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The Allobrain: An interactive, stereographic, 3D audio, immersive virtual world

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Abstract

This paper describes the creation of the Allobrain project, an interactive, stereographic, 3D audio, immersive virtual world constructed from fMRI brain data and installed in the Allosphere, one of the largest virtual reality spaces in existence. This paper portrays the role the Allobrain project played as an artwork driving the technological infrastructure of the Allosphere. The construction of the Cosm toolkit software for prototyping the Allobrain and other interactive, stereographic, 3D audio, immersive virtual worlds in the Allosphere is described in detail. Aesthetic considerations of the Allobrain project are discussed in relation to world-making as a means to understand and explore large data sets.

Keywords: Immersive environments; Sonification; Human–computer interaction; Wireless controller; Ambisonic spatialization

1. Introduction

The recent proliferation of relatively inexpensive high-performance computing is driving scientists to generate larger, more complex data sets from the simulations they develop. This observation is noted in the "NIH-NSF Visualization Research Challenges Report" (Johnson et al., 2006), which calls for a closer integration between new visualization/representation technologies and modern science. This can also be said of modern artworks that take place in virtual reality spaces, where immersion enables the audience to move inside the art, and shape and explore it interactively. We find this approach appropriate to incorporate for both scientific and artistic investigation of large data sets and introduce the Allobrain project as an example of an artistic exploration of scientific data.

The Allobrain project was commissioned as the debut content for the Allosphere. The Allosphere is a recently constructed immersive space for scientific and artistic visualization and sonification. It is designed for the purpose of gaining insight and developing bodily intuition about environments in which the body cannot venture: N-dimensional information spaces, the worlds of the very small or very large, from nanotechnology to cosmology, from neurophysiology to new media. One of the Allosphere's main functions is building immersive virtual worlds for the exploration of large scientific and artistic data sets.

The Allobrain project is an interactive, immersive, multimodal art installation that uses fMRI brain data to construct a virtual world. Inside this world are dynamic elements that assist the user in the exploration of the fMRI data. The Allobrain project makes digital data experiential, immersing the physical user into digitized physicality. The mapping of the fMRI brain data in the Allobrain project is shown in Fig. 1. The Allobrain project was designed to highlight the potential of the Allosphere as a space, to be a

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Fig. 1. Exploring fMRI data inside the Allobrain.

test bed for the hardware infrastructure, and to articulate, through its artistic statement, a vision of the possibilities of the space. In addition, a set of software-prototyping tools named "Cosm" was created that enable additional world-making and data exploration in the Allosphere (Hollerer et al., 2007).

We chose to create an immersive artwork for the debut content of the Allosphere, following the belief that content should drive technology. Choosing art as the content to drive the creation of the software and computing infrastructure of the Allosphere allows for unfettered development toward the type of visualization, sonification, and interactivity we envision. Art is unhindered by the strict practicalities that result from purely scientific pursuits and thus makes a good test bed for steering the design of the Allosphere toward open-ended possibilities.

Art is firmly embedded in the history of immersive virtual reality spaces. Indeed, Cave Automated Virtual Enviroments (CAVEs) are now an established medium for artists (Dolisnky et al., 2005). CAVEs provide a space where art can be dynamic, interactive, immersive, and multimodal. The Electronic Visualization Laboratory at the University of Illinois, Chicago EVL, is a pioneer in CAVE technology (Cruz-Neira et al., 1992). There have been an extensive number of artworks created for the space (evl|art, 2009). Many of these artworks capitalize on the immersive multimodal qualities of the CAVE to blur the boundaries between physical and digital experience (Kostis et al., 2007).

Ars Electronica in Linz, Austria has exhibited several virtual reality artworks throughout the past decade (Ars Electronica, 2009). Peter Kogler's "CAVE" is an artwork commissioned by Ars Electronica in Linz. This work has similarities to the Allobrain project in its ties to virtual architecture. In Kogler's work, users navigate a static virtual architecture using a 3-D mouse. Interactivity in Kogler's work is limited to user navigation. The virtual architecture is constructed by the artist and resembles an Escher painting. Kogler uses the immersive virtual architecture to explore the nature of orienting one's self in a space, either virtual or physical. Kogler creates a space that is only possible to explore in through digital immersion. Another related work is "Gray Matters: The Brain Movie" (Dannenberg and Fisher, 2001), which was created to teach fundamental scientific concepts about the human brain in a planetarium setting. During the show, the planetarium dome represents a giant brain enclosing the audience. Audience members are able to interactively play the role of neurons in various simulations and representations of brain functions through the use of simple buttons located at each seat.

The science of virtual reality has contributed to the world of art; however, the contribution of art to the science of virtual reality and the development of the software and hardware infrastructure of these spaces has received little discussion. Virtual reality artwork often challenges the capabilities of the spaces in which they are installed. These artworks often call for the construction of authoring tools to make the virtual reality experience possible (Kostis et al., 2007). This was indeed the case for the Allobrain project. There were several technical demands required by the Allobrain project. Since no software system or interactive design was in place for the Allosphere, there was ample opportunity to allow the art to drive the technological design. The technical demands of the Allobrain project were:

(1) Full range of synthesis and audio processing capabilities. These should be controllable at the sample level.
(2) 3-D placement and dynamic movement of sounds in the space as well as implementation of Doppler shift simulations.
(3) Vertex-level control of geometric constructions.
(4) Networked communication of navigation and scene data between computers.
(5) Input from wired and Bluetooth wireless instruments.
(6) Free navigation in 3-D space for users and for dynamic objects in the space.
(7) Spherical projection of the scene over numerous projectors (and associated computer nodes)

In Section 2 we describe the space design of the Allosphere and compare its capabilities to similar spaces. Next we explore the importance of multimodal representation with a particular focus on audio. We then discuss the Cosm toolkit, software designed for the prototyping of interactive immersive environments using higher-order Ambisonics and stereographic projections. Finally, we describe the Allobrain project, the driver of the prototyping toolkit and a compelling work of art that demonstrates the exploration of worlds constructed from large data sets. While the project incorporates both visualization and sonification of fMRI data, particular attention is paid to sonic interaction design for the user experience in the Allobrain project. We utilize unique interfaces and sound design methods to enhance human perception of 3D brain-scan data, and provide an aesthetically charged multimodal environment. We discuss how the aesthetic questions of sonic and multimodal interaction design were developed in the Allobrain project and how they relate to the design of immersive virtual worlds, particularly within the Allosphere.

