Multisensory Analytics: Case of Visual-auditory Analysis of Scalar Fields

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Abstract: A well-known definition of visualization is the mapping of initial data to a visual representation, which can be perceived and interpreted by humans. Human senses include not only vision, but also hearing, sense of touch, smell and others including their combinations. Visual analytics and its more general version that we call Multisensory Analytics are areas that consider visualization as one of its components. We present a particular case of the multisensory analytics with a hybrid visual-auditory representation of data to show how auditory display can be used in the context of data analysis. Some generalizations based on using real-valued vector functions for solving data analysis problems by means of multisensory analytics are proposed. These generalizations might be considered as a first step to formalization of the correspondence between the initial data and various sensory stimuli. An illustration of our approach with a case study of analysis of a scalar field using both visual and auditory data representations is given.

1 INTRODUCTION

Visual analysis of graphical representation of data has practically become an essential part of modern scientific research. Through applying analytical reasoning facilitated by visual representations hypotheses about the data can be either confirmed or rejected leading to a better understanding of the data and subsequently about a phenomena that data represents. Such a reasoning process using visual representations of data is called Visual Analytics (Wong, 2004; Keim, 2008).

Nowadays we deal with processes of intensive human interaction with large amounts of data offering the prospects of extracting useful hidden information. The growing complexity and amount of raw data require expanding the means of visual analytics, involving multimedia, virtual and augmented reality, tactile and haptic devices, 3D printing and other means of information representation for human perception and analysis. A general definition of visualization as "a binding (or mapping) of data to a representation that can be perceived" (Foley, 1994) gives the ground to expansion of visual analysis to become multisensory analysis. This expansion requires involving other human senses besides vision, namely hearing, sense of touch and others. Involving multiple human senses into the process of data analysis and analytical reasoning is the main feature of the Multisensory Analytics approach as an extension of the Visual Analytics. From the authors' point of view, this approach can be the next emerging topic in the field of comprehensive data interpretation and analysis.

The formalization of the multisensory analytics process and particularly of establishing correspondences between the initial data and multiple sensory stimuli is an open research question. In this paper, we propose a general approach to multisensory analytics and illustrate this approach with a case study of scalar fields analysis using hybrid audio-visual data representation.

2 RELATED WORKS

In this section we discuss related topics and concepts such as visualization and visual analytics, sonification and perceptualization, as well as geometric modeling using real functions.

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2.1 Visualization and Visual Analytics

Informally, visualization can be understood as making invisible visible, but more formally it can be defined as the process of transforming data into a visual form enabling viewers to observe and analyze the data (McCormick, 1987). Visual analytics as a method of data analysis is an extension of information visualization and scientific visualization with a focus on analytical reasoning enabled by interactive visual interfaces (Wong, 2004). Visual analytics software tools and techniques are used in various scientific disciplines to form certain judgments on the basis of the obtained data. Through applying analytical reasoning facilitated by visual interfaces, hypotheses about the data can be either confirmed or rejected leading to a better understanding of the data (Keim, 2008). The paper (Keim, 2008) introduces a formal description of the visual analytics process as interconnected mappings from initial data to some insight, which can be either directly obtained from generated visual representations or in a combination with automated analysis methods. We will provide a similar formal description for the proposed approach to multisensory analytics.

While (Keim, 2008) mentions a single-step mapping from a data set to its visual representation within the visual analytics process, (Pilyugin, 2013) goes further and states that to obtain such a visual representation (or a graphical image), one needs to put some geometric model (multidimensional in the general case) into correspondence with the initial data. It means that a spatial scene, which is an assembly of spatial objects with their geometric and optical descriptions, has first to be constructed and then a graphical image can be generated using some rendering procedure for its further visual analysis.

2.2 Sonification and Perceptualization

Among the sensory stimuli other than visual, the usage of sound has been widely investigated since early 80-s (Yeung, 1980; Bly, 1982). 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 and others is called data sonification (Kaper, 1999).

