framework we've chosen as base for sound analysis Cmajor scale of 1-3 octaves. Notes sound generated on piano, guitar, flute or other instruments of user choice. As we mainly concentrate on a simple rendering cases, easy to perceive and analyze, the cases believed that practically anyone (without no damage of hearing system) can can be capable to perceive and analyze after some simple harmonic ear training ( musical school level) we introduce following data preprocessing steps in order to take into consideration perception issues of musical training and analyses as well: If we consider visual analyses of scalar fields, on base of visual information we mainly carry out two forms of analyses:

1. Shape analyses.
2. Feature analyses, in particular change in form.

Sound analyses also permits to judge about these and in particular efficient in all sort of changes detection as it was mentioned above. But we are limited by value of interval between notes that we may distinguish aurally to perform more extended analyses (not only to judge it value is growing or decreasing or by what value it changed). Usually we aurally quite easy distinguish changes by interval from “whole tone” (for some well-trained users it is “semi tone”). And it’s more easy to work with scale of 2 octaves or one. The obtained scalar values are mapped into degrees on Cmaj 1-2 octave scale. So, for example 1 octave, that has 8 degrees represent values within selected [xmin, xmax] range. So [xmin, xmax] range is spitted on 8 subranges [Ximin, Ximax] in order each degree represents scalar value within according subrange. Like this researcher may judge on approximate scalar value aurally by according not (degree on Cmaj scale). As well in order to improve analyses we suggest user may remove “unnecessary” information he may neglect in analyses process. So we suppose user may do following recommended image preprocessing steps, before mapping to sound:

1. ImageThreshold – to remove scalar values not falling into selected range [xmin,xmax] we are interested in or may perform first step analyses without. For example, if we deal with some CT of medical organ within body it has signal within given range and we want to analyze only shape boundaries and it’s internal structures.
2. Morphological operations on selected boundary– to remove small “island like” parts and smooth shape boundary, to reduce noise caused artifacts.

This preprocessing steps are conditional, however they may significantly increase analyses efficiency.

It should be noted that in general approach is quite similar to basic techniques used for organ segmentation in image processing as entire procedure of segmentation helps in particular to analyze organs better visually. The used sound mapping technique we implement is similar to one used in medicine as well, where 3D image scan is previewed and analyses mostly as a set of 2D image slices, where scalar value is defined at each pixel with color. We project in general case multidimensional geometry to 4D space x,y,z,f and build with defined step it’s crossections zi=ci that represent 2D sound images where instead of pixel position we have sound source defined by x,y values and f is mapped according musical degree on Cmaj scale. We fix one by one some yj=cj values within y range and moving sound automatically with defined step xi along x axis with fixed yi we sonify our 2D image line by line, thus obtaining what we call “sound matrix”. Below on 4 is presented 2D image slice of simple 4D scalar field, presented on 3a and notes of according played sound matrix 6x6, that “duplicates” the same information that we analyses visually. To simplify auditory-visual analyses the scalar field was preprocessed with image threshold technique in order to exclude from analyses all values greater than 0.5 (on image marked with wight color), so C3 (C note of first octave) is played in all this range.

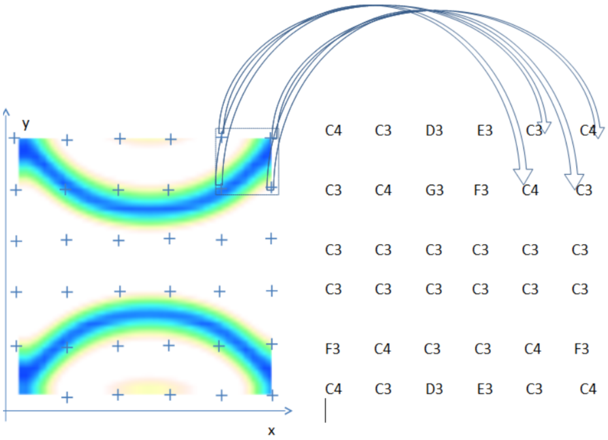


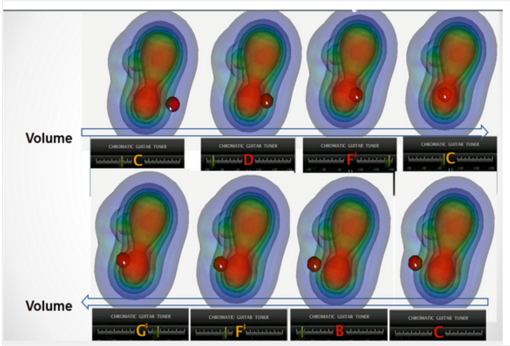
**Fig. 4.** Visualization of scalar order-parameter field distribution selected crossection and according sound matrix with defined resolution 6x6.