2. The CNSI Allosphere

The Allosphere (Hollerer et al., 2007; Amatriain et al., 2007) is composed of an acoustically porous metal sphere functioning as a 10-m diameter projection screen that is suspended within a three-story near-anechoic space. The space can accommodate approximately 20 people on a bridge that runs through the middle of the sphere (Fig. 2).

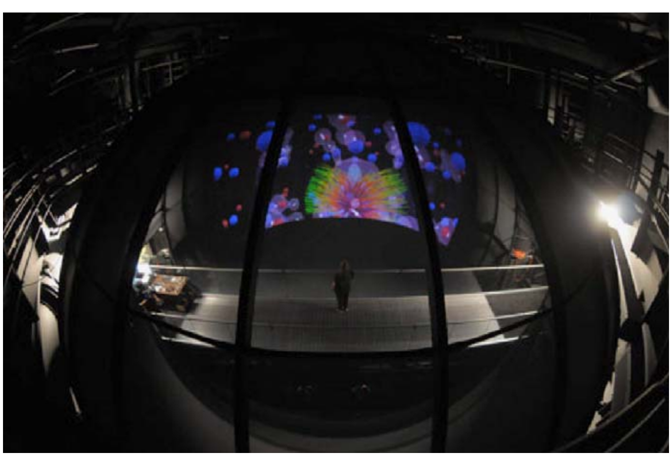

Fig. 2. Top view of the Allosphere with a user on the bridge. Photo credit: Paul Wellman, Santa Barbara Independent Newspaper.

Fig. 3 is a virtual model of the facility and its relation to the California Nanosystems Institute building, as well as an interior model of the sphere and bridge.

There are some important characteristics of the Allosphere that distinguish it from existing virtual environments such as the CAVE Cruz-Neira et al. (1992), virtual spaces navigated by head-mounted displays Cakmakci and Rolland (2006), or hemispherical immersive theaters Gaitatzes et al. (2006). The Allosphere's spherical shape, multimodal, multi-user capabilities, and its scenario of minimal encumbrance to the multiple users adds a new, unique, large immersive instrument to the list of the world's largest and most precise immersive 3D environments. These include

- the newly upgraded 24 projector C6 CAVE at the Virtual Reality Applications Center at Iowa State University
- the Fakespace FLEXT installation at Los Alamos National Laboratory LANL (2006), which is a 33 projector 5-wall CAVE with 43 M pixels in a $4.572 \times 3.048 \times 3.6576$ m room,
- the Samuel Oschin Planetarium at the Griffith Observatory in Los Angeles with its E&S Digistar 3 full dome laser projection system with claimed $8k \times 8k = 64$ M pixel resolution in its 22.86 m diameter dome,
- the Denver Museum of Nature & Science Gates Planetarium dome DMN (2006) with approximately 10 M pixels from 11 projectors,
- the Louisiana Immersive Technologies Enterprise center with its 8.8 M pixel 6-sided CAVE and smaller curved display immersive theater and conference room.

The Allosphere offers many improvements over CAVE environments (Cruz-Neira et al., 1992; Ihren and Frisch, 1999). It enables seamless immersive projection, even in non-stereo mode. Room geometry does not distort the projected content. Stereo is possible for a large set of users, since the audio and stereovision "sweet spot" area is much larger, the screen being consistently at least 5 m away. Single person head-tracked stereo is still possible, but the bridge structure and the exit doorways on either end restrict CAVE-like "walk-around-the-object" stereo

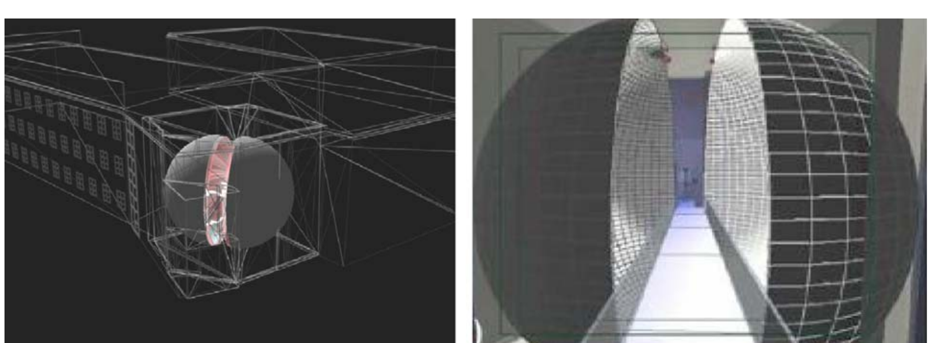

Fig. 3. A virtual model of the Allosphere within the CNSI building.

imagery to railing height or higher. The main technical and functional innovations of the Allosphere can be summarized as follows:

1. It is a spherical environment that includes full 4ð steradians of stereo visual information. In this sense it resembles state-of-the-art visual systems such as the CyberDome Shiboano et al. (2003) but on a different scale. It is known that spherical immersive systems enhance subjective feelings of immersion, naturalness, depth and "reality" (see Kalawsky, 1993, for instance).
2. It combines state-of-the-art techniques both on virtual audio and visual data spatialization. There is extensive evidence of how combined audio-visual information can help information understanding (McGurk and McDonald, 1976). Nevertheless most existing immersive environments focus on presenting visual data.
3. It is a completely interactive multimodal environment (Malkawi and Srinivasan, 2004), which will include camera-tracking systems, audio recognition and sensor networks.
4. Its size allows for up to 20 people to interact and collaborate on a common research task.
5. Although the space is flexible and general purpose, its focus is on scientific research in fields such as data mining (Wegman and Symanzik, 2002), geographic visualization or bio-imaging, as well as artistic research in world-making and data creation. The science and arts applications intersect (Hollerer et al., 2007).