Auditory perception has always been the human's early warning system, which operates in the background mode and requires full attention, only when the sound changes abruptly. In (Scaletti, 1991) a small survey was made on the situations when using audio analysis may be 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. Currently, it is considered that any person may be trained to develop an ear for music. A musical ear, traditionally viewed as a set of abilities that allows to fully perceive music and to adequately judge on all its nuances, but the presence of this ability allows one to take advantage of the most advanced extended analysis capabilities as well. In (Mezrich, 1984) the procedures of time-varying data representation in the graphical form using a musical accompaniment are considered. In the paper (Lodha, 1997), there are examples of the presentation of scientific data in the form of musical fragments. The software product MUSE presented in (Lodha, 1997) is the result of a collaboration of researchers and musicians. This is largely a matter of sensory capabilities of a specific researcher, but we can say that combining auditory and visual perception allows one to significantly enhance the ability to conduct analysis more efficiently, 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 (Grinstein, 1990; Ebert, 2004) or data sensualization (Ogi, 1996). The typical combinations are between visual and auditory stimuli (Grinstein, 1990; Jovanov, 1999), visual and tactile/haptic stimuli (Maciejewski, 2005), or three of these stimuli applied together (Ogi, 1996). Generalizing the above definition of visualization, we can say that the purpose of perceptualization is making abstraction perceivable.

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. The concept of multimedia coordinates was introduced and applied in multidimensional shape modelling and rendering (Adzhiev, 1999)). This concept provides a formalization of mapping from a multidimensional geometric model to a multimedia object including text, images, video, sounds and other types of sensory stimuli.

2.3 Function Representation in Geometric Modeling

In geometric modelling, the necessity of compact precise models with unlimited complexity has resulted in the development of the new paradigm of procedural modeling and rendering, where the geometric shape and properties are evaluated upon request using procedural rules. One of the approaches to procedural modelling is to evaluate a real function of point coordinates providing the point membership for the shape at the given point along with the measure of distance to its surface. A constructive approach to the creation of such function evaluation procedures for geometric shapes is called the Function Representation (FRep) (Pasko, 1995). FRep was extended in (Pasko, 2001) to the constructive hypervolume model, 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, and others. Later, it will be demonstrated that the use of the constructive hypervolume model can bring significant advantages to solving scientific data analysis problems.

3 AN APPROACH TO MULTISENSORY ANALYTICS

As it was mentioned above, multisensory analytics can be considered an extension of visual analytics involving more than one human senses in the process of data analysis. Based on the visual analytics process as presented in (Keim, 2008) and the idea of an intermediate multidimensional geometric representation of initial data (Pilyugin, 2013), we propose the following interpretation of the basic multisensory analytics process.

In the diagram (Fig. 1), the multisensory analytics process is presented as a transformation (mapping) M: D $\rightarrow$ 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.

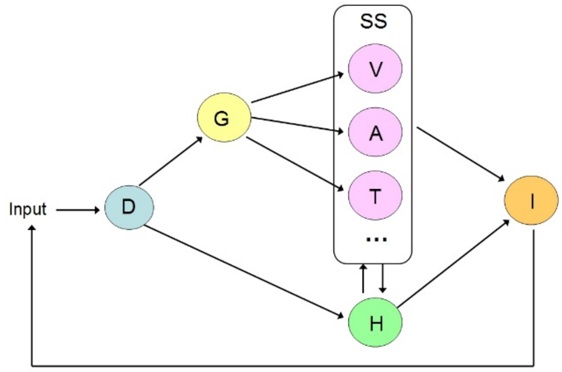

Figure 1: Multisensory analytics process.

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. The 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 define 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.

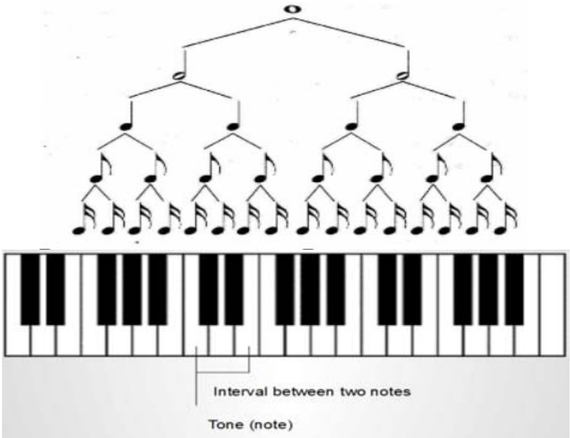

Figure 2: (Top) Aurally measuring the interval between two notes and determine the tone (note itself). For this a musical scale used in a musical composition should be defined first of all (minor, major, based on C,D,F note and etc.). (Bottom) Measuring the note duration. The basic rhythm parameters in a musical composition should be defined first of all.

The definition of the corresponding sound mappings that can be concretely analyzed and easily interpreted by researchers is also a question that should be studied. Here, we suggest that a researcher should be trained to interpret some not quite evident sound mappings similar to musicians training their ears for further music analysis. 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.

4 MAPPINGS VIA MULTIMEDIA COORDINATES

To obtain a multisensory representation we need to create a spatial scene, which is an assembly of spatial objects with their geometric, optical, audio and others properties. Then the corresponding visual, audio and other stimuli can be generated using some specialized mapping and rendering procedures for further multisensory analysis.

