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THE TEMPERED SPACE ON THE DESIGN OF SPATIAL MUSICAL INSTRUMENTS

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This study addresses the use of space as a design variable in forging unconventional musical instruments and introduces the notion of a tempered space. It is introduced a new strategy to create virtual spatial instruments by mapping sound/music information directly into spatial attributes and applying auralization techniques. The central idea is to associate a musical relevant quantity to a spatial quantity using well-defined mapping functions, in order to permit a clear perception of the varying parameter evolving in the space. In such a way one can say that the projection space of the instrument is tempered to accommodate the excursion of a varying parameter over the whole instrument geometry. The paper presents tools for the design of such spatial instruments and gives two examples of instruments that can be reshaped adaptively.

1. Introduction

Spatial musical instrumentation is a concept involving the design of virtual musical instruments, particularly useful to explore unconventional realizations. With the development of spatial audio technologies the behaviour of musical instruments can be altered creating sound fields, which escape from the physical logic, and inducing illusions.

In this paper we propose a way to create spatial musical instruments and to manipulate their spatial distribution in a virtual sound scene using a controllable and meaningful mapping of *sound parameters* into *spatial parameters*. The artistic motivation is to provide means to map musical information onto the space, for instance, assigning expressive gestures to emanate from specific points in the auditory space, or change the geometry of an instrument as it plays different notes with different loudness.

Given the known limitations of the auditory system to derive precise spatial cues and extract meaningful artistic expression from a distribution of sound objects in the space, some mappings are to perform more efficient than others, depending on the spatial distribution rule adopted. The notion of *scale*, *geometry* and *density* exhibited by sound objects in the auditory space are then central to drive stable spatial impressions and to index them over the space matrix.

One of the goals of these new explorations is to determine *mappings*, which lead successfully to good perceptual results (i.e. stable and meaningful images) by exploring a new concept of *tempering the spatial parameters* so to produce an optimum space matrix. Towards this we defined a mapping strategy to 3 key spatial parameters, which completely define the geometry, position and the space tempering for the auralization of virtual musical instruments. To test the concept we developed a tool for authoring virtual and augmented musical instruments and modulate their spatial images in the virtual space.

Section 2 discusses musical instruments and the space, an introduction to the motivations and references in spatial instrumentation. Section 3 presents the methodology to design spatial instruments. Section 4 presents two test implementations, consisting in the design of 2 virtual spatial instruments. Section 5 concludes discussing the results.

2. Musical instruments and the space

Many previous works have addressed the use of space in the perception and design of musical instruments concerning the physical location of sounds, a central aspect towards the concept of *spatial musical instruments*. However there are two different contexts regarding the space in musical instrumentation: the domain of the "luthier", concerning the *space as a playable instrument*, and the domain of the listener, concerning the *space as a listening matrix* in the auditory space.

In the first domain most people are concerned with modelling expressiveness in terms of gesture driving, regarding the playable interface, affecting other attributes rather than space[1]. There are many examples of virtual or augmented instrument design having the physical space approached as a playable interface. On the other side, the domain of the sonic space remains little explored, even though there are many techniques for auralization and manipulating spatial sound fields.

Spatial representations for music are mostly concerned with how the auditory system perceives musical acoustics. According to Lidji et al (2007), as observed in psychoacoustics experiments, musicians may favour the use of spatial representations for music through their learned associations between left-right space and pitch heigth[1]. The left-side association with low tones and right-side with high tones reveals a spatial mapping of tone (pitch) into space. This also suggests that musical training can drive the perception of sound in space. This spatial representation of pitch height was also observed by Rusconi et al (2006)[2].

Another context for spatial instruments has been the decoupling of the instrument (sound) of its (physical) body and turning them distributed to both performers and the audience[4]. In this conception the egocentric relationship and intimacy between the musician and the instrument is broken and extended inside-out to the audience and the acoustic spaces. The musician-instrument focal point is substituted by a disembodied sound generation, and the sound follows trajectories in the space driven by other entities, such as images, visual effects or the landscape acoustics.