With regards to audio we have carried out and published detailed measurements of the finished Allosphere space, its treatment and the projection screen's acoustical properties (Conant et al., 2008). We used a variety of synthetic and explosive sources and careful multi-microphone placement to ascertain the effects of having an aluminum sphere in our anechoic chamber. The space's wide-band T60 time of 0.45 s means that we can dissipate and absorb energy we introduce into the sphere, and the mirrored-microphone measurements confirm that the sphere itself is acoustically inert.

The system configuration at the time of the Allobrain project included a 360° surround view at the horizon and 16 channels of 3D audio. This is the basis of the system on which the Cosm toolkit was developed for the Allobrain project.

3. Multimodal representation and the importance of audio

The Allobrain project represents information in both sonic and visual modalities. Multimodal information representation in a virtual environment enhances information exploration. It has the potential to stimulate different senses and enable users to orient in 3D spaces. It also increases the amount of information accepted and processed by the user's perceptual system and thus the user's impression of immersion and presence in the virtual world.

Fully spatialized audio aids navigation, orientation, and human perceptual bandwidth. Directional hearing is a strong means for directing our sight. Our vision tends to require serial processing, thus needs to focus, whereas hearing is more likely to be processed in parallel (Kalawsky, 1993). In the context of virtual reality, *presence* is defined as the feeling of being in the virtual environment. Research in presence has shown that there is a weak but consistent positive relationship between the feeling of presence and task performance in virtual environments (Witmer and Singer, 1998). Although the role of audio is less well understood, it is observed that more realistic audio models lead to higher presence (Borman, 2005). The relationship between audio spatialization and increase in presence may be explained according to criteria of realism, better externalization cues, inter-sensory correlation or the increase in the utility of audio with regard to task completion.

In addition to the above two important functions of audio in a virtual reality environment, utilizing audio for data sonification adds to its significance. Brewster et al. utilized a sonification experiment to test the idea that sounds can be used in place of limited screen space in a mobile PDA device. The task was to make as much profit as possible by buying and selling shares using either the sonification or a line graph to monitor the price over time. Results showed no difference in performance between the two modes, but subjects reported a significant decrease in workload with the sonification, which allowed them to monitor the price while using the visual display to buy and sell shares (Brewster and Murray, 2000). Sonification of some part of an N-dimensional data set along with visualization of another part of the same data set increases the number of dimensions of data processing by using more than one sense to process the information. Multimodal representation is critical as the dimensions increase (Nesbitt and Barrass, 2002).

4. The Cosm toolkit

Creating inaugural content for the Allosphere gave us the opportunity to identify the key challenges of content creation for this space in general, creating a knowledgebase of use to the community. We capitalized on this opportunity by reifying many of the more pragmatic components into a reusable software toolkit named *Cosm*. In brief, Cosm enables the rapid design, development and deployment of interactive and multimodal content for the Allosphere, providing 3D-navigation, spatialized audio and stereographic rendering across multiple projectors. Cosm lies at the core of the Allobrain project.

In this section, we describe the Cosm toolkit along with key challenges and responses through its development. Cosm was developed primarily according to the conditions of the Allosphere: both the physical and technological properties and also the academic research context. In particular, this led to an increased emphasis on audio synthesis and spatialization in the toolkit, scope to control the simulation down to the level of polygons and samples, and lucidity in the process of design and composition for experienced multimedia authors (an intuition which has been borne out in the subsequent scientific and artistic projects carried out in the Allosphere (Amatriain et al., 2008; Ji and Wakefield, 2009)). We identified the following core requirements for the Cosm toolkit:

1. Rapid development of project-specific sonifications/ visualizations
2. Spatialized audio over potentially hundreds of loudspeakers
3. Stereographic projection over numerous projectors
4. Six-degrees of freedom (6DoF) navigation
5. Adaptability and scalability to distinct or changing hardware configurations

4.1. Choice of development tools

We opted to make use of Max/MSP/Jitter (Puckette, 2002) as a flexible rapid prototyping environment in which to develop the Cosm toolkit and the Allobrain project. Max/MSP/Jitter is a general purpose and open-ended visual dataflow programming system for authoring multimedia systems. It has a wide familiarity and support particularly in the electronic arts and computer music communities. In Max/MSP/Jitter designers connect nodes (algorithms and data storage) with arcs supporting a variety of asynchronous and synchronous packet streams to construct event-driven networks and signal-processing graphs stored as *patches*. Algorithms and interactions can be specified at high and low levels and rapidly interconnected through the modularity of the message types. As a result, the design emphasis rests on dynamic process rather than structured data.

The choice of Max/MSP/Jitter satisfied the requirements for rapid development and flexibility. Systems (patches) can be constructed and edited while they execute, greatly reducing the design and test loop, much like scripting languages employed in most virtual environment frameworks and game engines. Strong, diverse and mature support for audio, 3D graphics and interface I/O within a unified environment allowed us to concentrate on the composition of the content. Scalability and modularity allowed the generation of prototypes on a desktop machine that later we merged into the main project. The wide range of available low-level algorithms allowed the design of rich real-time audio content at the level of signal processing and synthesis.

However, we were still missing several key capabilities necessary for deployment in the Allosphere, spatialized audio integration, 6DoF navigation and stereographic scene control. We used the developer software development kit to extend Max/MSP/Jitter, authoring extensions (externals) in C++ to satisfy these requirements as a component of systems research for the Allosphere facility in general.

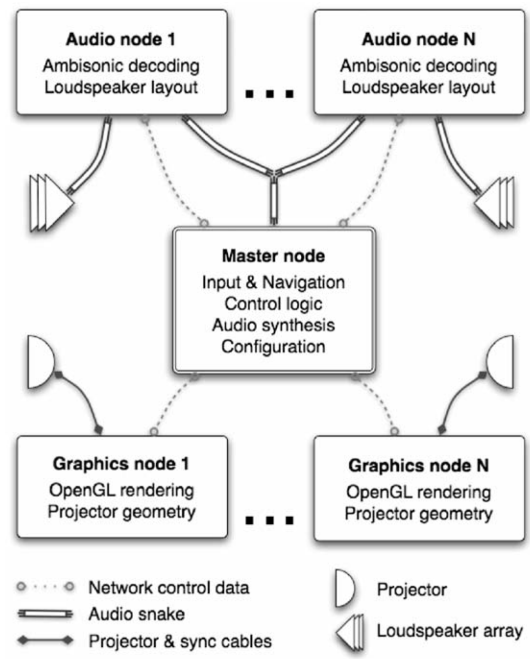

Fig. 4. Cosm toolkit architecture.