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. We believe that the concept of multimedia coordinates introduced previously in (Adzhiev, 1999) and applied in multidimensional shape modeling can be a good framework for formalization of mapping from a multidimensional geometric model to a multimedia object. This object can be treated as a multidimensional object with Cartesian, visual, audio, haptic and other types of multimedia coordinates, which represent various sensory stimuli. 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.

Fig. 2 presents some musical (sound) characteristics that musicians can distinguish auditory and describe quantitatively: tone, note duration, interval between two notes are most often used ones. In this article we deal with a particular type of musical hearing called harmonical hearing that is believed to be developed practically by everyone after some musical training (Zavadska, 2015).

From our 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. In this article we are going to go further and propose some theoretical generalizations about solving data analysis problem of complex multidimensional data by multisensory visual-auditory analytics.

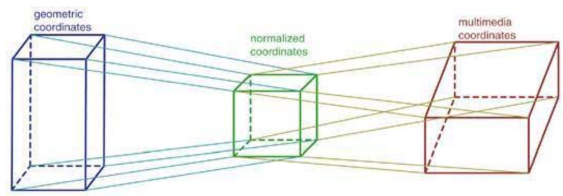

Figure 3: Mapping of geometric coordinates to multimedia coordinates.

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 (Fig. 3).

Each geometric coordinate variable takes values within a given interval. On the other hand, multimedia coordinates also have their own variation intervals. For example, a time interval means life time of the multimedia object, color varies inside the color space (RGB cube) and so on. To define the mapping, one has to establish a correspondence between these intervals through the normalized numerical coordinates.

There are some special ways of dealing with the above mappings. By assigning a finite set of constant values for some geometric coordinate, one can first reduce the dimensionality of the introduced geometric model before establishing some mapping to multimedia coordinates.

Generally methods and approaches that aim at visual analysis of geometrical objects representing multidimensional data are called multidimensional visualization methods (Wong, 1997). These techniques usually suppose not only reducing dimensionality through application of specific geometric operations, but mapping data to different photometric characteristics (color, transparency), and include interactive techniques as well. Most well-known of these techniques are covered by different types of multimedia coordinates, introduces in (Adzhiev, 1999), among them are:

- Dynamic coordinates represent continuous coordinates that can be mapped onto physical time
- Spreadsheet coordinates take discrete values in the given bounding box.
- Photometric coordinates include color, transparency, texture and other parameters of visual appearance of the multimedia object.

Another type of multimedia coordinates, mentioned previously is audio. In this paper, we propose some generalizations on the basis of multimedia coordinates approach for the specific type of multidimensional data multisensory analysis, namely of scalar fields, bringing together some most well-known interactive, photometric and geometrical techniques and demonstrating how they can be extended by other multisensory techniques involving sound.

5 MULTISENSORY ANALYSIS OF SCALAR FIELDS

On the basis of the proposed approach to multi-sensory analytics, let us describe the process for solving high dimensional data analysis problem involving hybrid visual-auditory representations. The data analysis problem can be formulated as follows:

Given - numerical data D describing the object under consideration;

Required - to obtain an insight I of interest to the researcher regarding the initial object.

Let us consider the solution of the above stated problem by reducing this problem to the following two problems solved one after another:

1) the problem of obtaining a multisensory representation (SS in Fig. 1) of considered data in the hybrid visual-auditory form;

2) the problem of human sensory analysis and interpretation of the results of the analysis with respect to the original description.

Note that we will deal here only with the upper path in the diagram in Fig. 1 from the initial data to sensory stimuli, leaving the hypothesis H formulation, visualization and analysis out of the discussion.

It should be noted that initial data may be multidimensional and very complex. From our experience of research in nuclear physics, chemistry and other disciplines, it is very often the case that the initial data can be presented as a set of real functions of several variables

$$f1(x1,x2,...xk)\ ,\ f2(x1,x2,...xk)\ ,\ ...\ fn(x1,x2,...xk)$$

or scalar fields in an abstract k-dimensional space describing different characteristics of a complex object under investigation. When the initial data is given in the form of discrete samples, it still can be presented in the above form by applying appropriate interpolation procedures.

There are two alternative ways to introduce a multidimensional geometric interpretation (set G in Fig. 1) of such a data. One is quite straightforward as each of the above set of real functions can be considered as a definition of a k-dimensional surface in a k+n-dimensional space. However, this interpretation can turn too abstract for the further multisensory perception and analysis. Alternatively, all the given data functions can be presented in the form of a vector function

$$f = (f1, ..., fn),$$

which then can be interpreted as an FRep constructive hypervolume model (Pasko, 2001) mentioned earlier. This means the function f1 is describing some multidimensional geometric object and all other components of the vector-function represent the attributes associated with this multidimensional geometric shape.