Promoting an illusory perception of an extended/virtual instrument is a pragmatic instrument spatialization. This concept somehow mixes both contexts for the space: as playing interface and as an entity to structure the audition. Perhaps a more focused view on this subject has been proposed in the ideas of Beck (1996), discussing the *virtual instrument paradigm* to an alternative for real-time interaction between human performer and computer-resident mechanical systems[5]. Although Beck was concerned in the instrument interface domain, by using the metaphor of a mechanical instrument to model a virtual one, he proposed ideas of translating musical information (e.g. velocity) into spatial imaging, which directly relates to the auditory domain design, a central concern here.

There have been works exploring auralization techniques to position sound objects in an auditory scene, on most of them the objects are essentially mapped to *focal points* rather than to a *larger image*[6]. Verron et al (2008) report a technique for creating point-like and also extended sound sources in the space by breaking the sound source into uncorrelated copies (secondary sources) and positioning them in different locations[7].

In this work the focus is on the *listening domain*, and some of the ideas of Beck (1996) and Verron (2008) were implemented, such as the pitch/note mapping spatial location in the left-right panorama, and the instrument harmonic partials assigned to distinct sources. Differently in this approach, the sources are properly placed along a trajectory in space so to constitute geometry of a wider compound source.

3. An strategy for designing spatial musical instruments

We propose a practical strategy to design virtual spatial instruments that can be tailored interactively using a set of controlling metadata. These metadata will drive functions that determine the "physical" realization of the instrument in the virtual space, defining its geometry (size and shape) and position. Particularly we introduce a new concept of *tempered space* as a strategy to adjust the spatial perception of the instrument in the listening space.

To test the concept, a software tool was developed to design and auralize virtual instruments that can be controllable through user interaction or by means of automatic processing. The next subsections address (1) the specification of the spatial musical instrument, (2) the tools developed to construct them, integrated to an auralization engine, and (3) how to use these tools.

3.1 Defining the spatial musical instrument

In the current proposal the instrument is defined as an arrangement (or a cluster) of individual *cells* C_i with $i = [1..N]$ that are treated as individual punctual sound sources. Each cell is completely defined by the sound S_i assigned to it and its position $C_i\ (x_i,y_i,z_i)$ in space. An ordered spatial arrange of cells will produce the geometry of a *compound instrument*.

To be useful, it must be possible to rotate the instrument and to modify its shape and size. This requirement imposes a set of parameter that defines the instrument geometry and parameterizes its position in space. This is accomplished with the following spatial attributes proposed:

- *Instrument granularity*, i.e. the number of cells in the body of the instrument. Spatially this imply in the number of samples or punctual sources of the instrument in the space. A simple parameter for granularity would be the number of desired cells $\boldsymbol{N}$.
- *Instrument geometry*, regards the shape of the spatial distribution. An useful way to determine the instrument geometry in 3D space would be through a *trajectory* function $\boldsymbol{T}$ that will determine the position of every cell in the space.
- *Scale*, which determines the spatial interval between instrument cells (spatial samples) and is a direct measure of the space discretization. The scale $\boldsymbol{S}$ is fundamentally the *spatial tempering parameter* that will govern the *spatial distribution density* of the instrument cells, and thus its apparent size perceived.

A T function is a trajectory function for the instrument cells along the space. It can be defined analytically or using a table of points, and depends on the number of cells, their trajectory type (e.g. linear, circular, etc.) and the scale. Moreover, T can be defined using an auxiliary set of variables T_l such as the curve slope, the geometry eccentricity, Cartesian coordinates and weights.

The position of every cell is a function of N, S, and T. The actual size of the instrument will be defined through the combination of these parameters. These attributes are shown in Fig. 1 which also shows that notion of source width, related to its perceptual size.