4.2. The Cosm toolkit architecture

A distributed architecture is necessary to support the large number of audio channels and video projectors (Cosm requirements 2 and 3). To maintain simplicity in development and flexibility of control, we opted for a simple star network topology of a single master control node and any number of remote-rendering nodes (Fig. 4).

The Cosm master node handles user navigation, audio/ video-rendering settings and overall system state, as well as broadcasting audio, data, and control messages. The Cosm graphics render node manages stereographic OpenGL rendering adjusted to match the attached projector's orientation. The Cosm audio render node decodes the Ambisonic domain signals according to the attached loudspeaker geometry. Audio-rendering settings include reverberation parameters, virtual air absorption coefficients, and the speed of sound for spatialization in realistic or non-realistic environments. Video-rendering settings include stereographic mode, depth of field, and stereo separation. These settings are stored in local configuration files on each graphics node. A special patch was developed to quickly and visually define and store remote configurations from the master node computer, useful for installations in which audio and graphics render node machines are not easily accessible.

A project utilizing the Cosm toolkit, such as the Allobrain, consists of two components implemented as Max patches (Fig. 5). The project-specific master node

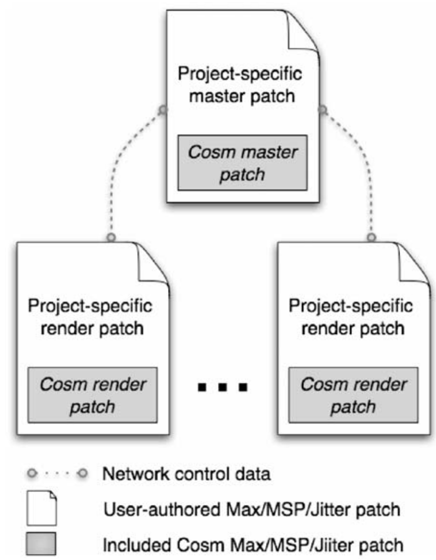

Fig. 5. General architecture of a Cosm project.

incorporates all project control logic, interaction, and audio synthesis. The project-specific graphics render node incorporates all project-specific graphical rendering objects. The Cosm master and render patches embed the respective elements of the core Cosm engine within these project-specific nodes (akin to a static include.)

4.3. Communication

Maintaining coherent state at high resolution (both graphics and audio) across a distributed rendering network can be achieved by a number of strategies (Eilemann), however the process-oriented aspect of the Max/MSP/Jitter environment suggested an alternative strategy to multipipe rendering or distributed shared memory. In Cosm, algorithmic structure and content is replicated at launch-time. Runtime scene state is maintained through light-weight control updates from the master node. It is similar to the slot messaging used in Ygdrasil (Pape et al., 2003) or the high-level events in FAVE (Patel et al., 2003).

The master node multi-casts application high-level events and system global control state to all render nodes via TCP or UDP. All nodes self-register their IP addresses with the master node upon initialization, allowing users to also direct control messages to specific nodes where necessary, such as remote diagnostics and configuration. Since messages in Max/MSP/Jitter are global, all Cosm names and message selectors are prefixed with *_cosm* to avoid collision with project-specific messages. In addition, a basic namespace is provided for project-specific distributed control over the network.

4.4. Spatial audio

We considered three different spatialization techniques for the Allobrain project and the Cosm Toolkit based on the 16-channel configuration of the Allosphere at the time. There are three techniques for spatial sound reproduction used in current state-of-the-art systems:

1. Vector-base amplitude panning (VBAP) (Pulkki, 1997)
2. The Ambisonic representation and processing (Malham and Myatt, 1995)
3. Wave field synthesis (WFS) (Spors et al., 2002; Berkhout, 1988).

Each of these spatialization techniques provides a different set of advantages and presents unique scalability and complexity challenges when scaling up to a large number of speakers or virtual sources. VBAP (Pulkki, 1997) is a signal-processing technique by which a sound source can be located in the space by setting the balance of the audio signal sent to each of several speakers, which are assumed to be equidistant from the listener. Ambisonics (Gerzon, 1973) is a technique to synthesize a spatial sound field by encoding sound sources and their geometry and decoding them using the Ambisonic transform, a multi-channel representation of spatial sound fields based upon spherical harmonics. Finally, wave field synthesis (WFS) recreates wave fronts with large arrays of loudspeakers by building on the Huygens principle of superposition. Although WFS presented the most interesting method of spatialization, we lacked the number of speakers required to implement this technique. Instead, we chose Ambisonic representation and processing.

The Cosm toolkit employs third-order 3D Ambisonics for audio spatialization, using Ambisonic extensions to Max/MSP/Jitter (Wakefield, 2006). In contrast to VBAP and WFS, Ambisonics was chosen for ease of scalability from small to large speaker arrays and wide acceptable listening area, both concerns in the developing content for the Allosphere. Canonical Ambisonics models spatial orientation well (Malham and Myatt, 1995), but does not inherently model distance. We have extended our implementation to incorporate multiple distance cues for point sources using standard techniques (amplitude attenuation, medium absorption/near-field filtering, Doppler shift and reverberation, Chowning, 1971). We implemented a rudimentary (sound-cone) radiation pattern simulation by mixing distinct filtered outputs for different directions according to the orientation of the object relative to the listener.

Point source synthesis, distance coding and Ambisonic encoding take place in the master node. The encoded Ambisonic domain channels (16 channels for 3rd-order 3D) are distributed to multiple audio-rendering nodes for decoding to potentially hundreds of loudspeakers. In this situation, the portability of the Ambisonic domain makes it very easy to support growing numbers of loudspeakers by adding new decoder nodes, requiring no changes or additional overhead for the master node (supporting the scalability requirement).

4.5. Navigation

All navigation and object orientation uses a quaternion representation to fluidly support navigation in any axis, taking advantage of the geometry of the Allosphere itself. A set of extensions to Max/MSP/Jitter was developed to support quaternion rotation and conversion to/from axis/angle, Euler angle, matrix and Cartesian unit vector representations.