It should be noted that different approaches depending on musical practical knowledge of researcher that analyses data with sound should be taken into consideration as well. So to move from basic analyses of scalar field main features (approximate form, symmetry) into details, we suggest the analyses process reiterativeness in general case, so it’s complexity may vary. This may suggest mapping to bigger interval, or readjusting or removing some preprocessing steps described above, or increasing sound matrix resolution to perform more detailed shape analyses. This may as well include additional interactive selection of image region of interest and it’s sonification, a technique that will be demonstrated further.

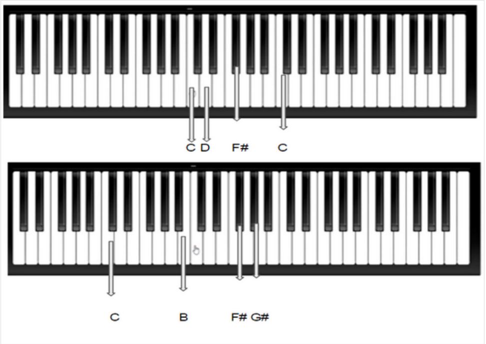
As in our case we mostly concentrate on use of the advantages and particularities of human hearing system (alarming system, that may operate is silent mode, those perception principles are quite different comparing to visual system) in analyses process in order to enhance it’s efficiency we suggest it’s most efficient combination with visual analyses . It should be noted that visual information content may duplicate those mapped in sound, or some extended techniques for image features extraction and visualization may be used as combination with sound analyses.

In example below, we'll concentrate on molecular fields as their form in crossection in general case is quite simple (one or several spheres) and in case of such fields usually some general features are subject of study (symmetry, how fast is changing and etc.).

In[8] we've studied in detail a auditory-visual analyses of two molecular scalar fields, presented on 3(b) that are supposed to by analyzed together (a quite usual task in physical or medical research filed). In studied auditory-visual analyses case the sound wave was generated by a sound terminal with the frequency corresponding to the location of the point sound source and perceived by the user as a specific sound tone. Each sound tone generated at the location of the point source was defined on selected 2 octaves musical Cmajor scale 5. Here we receive following tones presented in 5(a) and can graphically present their place on musical scale 5(b). Here a basic guitar tuner was also used to illustrate the current note value 5(a).



**(a)** The use of an interactive "sphere" widget to define sound frequency w and volume v of the generated sound defined by the functions A2 and A3 values at fixed values of world coordinates x,y,z.



**(b)** Presentation of according notes on Cmajor scale (2 octaves) on piano. A researcher with well-trained musical ear and appropriate «auditory tuning" on Cmajor scale can easily aurally determine these notes and their place on piano musical scale and judge about how quantitatively sound was changed.

**Fig. 5.** Exploration of two scalar fields dependency and change with pitch and volume.

We may as well study both scalar fields slice by slice, obtaining crossections with z=zi while moving along z axis with defined step 6.