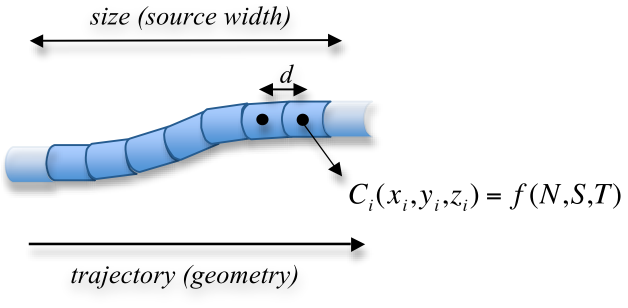

Figure 1. Spatial instrument anatomy. It is composed of cells C_i apart d meters from each other and distributed in space according to a given trajectory/geometry

3.2 Building the spatial instrument

The spatial instrument is composed of three parts: (1) body generator, (2) sound generator and (c) auralization engine. The body realization is accomplished with a spatial instrument generator, a module that admits the parameters *N*, *T* and *S* and calculate every cell instantaneous position. Every cell position maps a sound provided by a sound generator (e.g. a synthesizer). Finally, an auralization engine is responsible for positioning every sound S_i in a given position (x_i,y_i,z_i) within a sound scene and generate the corresponding sound field that will be appreciated by the audience.

The modules were developed using Pd[1], the AUDIENCE auralization library[8,9], and the free synthesizer Fluidsynth (v.1.1.2), an open-source midi-controllable wave-table synthesiser based on soundfont banks. The AUDIENCE is a software for spatial audio and auralization that can decode to several multichannel modes. In its intuitive operation, the user create a sound scene using a graphical user interface where there is an icon representing the listener position in the auditory space, and an icon for every sound source in the space. In the current application, the sound sources are the instrument cells, and their combined effect will result in the rendered spatial instrument.

The spatial instrument generation is accomplished with the newly built object "spatinst", which receives all the *N*, *S*, and $T(t_1, t_2, t_3, t_4)$ metadata and generates the coordinates C_i (x_i,y_i,z_i) of every instrument cell. An image of the instrument is then drawn onto an interactive virtual sound scene, so that the user can see and manipulate it. The coordinates C_i are passed to the AUDIENCE auralization engine, together with the S_i sounds generated for each cell, to be rendered accordingly. The Fig. 2 shows an example with these modules, a patch consisting of a sound scene (80m x 20m) with an elliptical-shaped instrument inside with *N*=10 cells, detaching the 'spatinst' object above the sound scene and the auralization engine modules just below it.