Sound source direction in Ambisonics is expressed using Euler angles of azimuth and elevation.[1] A custom Max/MSP/Jitter external (*xyz2aed*) was written to simplify the process of deducing the appropriate azimuth, elevation and distance for Ambisonic encoding and distance simulation in audio from the relative object position and user navigation orientation quaternion. In this process the unit vectors of the navigation orientation are multiplied by the viewer-to-object vector. The azimuth and elevation are derived using trigonometric arctangent and arcsine of the resultant up, side and forward scalars. Distance is calculated using the Pythagorean formula.

An Ambisonic sound field in its entirety can be rotated around three axes using equations based upon spherical harmonics (Malham, 1999). Unfortunately, if the listener is a mobile point in a virtual world, the combinations of translation and rotation are not trivial to constantly change. Under such conditions sound field rotation is no longer a great advantage, since sound source direction and distance for every active source must be recalculated (and interpolated) continuously. Further discussions on audio-based navigation through localization and orientation can be found in Gröhn (2006).

4.6. Graphical rendering

The Cosm toolkit implements active stereographic projection. Active stereo uses one graphics window that alternates left and right frames, requiring twice the frame rate and additional configuration of the graphics context. For an active stereo system, a sync signal is generated by the graphics card to drive the shutter rate of the active stereo glasses and to synchronize the appropriate left and right eye images. To enable this type of configuration in Max/MSP/Jitter, the OpenGL rendering and windowing objects (jit.window and jit.gl.render) were modified to enable quad-buffered stereo. Eventually these changes were folded back into the standard Max/MSP/Jitter distribution as of Jitter 1.6.3 beta 2.

Calculation of the left and right eye viewpoints is done using a quaternion camera. Given the camera's orientation, a local coordinate system is derived. From this, the left and right viewpoints are projected out into space based on the interocular distance parameter, providing each eye with a unique image that when viewed through the 3D glasses is perceived as existing in space. Global adjustments for parallax and focal distance can be configured to match the projection environment.

5. The Allobrain project

The following sections will explain the various components of the Allobrain project. We begin with an overview of the project where we discuss the background of the Allobrain's development and the aesthetic intentions. Next we introduce the use of artificial semi-autonomous agents to assist user exploration of the data and provide elements of dynamic activity in the Allobrain. We then discuss the strategy of the sonic interaction design for the Allobrain. Finally we discuss the interfaces developed for user interaction.

5.1. The Allobrain project—an overview

The Allobrain presents an immersive virtual world constructed from fMRI brain imaging data. When rendered visually, the fMRI data creates an intricate spatial architecture. The origin of the Allobrain concept stems from digital artist and transvergent architect Marcos Novak's research into the neurophysicological basis of aesthetic appreciation. To produce the brain imaging data, Novak undertook fMRI brain scanning while viewing unanticipated visual stimuli produced by a generative algorithm. Both conscious and neurophysiological data were captured during this presentation. The fMRI data was stored in 3D volumes in the Analyze file format. A custom object was built for reading the files and outputting them as 3D Max/MSP/Jitter matrices.

The Allobrain project capitalizes on the immersive qualities of the virtual reality space to blur the divide between the physical and the digital. In plain terms, it digitizes the physical brain thus permitting users to physically inhabit this digital data space. Using the brain as virtual architecture succeeds as a poetic image, synthesizing many things into a seemingly simple gesture that creates an effective aesthetic experience. First, in its shape, it seizes on the elective affinity of the parallel between the two hemispheres of the brain and the medium of the Allosphere. Second, it engages a centuries-old debate about the relation of Architecture and the body. It consciously inverts the historical relation, where the exterior body was used to proportion architecture, and proceeds to create a compelling space from the geometries of the brain. Finally, it indicates the strangeness of a cultural moment when the mind has given to the brain, psychology to neurophysiology, and it has become possible for the artist/scientist to invite people, quite literally, inside one's head.

The Allobrain project has been exhibited many times in the Allosphere, including the ACM Multimedia conference in October 2006. The Allobrain was also exhibited at the opening of the iWeb/Protospace Lab of the Department of

[1]The third angle, bank, is not directly relevant to Ambisonics, but could be important for raycast reverberation simulation.

Architecture at Delft University of Technology in the Netherlands in March 2007 TU Delft (2007), and simultaneously (through telecommunication) in the Allosphere, in which participants in both the USA and the Netherlands were represented in the space as avatars.

5.2. Artificial semi-autonomous agents

We added dynamic elements to the static architecture of the brain data by introducing artificial semi-autonomous agents. These assist the user in exploring the data and aid in creating an aesthetically charged dynamic and interactive experience. A narrative for the installation was introduced, based upon the concept of computer-assisted data mining by means of a multi-agent system. A notion of dynamic search is embodied by a number of artificial semi-automonous agents sharing the data space with the users, and supervised by the users utilizing interactive physical interfaces (Fig. 6).

The narrative introduces two types of artificial semi-autonomous agents. The first are 12 "explorer agents" that navigate the brain measuring blood flow densities and changing color according to the region of the brain they are exploring. A user can call specific explorer agents to report the status of their measurements. Sonification of the data set becomes the responsibility of each of the explorer agents, providing a complex and evolving sound-scape of multiple discrete spatialized paths. The second type of agents is the "clustering agent." The number of clustering agents is variable but is generally set to approximately 100. These clustering agents group themselves in various formations based on signals from the explorer agents. Both explorer and clustering agents allude to the possibility of a richly dynamic mode of human–computer interaction, merging the best use of human and digital pattern-matching capabilities.

By making use of the artificial semi-autonomous agents in the Allobrain project, we are presenting the possibility of extending human perception to include normally non-noticed stimuli. In a sense, this provides an enhancement of human "input/output" (I/O). For example, although not visible to all users all the time, the explorer agents are continually changing depending on the amount of neural activity (indicated by blood flow density). However, by hearing the *song* of a particular explorer agent (possibly behind the user's head), the user may be prompted to call the explorer agent into view using the interface described below. Once called forward, the user can observe the information gathered by the explorer agent. The sonic interaction design here is a key element of the mapping, as the *song* that is "sung" by each explorer agent is a unique sound that can be recognized by it's pitch and other audible properties. Human output is also extended through the ability to "reach out and grab" these intangible elements in the simulation.