The latter geometric interpretation can effectively be used for constructing a spatial scene description that can be used by rendering procedures. If the number of independent variables xi k ≥ 3, we first need to assign constant values to some of the variables to reduce the space dimensionality to 2D or 3D. Then, we can assign one or several values to f1, which means applying geometric cross-sections and projections to obtain 2D or 3D geometric objects (isolines or isosurfaces correspondingly) for the spatial scene. The attribute functions f2, ..., fn defined on the obtained geometry can represent various object properties such as material, color, emitted sound, rigidity and others that can be directly mapped to sensory stimuli. Rendering of the spatial scene generates several sensory stimuli as outputs. This process will be illustrated in more detail by the case study below.

6 CASE STUDY OF VISUAL-AUDITORY DISPLAY OF SCALAR FIELDS

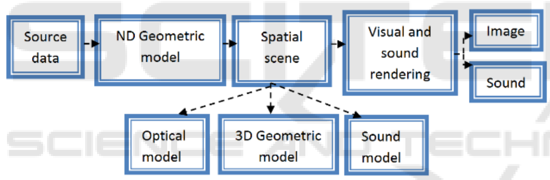

Figure 4: Effective multisensory analysis pipeline.

Let us illustrate the process of the multisensory analysis with a certain class problems, where given data represent various scalar fields. We will involve both visual and auditory stimuli in the analysis process. The effective multisensory analysis pipeline for this case study is shown in Fig. 4.

- Problem statement

The objects under study are an electron density field and an electrostatic potential field of CNH molecule. These two scalar fields are used to be analyzed together.

- Given

The mathematical model consists of the values of two real functions of three variables f1(x,y,z) and f2 (x,y,z), where (x,y,z) are coordinates of points in space. The fields are given in the tabular form at the nodes of a rectangular regular grid in the function's domain

- Required

To analyze variations of the functions depending on changes of independent variables x,y,z.

- Geometric model

Let us introduce two interpolation functions Y1(x,y,z) and Y2(x,y,z) corresponding to the initial tabulated functions. The geometric interpretation of the functions Y1 and Y2 are the hypersurfaces G14 and G24 in the Euclidean subspace E4 with coordinates (x, y, z, γ), where γ is a function coordinate. To facilitate further multisensory analysis, we introduce the following additional attribute functions:

1) A1=a1(x,y,z) that will correlate with Y1 function values and will correspond to some visual attribute values. This function defines a hypersurface A14 in the attribute subspace (x,y,z,a1).

2) A2=a2(x,y,z) that will correspond to some auditory attribute and will correlate with Y1 function value.

3) A3=a3(x,y,z) that will correspond to some auditory attribute and will correlate with Y2 function value.

4) A4=a4(x,y,z) that will correlate with Y2 function values and will correspond to some visual attribute values.

Here the vector-function (Y, A1, A2, A3, A4) can be considered a constructive hypervolume model with each of its components representing a 4D hypersurface in 8-dimensional space with coordinates (x, y, z, γ, a1, a2, a3, a4).

- Spatial scene

The hypersurface G14 can be put into correspondence with a collection of isosurfaces Cj in the space E3 by selecting level values cj for the function Y1. We choose a color scale of selected isosurfaces and thus define the range for the A4 function values and map points (xi,yi,zi) on each isosurface cj to corresponding values Y2(xi,yi,zi) and assign the corresponding color. We also map each value Y1 = cj to transparency according to the value of A1 function within the selected transparency scale. The sound model includes an introduced point sound source to be used in sound rendering. The location of the sound source (xs, ys, zs) within the spatial scene defines the selected point in space and the sound frequency w of the generated sound is defined by the function A2 value at this point. We define the sound frequency as w =k1*a2 (xs, ys, zs), where k is a scalar coefficient. Also the sound volume as v=k2*a3 (xs, ys, zs) is defined by the function A3 and thus we generate complex sound with these two characteristics, pitch and volume, analyzed simultaneously.

Thus we form the geometrical, optical and sound models. Schematically the mapping of 4D hypersurfaces in 8-dimensional space with coordinates (x, y, z, γ, a1, a2, a3, a4) into corresponding multimedia coordinates will look like:

{x,y,z} $\rightarrow$ world coordinates “x”,“y”,“z”

{a1,a4} $\rightarrow$ photometric coordinates of “transparency” and “color”

{a2,a3} $\rightarrow$ audio coordinates of “sound frequency” and “sound volume”.