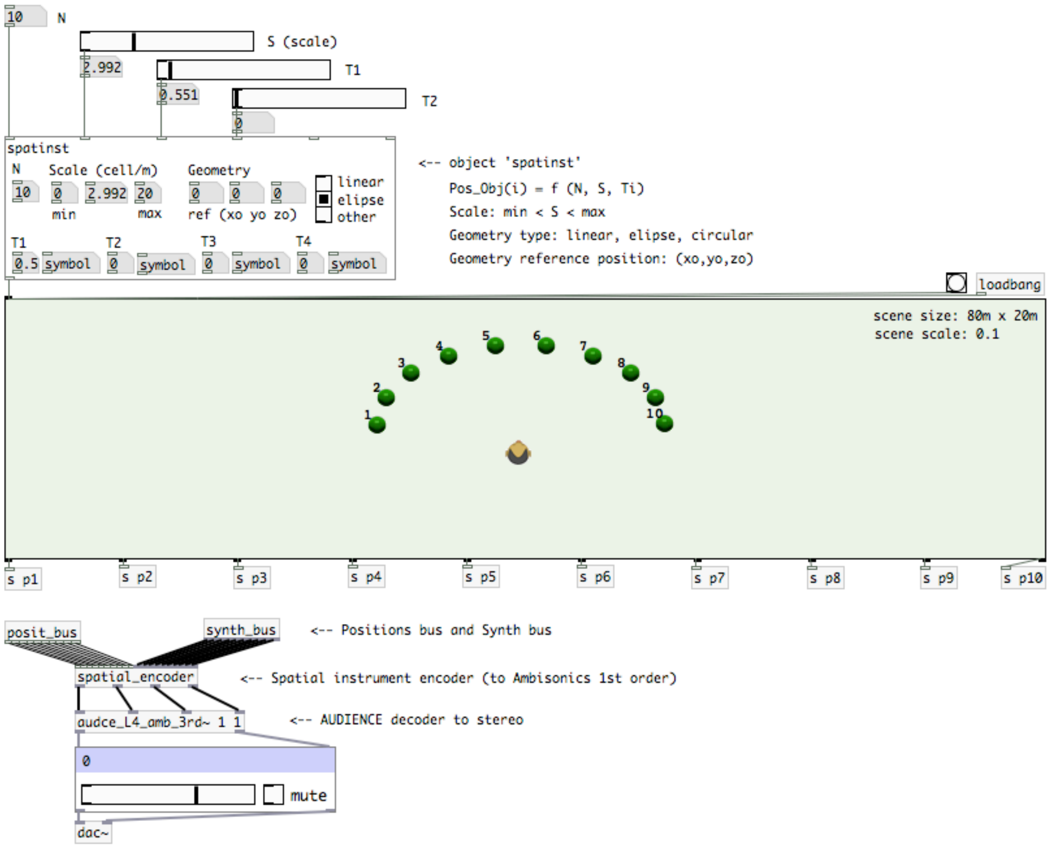

Figure 2. Patch of spatial instrument generator, instrument scene and auralization module

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[1] Pure Data, a graphical programming platform for audio processing, http://puredata.info

In the object 'spatinst' the user defines the type of geometry of the instrument (linear, ellipse/circular, other) and the initial position of the instrument reference. In the case of linear trajectory, the reference is the position of the first cell. In the case of the ellipse/circle, it is the center. With this object the instrument geometry can be dynamically changed, enlarged and shrunken, and its position can be shifted in space with 3D freedom.

3.3 Using the spatial instrument

Using the spatial instrument means to be able to create and manipulate its spatial image in the virtual scene. There are quite a number of possibilities to do it. By defining N, S and T one can determine how the instrument will be rendered and perceived in the auditory space.

In a typical use case, the musical instrument physical disposition will be a function of the three metadata N, S and T which can be driven by an external entity. Mathematically speaking, $N = h_i\,(m_i)$, $T = h_j\,(m_j)$, and $S = h_k\,(m_k)$, where m_i, m_j and m_k are the external controlling parameters.

Features of the own instrument (e.g. its acoustic signature, such as a harmonic content), features extracted from the music and also from musical gestures can be mapped into the three spatial parameters and then reconfigure the spatial disposition of the instrument. One of the most exciting applications would involve mapping *musical information* into *spatial attributes* of the instrument. which can be, for example, musical attributes (e.g. notes, events, tempo, duration, dynamics, etc.).

In this way, a certain mapping function that takes the values of the music/instrument attributes to calculate a set of spatial attributes of the instrument will completely describe the spatial characteristics for the instrument. These possible mappings are illustrated in Fig. 2.