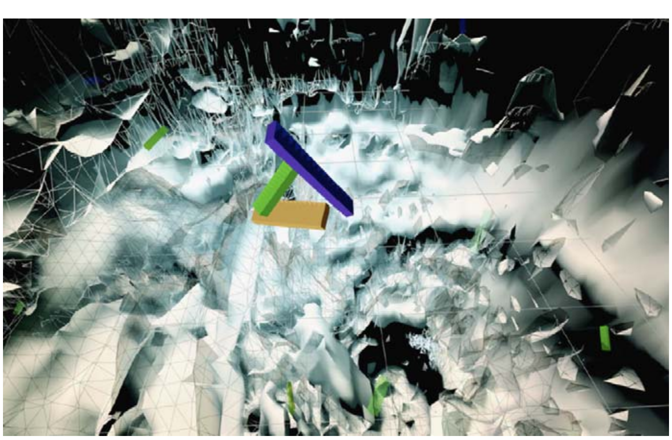

Fig. 6. View inside the Allobrain with artificial semi-autonomous agents.

5.3. Aesthetics of sonic interaction design in the Allobrain

In this section, we describe the overarching aesthetic position we adopted for sound synthesis in the Allobrain. The decisions we made about the sonic design were based on the following motives:

(1) We create algorithmically.
(2) We stress interactivity.
(3) We desire causality and connectivity.

By algorithmic generation of sounds we mean that specific elements of the simulation, such as agent motion, are mapped directly to parameters of synthesis instruments. We believe this is an important criterion to allow novel sonic landscapes to emerge. If this synthesis model is too rigid, such as triggering pre-recorded samples, it is possible that the sounds will not effectively reflect subtle changes in the simulation. On the other hand, if the synthesis is too fluid, such as mapping continuously to sinusoids, there is a chance that it will not be informative enough and instead produce cacophony. In the end, we decided that voice-like subtractive synthesis instruments consisting of a spectrally rich source and one or more format filters would provide a reasonable middle ground.

The Allobrain offers a dynamic and interactive world to be explored. It was our challenge to embed a narrative that would be compelling when conjured through user interaction, since in the Allobrain, there is no director to deliver a time-based experience. The Allobrain project gravitated toward a new type of cinema experience in which the cinematic world exists as a habitable object. The corollary in music and sound design is navigable music, where music, rather than being organized on a timeline, takes on the spatial qualities of architecture (Novak, 1991). Through interactivity, users are given freedom to explore the sonic architecture and to create their own trajectories through the musical object. We created an environment of sonic potentials, rather than a "film score" for the installation. To put it simply, the sonic narrative is non-linear.

Causality in the interaction design means that user actions have an immediately perceptible effect in the virtual world. In the Allobrain this cause and effect scenario is extended to the actions of the artificial semi-autonomous agents. The space contains many potential sonic outcomes that may or may not occur based on the actions of the artificial semi-autonomous agents and the users. The actions of the users and the artificial agents do not happen in isolation, but have an impact on the actions of other elements in the virtual world, thus there is connectivity between these elements. Because of this connectivity, actions of the user and of artificial semi-autonomous agents in the world have a propagating effect. To give a concrete example, when an explorer agent finds a blood-density level that exceeds a certain threshold, it transmits a signal that is received by clustering agents. The clustering agents respond to this signal by changing their clustering formation and momentarily altering the ambient sound field. In turn, the movement and sounds of the clustering agents alert users to events of interest in the world, and alter the actions of the users.

To be specific about how we addressed the aforementioned sonic design criteria, we describe how the artificial semi-autonomous agents and overall system behaviors are sonified. The behavior of the explorer agents is to move about the space, pausing in between each movement to take measurements of blood flow densities in the surrounding region of the brain. Since the explorer agents move all about the space evaluating information, it is important for users to be able to perceive their location in the space at all times. The explorer agents emit short duration, filtered noise bursts whenever they change their position. For each explorer agent, the center frequency parameter of the filter is derived from the local blood flow density level. Higher values blood flow density levels result in higher pitches. A wide-band signal is used since they have been found to provide more precise elevation cues (Hollerweger, 2006).

Users interact with explorer agents by bringing certain agents forward into view. Here the explorer agents provide additional information about the blood flow density levels in the area of the brain they were exploring through sonification. Calling several agents, the relationship between these data can be delivered polyphonically. Rhythmic traits (envelope speed based on blood flow density levels) and pitches (frequency content based on location within the brain) differentiate the "songs" of each agent.

Linked to the actions of the explorer agents is a set of clustering agents. When an explorer agent finds a blood flow density above a given threshold it sends a signal to the clustering agents. The clustering agents group themselves into a different formation based on this signal. As the clustering agents move, an ongoing ambient sound is briefly passed through a reverberator with a long decay time to give a sense of spectrally freezing the sound-scape. The unique nature of the sound transformation alerts the user to the event, but does so in a non-disruptive manner.

Without the users' participation, the environment by itself contains both explorer and clustering agents that continue their semi-autonomous behaviors. This creates a sound world that invites the user to step into the environment and explore. We found that in this sonic atmosphere users felt more inclined to spend longer stretches of time within the virtual world. However, once the user is inside the virtual world the ambient sound world is not unaffected. Doppler effects and spatial cues tied to the user's location and movement alter the ambient sound world providing the user a strong sense of causality.

6. Interfaces

The Allosphere presents a significant challenge in the interaction design and engineering of new human–computer interfaces (Turk et al., 2007). New data types pose new interface requirements; for example, higher dimensional data poses the specific problem of how to achieve intuitive navigation without sacrificing maneuverability. Interfacing to a highly abstract environment creates the opportunity to engage users in physical interaction within the context of a conjugate space that couples the system to users via many interconnected bindings. Emergent interface technologies are being explored and new ones will potentially be discovered through this process. Multimodal mapping of data to multiple interactive wireless devices is an essential part of our approach. Musical ensemble scenarios such as group performances inspire this approach. An important part of our vision is to foster creative collaborative interactions through flexible systems that allow for simultaneous deployment and use of both traditional and novel interaction devices.