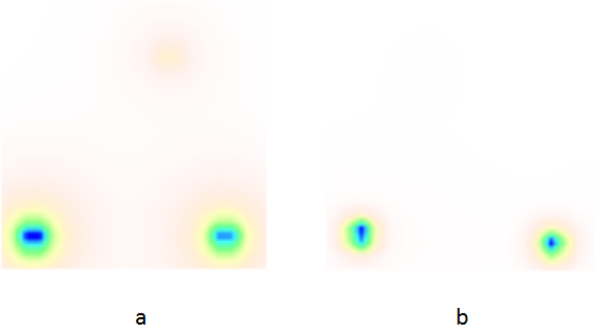
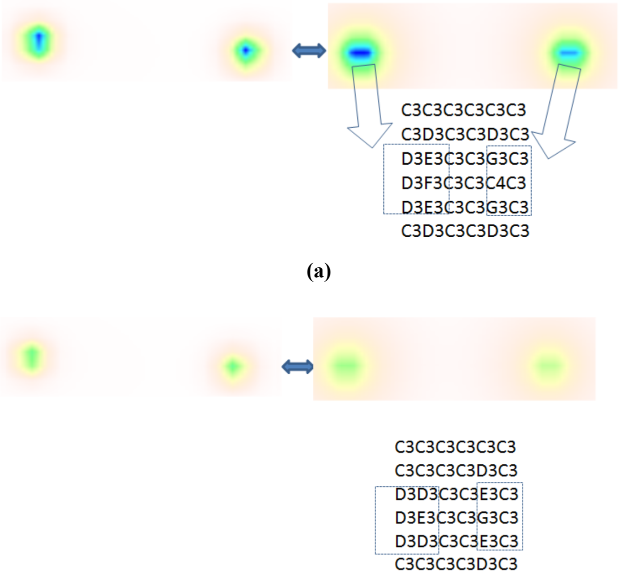


**Fig. 6.** Visualization of scalar fields selected crossections z=0, electrostatic potential(a) and electron density(b) accordingly.

Such mapping will help us to define region where both scalar fields take biggest values and detect that their intensity spread can be characterized as caused by point source type (atoms position) for both fields, but those centers are a bit shifted in electron density field (a shift that is even hard to distinguish visually). The alternative to this approach may be selection of region of interest, where both fields take biggest value and simultaneous visualization of selected crossections of one field (electron density) and sonification through sound matrix mapping of obtained crossection of second field (electrostatic potential) as presented on 7. This will permit us to immediately and easily detect the main trend as sound matrix of second field will demonstrate practically symmetrical trend.



C3C3C3C3C3C3
C3D3C3C3D3C3
D3E3C3C3G3C3
D3F3C3C3C4C3
D3E3C3C3G3C3
C3D3C3C3D3C3

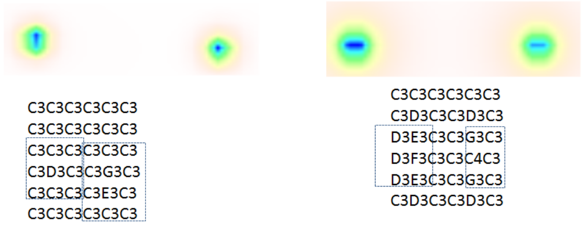
**(a)**

C3C3C3C3C3C3
C3C3C3C3D3C3
D3D3C3C3E3C3
D3E3C3C3G3C3
D3D3C3C3E3C3
C3C3C3C3D3C3

**(b)**

**Fig. 7.** Visual auditory analyses by selected crossections (a,b) and sound matrixes of two scalar fields electron density and electrostatic potential accordingly of CNH molecule.

As well, to judge about difference in scalar field value change more efficiently we may compare generated sound matrices for two scalar fields, but for such analyses 8.



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C3C3C3C3C3C3
C3C3C3C3C3C3
C3C3C3C3C3C3
C3D3C3C3G3C3
C3C3C3C3E3C3
C3C3C3C3C3C3
```

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C3C3C3C3C3C3
C3D3C3C3D3C3
D3E3C3C3G3C3
D3F3C3C3C4C3
D3E3C3C3G3C3
C3D3C3C3D3C3
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**Fig. 8.** Visual-auditory analyses by selected crossections of two scalar fields. Sound matrix comparison.

## 5. Conclusions

In conclusion it may be said that the formalization of the mapping between the multidimensional geometric models and the spatial scene available for rendering multiple sensory stimuli is a big research question, still to be address. However, we have shown a possible solution in the case of the initial data represented by scalar fields (real functions of several variables) and illustrated this by the case study of the scalar fields analysis using interactive visual-auditory display on base of two possible techniques. Different types of interactive visual-auditory or auditory widgets, not only those based on combination of described two, as well as different types of sound mappings can still be studied as well as possible image preprocessing techniques that are used to simplify analyses orocess. We are planning to continue to involve the concept of multimedia coordinates as a way to establish even more complex correspondences between initial data, the introduced multidimensional geometric models and multiple sensory stimuli.

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