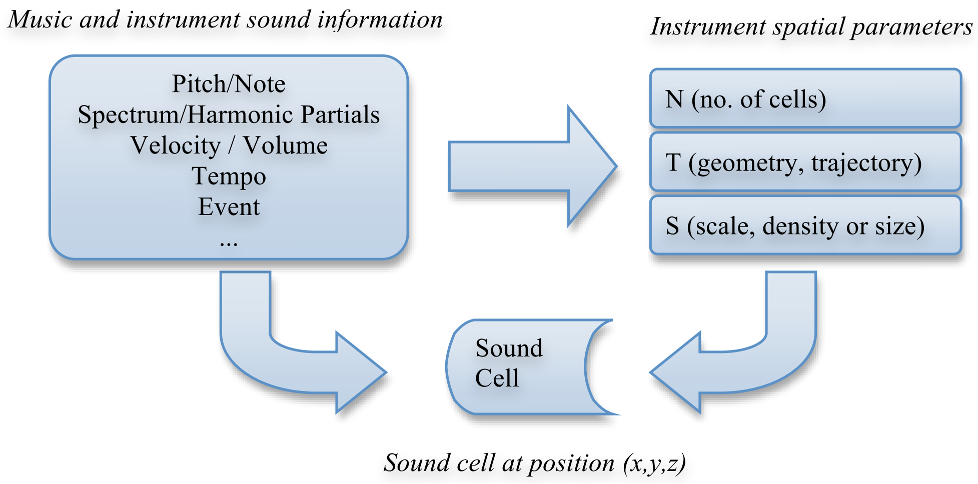

Figure 3. Mapping music and/or instrument features to spatial features and having both determine the sound of every instrument cell

The set of positional functions proposed will determine the spatial condition, but we still need to specify what each cell will sound, i.e. the individual sound of every cell. Obviously, for attaining the desired results, each cell sound shall be a function of its position. A general approach would be consider this directly controllable by the musical information or indirectly by the spatial parameters, which can for instance drive a synthesis algorithm or the selection of sound samples to play. Mathematically, the sound $S_i\,(x_i,y_i,z_i) = g(N,S,T)$, where $g()$ is a sound generator unit controlled by {N,S,T}. External controllers shall be able to modify N, S, T, the type of trajectory, and eventually to locate individual cells of the instrument anywhere in the space. Several movements can be performed by controlling this small set of parameters, making possible to shrink, stretch, send the sound elsewhere, collapse, and spread. Obviously the determination of instantaneous cell positions will take into consideration the trajectory function T, the number of cells N and the scale parameter S.

A functional block diagram of a practical setup is depicted in Fig. 4. The spatial instrument and sound generators receive data from the instrument controller and from the $\{N,T,S\}$ generator, and will output $C_i\ (x_i,y_i,z_i)$ and $S_i\ (x_i,y_i,z_i)$, respectively. The $\{N,T,S\}$ generator performs $\{N,T,S\} = h(m_1, \ldots, m_z)$ where m is a musical/instrument sound information according to Fig. 3. Notice that T may be actually a set of parameters $T(t_1, t_2, t_3, t_4)$ that will define the trajectory function.

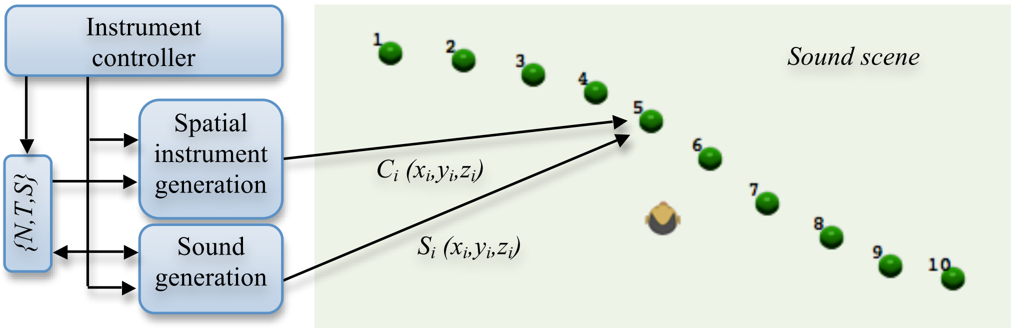

Figure 4. Scheme to calculate the position of a cell C_i and to generate its sound S_i

4. Test implementations

The Table 1 shows two mappings of instrumental features into the space that were tested. The first is a *frequency to space* mapping, taking the instrument sound partials and assigning each one to an individual cell of the instrument. The second is a musical *note to space* mapping, assigning notes (individually or in groups) to a specific position in the space to be heard.