We designed a set of novel user interface devices (Kuchera-Morin et al., 2007; Overholt, 2009) motivated and guided by musical and media arts performance and by creative artistic exploration. One such example is the spherical input device named the *Sphere Spatializer* (Overholt, 2009). This custom interface device, depicted in Fig. 7, is about the size of a small volleyball. The Sphere Spatializer is a multimodal input device that can control the spatial locations of multiple sound sources rendered through the Ambisonic loudspeaker array. A user of the device interacts with the explorer agents in the Allobrain project. The form factor of this interface is based on a 4-dimensional geometric polytope, the hyperdodecahedron, with the physical shape representing a shadow of this 4D object projected into 3D (Fig. 9).

The Sphere Spatializer was developed using procedural modeling techniques, and was algorithmically sculpted to provide an organic and ergonomic look and feel that is aesthetically linked to the content in the Allobrain project. The form was made with a 3D printer capable of building solid objects (ZCorp, 2009). We consider the Sphere Spatializer to be an "everted" object. Everted objects are digitally created objects are brought out of the virtual and into the physical. We believe that placing these everted physical objects in the hands of users enhances the suspension of disbelief, which plays part in the quality of sense of immersion. It helps to blur the boundaries between the physical and the digital.

The *Sphere Spatializer* includes twelve buttons, evenly spaced around its surface, which provide control of the explorer agents within the Allobrain. Using the device a user calls explorer agents to the current field of view and shifts their spatial focus in order to specify a new region to explore. We chose not to use more traditional 3D user input devices such as 3D-mice, space ball, or data glove solutions in order to be able to target specific functionalities required for the Allobrain project with the custom interfaces developed, as well as extending the capabilities of interaction to multiple users as described below.

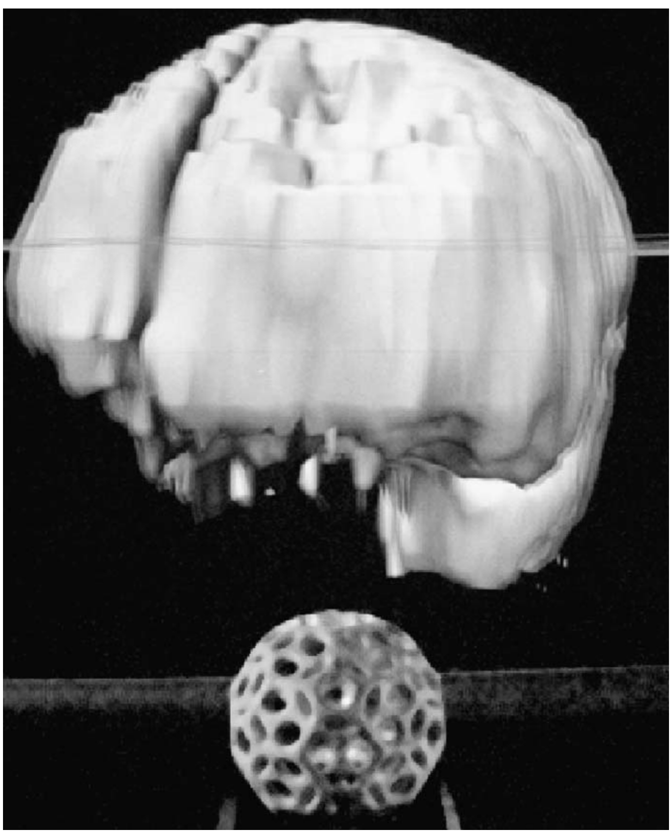

Fig. 7. Sphere Spatializer on the bridge of the Allosphere.

In total there are three interface devices used for the Allobrain project in order to provide multimodal navigation within the fMRI data and control the explorer agents in the simulation. The *Sphere Spatializer* and the *Visual Navigator* shown in Fig. 8 both utilize a custom-developed Inertial Measurement Unit (IMU) based on the CREATE USB Interface (CUI) Overholt (2006). The visual navigation and sound spatialization are cooperatively managed by two primary users holding these wireless devices, while secondary users are able to interact through the electric-field sensors described below. The CUI electronics boards are used with Bluetooth wireless and multiple Micro-Electro-Mechanical Systems (MEM) sensors including 3-axis accelerometers, gyroscopes, and magnetometers. Both absolute and relative orientation can be derived from the real-time data through algorithms such as Kalman or washout filters. The raw sensor data from each interface is mathematically combined to provide relative rotation representation (either axis/angle or quaternions) from each IMU sensor array embedded in the devices. In this way, the users can control both movement and virtual orientation within the simulation space. As shown, the visual navigation device is a small handheld unit with two buttons—one of the buttons activates movement within the space via the user's gestures while the other provides orientation changes via the real-time IMU data. The average latency of wireless data transmission from both the *Sphere Spatializer* and the *Visual Navigator* is between 7 and 10 ms on average; this is sufficient for a perception of audio and visual responsiveness.

Another interface we have developed is an array of six capacitive electric-field sensors embedded into the handrails along either side of the bridge in the Allosphere. The general idea of electric-field sensing is that it can be used in a variety of applications in which the set of antennas provides spatial data via capacitively induced changes in a set of oscillators' characteristic frequencies. Details of related work from the MIT Media laboratory involving a set of similar sensors used for different modes of navigation in a 3D world via free hand gestures can be found in Smith (1996), Paradiso and Gershenfeld (1997) and Smith and et al. (1998). These non-contact human proximity sensors function as a multi-person interface that makes the

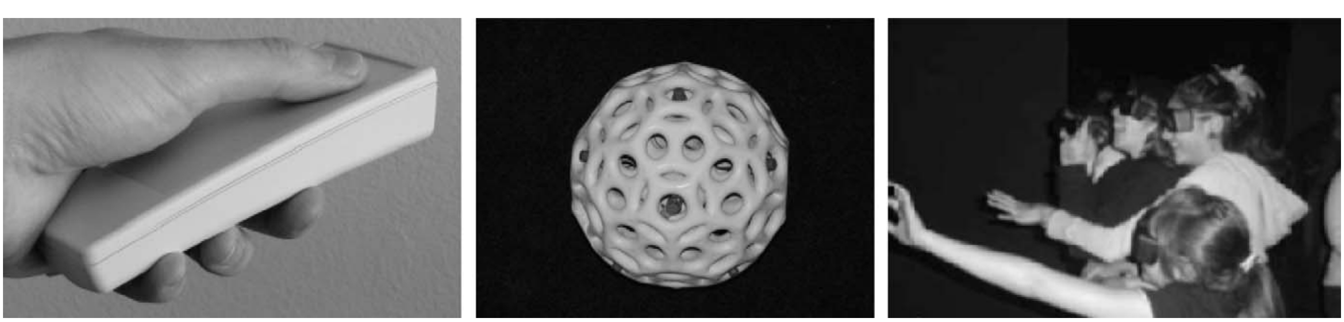

Fig. 8. From left: The Visual Navigator for the Allobrain project, The Sphere Spatializer interface, and the interactive bridge with users interacting via electric-field sensors.