- Rendering and analysis

The results of the visual and auditory rendering of the spatial scene are as follows (illustrated by Fig. 3):

- a graphical image of projections of semi-transparent colored isosurfaces on a graphical terminal;

- the point sound source represented by the red sphere with the sound source located in its center. Its location is specified interactively by the user;

- a sound wave 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. Here, according to the multimedia coordinates concept a “musical tone scale” was defined. In this case we consider a simple 2-octave interval in Cmajor gamma to be such a scale. These intervals and notes may be presented with a piano. Quite often, when musicians aurally analyze a musical composition, they determine note places on the piano keyboard before writing corresponding musical sheets. Here we will take the representation of notes on the piano as our musical scale graphical representation.

Each sound tone generated at the location of the point source is defined on the musical Cmajor scale (Fig.5). Here we receive the following tones presented in Fig 5(top) and can graphically present their place on musical scale Fig.5 (bottom). A basic guitar tuner was also used to illustrate the current note value (Fig.5 top). However, a well-trained musical ear can distinguish intervals between these notes and determine the current note itself and its place on the piano musical scale. This allows for drawing conclusions about of quantitative parameters of the scalar field current value (according to the mapping from the field value to an according tone) and then change the value (according to the mapping from the change in the field value to the interval).

Taking into consideration the presented multisensory analytics concepts and the specific pipeline in Fig. 4, we have developed an algorithm for visual-auditory display of a scalar field. This algorithm has been implemented as an application program in C++ using 3ds Max and OpenAL (OpenAL, 2016) as the instrumental tools. The results of the visual and auditory rendering of the spatial scene are illustrated by Fig. 5.

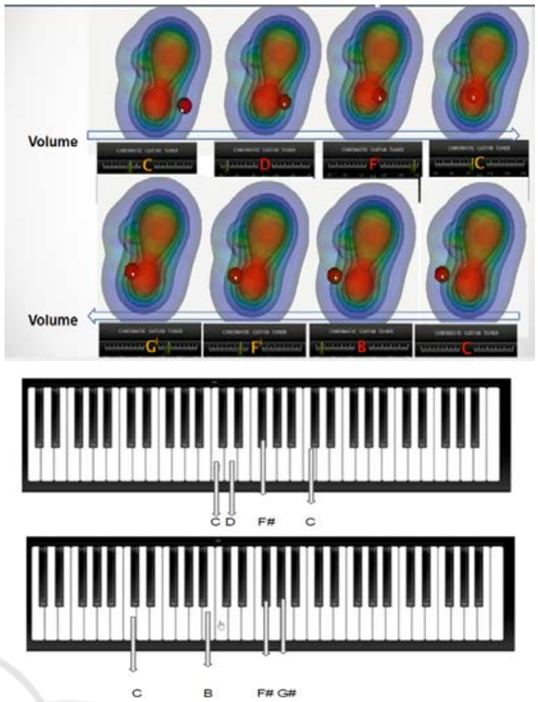

Figure 5: Exploration of two scalar fields dependency and change with pitch and volume. (Top) Here we use an interactive “sphere” widget to define sound frequency w and volume v of the generated sound defined by the functions A2 and A3 values at fixed values of world coordinates x,y,z. (Bottom) Presentation 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.

7 CONCLUSIONS

This paper deals with the emerging area of multisensory analytics involving human senses besides vision, namely hearing, sense of touch and others in the process of data analysis. We proposed an interpretation of the multisensory analytics process as a set of mappings starting with the initial data sets and leading to some insight regarding this data. The key steps of the process are introduction of multidimensional geometric model of data, creation of a spatial scene with lower dimensional geometric models augmented by optical, sound and other models related to the human senses, and rendering of this spatial scene with the generation of visual, auditory, tactile and other sensory stimuli for further analysis.

The formalization of the mapping between the multidimensional geometric models and the spatial scene available for rendering multiple sensory stimuli is the next research question to address. 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 a case study of the scalar field analysis using interactive visual-auditory display. This specific approach of using vector function gives researchers an opportunity to operate with high-level abstraction, namely create their own functional dependencies and use various mathematical operations. They can introduce new functions and their superpositions and thus build geometric, optical and other components of the spatial scene for further rendering and analysis.

In the more general case of input data, the mapping to sensory stimuli can be more complex and non-linear. We are planning to further develop the concept of multimedia coordinates (Adzhiev, 1999) as a way to establish more complex correspondences between initial data, the introduced multidimensional geometric models and multiple sensory stimuli.

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