Table 1. Mapping instrument sound features into the auditory space

Feature	Mapped into space
Partials of the harmonic timbre	Individual partials are fed to distinct cells positioned in the space apart "d" meters along a given trajectory/geometry (ex: linear, elliptical, circle)
Notes of the instrument (maps pitch or tone)	Notes of the musical scale are mapped to distinct cells in the space apart "d" meters along a given trajectory/geometry (ex: linear, elliptical, circle)

Two Pd patches were prepared for these implementations: one for the sound scene auralization (containing the spatial instrument and the listener, as in Fig. 2) and the other to generate sounds of the instrument cells (the sound synthesis patch, not shown due to 'space' limitations). In the tests we used as instrument controller a MIDI keyboard or file, sending events to the sound synthesis patch. All experiments were executed in a MAC Book Pro machine with an Intel 2.4GHz Core 2 Duo and 4GB of SDRAM memory.

It is important to notice that the proximity of the instrument to the listener (user) is not a modelled parameter of the instrument, but one of the sound scene. Near-field and far-field instrument perception will be essentially governed by approximating the listener to the instrument body or moving away from it. This can be done interactively in the sound scene graphical user interface.

The scale parameter is approached in two ways in the test patches. First, the sound scene in AUDIENCE is built defining a scale for drawing the graphical interface. This parameter defines the number of pixels per actual meters, thus reflecting the real spatial scale of the auditory scene. The second scale parameter concerns the actual instrument scale S (i.e. the distance separating cells in meter) that governs the instrument density in the space.

Two basic 2D instrument geometries were tested, a linear and an elliptical trajectory for placing the cells in the scene. By assigning the ellipse eccentricity parameter $T_l = 1$ we can also obtain a circle. The lower to the higher tones were sorted left to right in the trajectory. However, in the auralization patch it is quite easy to re-route the sound of every cell abandoning this ordination as well it is to move the cells everywhere in the scene, creating a different physical configuration.

4.1 Pitch / Note mapping to space

In this experiment we took 3 instrument octaves and mapped every group of 3 consecutive notes to a different cell in space, summing up 10 cells. In the synthesis patch, ten independent synthesizer threads were used to generate the sound of every cell, thus decoupling the cells to individual acoustic zones. From the implemented scene one can analyse the influence of instrument cell density designing a large instrument (low density, large apparent size) and a smaller one (higher density, smaller apparent size). By moving the listener position in the virtual scene we could evaluate the audible effects in every position, and also evaluate how the movement can shape the perception of the instrument in different positions, qualifying the proximity and distance perception. We can also analyse different geometries to spread the body of the spatial instrument.

4.2 Harmonic partial mapping to space

In this experiment we mapped the partials of a simple additive synthesis instrument in cells in the space. Similar to Verron et al (2008) the idea was to have the sound components separated driving a cloud of secondary sources within the auditory scene. As before, we analysed the influence of density of cells in the perception of the instrument in space. Diverging from what happens in acoustic instruments, in this case the partials emanate separately in distinct points, challenging the auditory perception to fuse them together. The tempering of the space was found more critical in this experiment, affecting the perception of the instrument as a whole.

5. Conclusions

Music technology is progressing towards new paradigms in interfaces for creating and consuming music, and the space is a vital and strategic sound attribute to work out, together with the melody, harmony, timbre and the rhythm. In the domain of virtual musical instruments, the space is fundamental to materialize the instrument in the auditory perception. This work has investigated the effect of tempering the space in designing the geometry (shape and size) and spatial distribution of virtual musical instruments.

A spatial instrument constructor was developed in Pd using a triple parameter set *{N,T,S}* to completely define the spatial attributes of the virtual instrument, and that could be controlled by an external parameter, such as a varying musical attribute. The scheme makes possible to set functional mappings, having music information or instrumental parameters directly modulate spatial attributes of the virtual instrument, determining the sound and its localization over a physical space. Rendering the instrument to audio was possible using the AUDIENCE auralization engine.