presence of every audience member "felt" (i.e. seen or heard) in the Allosphere, while maintaining the principal interactivity through handheld devices for a set of primary users. This provides a virtual presence to any "secondary" users present on the bridge, as the electric-field sensors are receptive enough to detect the presence of even a single user halfway between the handrails. The group efforts of secondary users can manipulate either supplementary components of primary users' navigation inputs (e.g., the primary users control the direction of movement, while secondary users change the camera zoom as they approach the handrail), or other peripheral components of the Allobrain project such as the activity level of artificial agents.

Collaborative sensing environments such as the Allosphere can blur the distinctions between those who directly interact and those who observe, by allowing primary and secondary users to simultaneously control different aspects of the simulation. In this research project we have integrated various interface devices and levels of control in order to have sophisticated groups of researchers control higher dimensional data multimodally within group "performances". Further explaining our metaphor to musical ensembles, the primary users can be seen analogously to the section leaders in an orchestra, while secondary users follow along naturally, responding to the section leaders for guidance. This natural and intuitive (Yelistratov et al., 1999) method of interaction is afforded by the electric-field sensors together with the *Sphere Spatializer* and the *Visual Navigator*, and serves to provide collaborative interaction with all people present in the Allosphere—in fact it is simply not possible to be an observer with no effect on the interaction while standing on the bridge.

Some users noted a vast improvement in the sense of presence and immersion over other similar spaces when experiencing the Allobrain project in the Allosphere. Our general observation is that users seem to navigate with ease and note a sense of wonderment when using the novel methods of interaction such as the Sphere Spatializer (rather than more customary 3D-navigation devices). We speculate that this wonderment ties to the suspension of disbelief that is important for the elusive senses of presence and immersion. Additionally, we notice that when more familiar devices such as gamepads or joysticks are used to navigate in the Allobrain, they tend to encourage a distinctive "game-play" style of interaction (quick-action movements likely influenced by "First-Person Shooters" or racing games). We purposely designed the interaction devices and modalities in the Allobrain to put forth a sense of comprehensiveness and fluid action in the immersive world that completely envelops the users.

7. Future work

The Allobrain is an evolving project. As our current fMRI data set is static, we recently initiated interface experiments proposing to explore how visualized and sonified EEG data can be integrated into a real-time interactive environment with biofeedback. Work to date has resulted in a Java-based extension to Max/MSP/Jitter that captures real-time data from BIOPAC Inc.'s (BioPac, 2007) line of bio-signal sensors (EEG, ECG, EOG, EMG, etc.), allowing visualization and sonification of user's brain and body activity (Fig. 9). This line of research may well provide further insights into the human perceptual system's responses to real-time biofeedback displays of brain activity as visualized and sonified interactively in the Allosphere.

Fig. 9. Marcos Novak with 16-channel EEG test.

The Cosm toolkit continues to be developed and has proved its capacity as a rapid prototyping toolkit for virtual environments within a pedagogical context at the Media Arts & Technology program, University of California Santa Barbara, USA (UCSB), and at the Southern California Institute for Architecture, USA (Sci-Arc.) Numerous areas for improvement are readily apparent (near-field compensation (Daniel, 2003) and radiation patterns (Menzies, 2007) for Ambisonics, improved network timing, etc.). Other more general trajectories of human–computer interaction research in the Allosphere may feed back into its evolving software infrastructure. However, for a number of reasons, Max/MSP/Jitter is not suitable as a long-term strategy in the Allosphere (including but not limited to restrictions of platform portability and closed-source nature). Nevertheless Cosm has also served as a design template for the developing C/C++/Lua software infrastructure within the Allosphere.

8. Conclusion

This paper has described the creation of the Allobrain project for installation in the Allosphere, a space that presents unique challenges of conceptual, aesthetic and technical natures. Content creation for the Allosphere depends upon such technical problems being solved, but what the content creator actually faces are the more open-ended challenges of multimodal interaction design. Our belief is that the concerns raised in this challenge of content creation are the driving forces behind the development of both technology and theory.

The Allobrain project has borne out this belief by serving as an invaluable case-study for both artistic and scientific projects in the Allosphere. Although the Allobrain project has been followed by numerous subsequent projects of varied natures and subject matters, the Allobrain remains an exhibit of celebrated impact within the Allosphere. Though difficult to evaluate, we believe that this impression follows from several factors: the potency of the brain as a poetic image within the Allosphere (both in suggestive immediacy and implications), in the rich complexity of the space as an architectural proposition conducive to exploration, the detailed layers of sonic composition (at least three levels of sonic event, spectral diversity, spaciousness, vocal-like agent songs), and the integration of these through interaction design. Subsequent projects in the Allosphere have been able to draw significantly from the knowledge gained in the Allobrain project, both technologically and creatively, confirming its significance across many levels.

Not only have there been significant technical and creative contributions of more general applicability as a result of the Allobrain project, such as the Cosm toolkit and novel interaction devices detailed in this paper, but in addition this work has also helped to construct a conceptual and aesthetic approach to the challenges of the Allosphere. This approach may be centered around a general characteristic of immersion or *presence,* with notable methodologies including an approach to narrative characterized as 'inhabitable or navigable cinema', an approach to interaction in terms of a musical notion of ensemble and an approach to cognitive and sensory expansion by means of artificial semi-autonomous agents. Many of these contributions are applicable to the creation of virtual environments in general and thus our work may be of significant value to a broader community.

Appendix A. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijhcs.2009.05.005.

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