Two spatial instrument implementations were done to test the concept: one mapping note-to-space and the other, harmonic-partial-to-space. In every case, there will be a *{N,T,S}* combination that provides the best space tempering, i.e. the best spatial impression which effectively produces the desired effects. However, a set of perceptual test cases to qualify psychoacoustic impressions and quantify optimum parameters range were beyond the scope of the current work, and left to future works.

From auditions, it was verified that the sampling condition (the number of instrument cells and the space distance between them) will impact the effectiveness of the spatial perception of the whole instrumental body, and there will be a *{N,T,S}* combination which delivers a best perception of the spatial distribution of the instrument. This effect partially derives from the accuracy of the ear in discriminating individual sources in the space.

On the other side, an artistic effect is achievable with a lower density of cells, as intentionally corrupted instruments may deliver more fun than realist simulations. One has to pay attention, however, to the fact that, differently from what is done in panorama effects, in this framework it is possible to create complex coherent sound fields controlling the interference of individual punctual sources, opening different fronts for acoustical and artistic experimentations.

As virtual instruments are to be really realized through artificial sound fields from loudspeakers, the accuracy in positioning the instrument cells in the auditory space is critical. Furthermore, the simulation of acoustic propagation phenomena in the virtual scene is vital to attain the desired auditory effect, which will be as much appreciated as higher the realism of the auralization.

In the present stage the instrument size/width, location and acoustic rendering in the environment is accomplished by the auralization system and the instrument directivity is left to a future development. Many tests are ongoing, for example to assess the dependency on the timbre. From auditions it was verified that timbre affects perceived location of the instrument cells. With xylophone and marimba, for instance, the impression of localization was less blur. Experiments are planned to test other mappings proposed in Fig. 3 and analyse how distributing the instrument over the space affects its perception of cohesion. Another category of possible applications include the auralization of complex sounds composed of many individual sound sources acting together, as in dynamics of fluids, rolling sounds, environmental noise, etc. The possibilities are virtually uncountable and more experiments are expected as the tools are deployed and used by more people.

5.1 Acknowledgements

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REFERENCES

1. P. Lidji, R. Kolinksy, A. Lochy and J. Morais, "Spatial Associations for Musical Stimuli: A Piano in the Head?", *Journal of Experimental Psychology: Human Perception and Performance*, **33**, No. 5, 1189-1207 (2007).
2. E. Rusconi, B. Kwan, B. L. Giordano, C. Umiltà and B. Butterworth, "Spatial representation of pitch height: the SMARC effect", *Cognition*, **99**, Issue 2, 113-129 (2006).
3. D. Arfib, J-M. Couturier and L. Kessous, "Expressiveness and Digital Musical Instrument Design", *Journal of New Music Research*, **34**, Issue 1, 1744-5027 (2005).
4. Y. Harris, "Inside-out instrument", Contemporary Music Review, **2525**, Issue 1&2, 151-162 (2006).
5. S. D. Beck, "The Virtual Instrument Paradigm: An Alternative Approach to Interactive Computer Music", *Computers Math. Applic.*, **32**, No. 1, 5-10 (1996).
6. L. Grace et al, "Grainstick: a colllaborative, interactive sound installation", *Proceedings of the International Computer Music Conference (ICMC)*, New York, June 1-5 (2010).
7. C. Verron, M. Aramaki, R. Kronland-Martinet and G. Pallone, "Spatialized additive synthesis of environmental sounds", *Proceedings of the 125th Audio Engineering Society (AES) Convention*, San Francisco, October 2-5 (2008).
8. R. R. A. Faria et al, "AUDIENCE - Audio Immersion Experiences in the CAVERNA Digital", *Proceedings of the 10th Brazilian Symposium on Computer Music (SBCM 2005)*, Belo Horizonte, October 3-6, p.106-117 (2005).
9. L. F. Thomaz, R. R. A. Faria, M. K. Zuffo and J. A. Zuffo, "Orchestra spatialization using the AUDIENCE engine", Proceedings of the International Computer Music Conference (ICMC), New Orleans (2006).