Interactive Sonification of Neural Activity

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ABSTRACT
We discuss our ongoing research in sonification of neural activity as demonstrated in the "Fish and Chips" and "BrainWaves" projects. We argue that sonification can serve as an effective technique for the representation of complex spatial information such as neural activity due to the auditory system's ability to perceive stimuli at a wide spatial cover and its inclination to perceive spatial patterns in sonic input. The paper discusses aesthetic and functional aspects of sonification in this context and describes the evolution of our technique, artistic approach, and interaction design – from the low-resolution graphical user interface in "Fish and Chips" to the high-resolution tangible interaction with newly developed controllers in "BrainWaves". We conclude with an evaluative discussion and a number of suggestions for future work.

Keywords
Sonification, interactive auditory display, neural patterns.

1. BACKGROUND AND MOTIVATIONS
With new developments in biological research, scholars are gaining more accurate information about complex systems such as the brain. These developments create a need for effective mechanisms for representation and new approaches for user interaction with such complex datasets. Several visualization techniques have been proven to be useful in addressing similar challenges [1, 5]. For other applications in fields as diverse as oceanographic buoy readings [13] to stock market trends [7], sonification of data has been found effective, utilizing the auditory system's unique strengths such as wide spatial cover and inclination for pattern recognition. Some sonification systems focus on scientific and functional depiction of data [8, 16, 17] while others focus on aesthetics and musical representation [9, 10]. Several recent efforts also addressed user interaction design with sonification, guiding users through dataset queries [3, 6]. Most interactive sonification systems, however, do not support dynamic hands-on interaction that can provide both functional and aesthetically pleasing sonic experiences. We believe that tactile dynamic interaction with auditory displays, which immerse players artistically and scientifically in the experience can provide deeper and more intimate sonic familiarity with complex real-world data. Our main research goal, therefore, was to provide an aesthetically satisfying and educationally useful representation of complex datasets of neural activity through hands-on interaction. Our preliminary effort in this area was in the framework of the "Fish and Chips" project (in collaboration with the Symbiotic Research Group, Perth Australia [14]), where we sonified low-resolution audio signal from an in-vitro culture of fish neural cells. For this project we developed a simple graphical interface for users to choose between datasets. Based on observations from this study we developed a new system, titled "BrainWaves" (in collaboration with the Laboratory for Neuro-Engineering at Georgia Tech [11]), in which we analyzed higher-resolution signals, allowing a group of players to interact and manipulate the data in a performance setting using new tactile controllers that we have developed. Our main goal in "BrainWaves" was to enable players to explore and perceive the neural information in an immersive manner, providing a direct and intimate connection to the information through tactile interactions. We believe that such an approach for interaction with auditory displays can provide artistic, scientific, as well as educational merits.

2. "FISH AND CHIPS"
"Fish and Chips" was a bio-cybernetic research project, originating from the SymbiocA research group in the University of Western Australia, which explores aspects of creativity and artistry in the age of biological technologies [2]. As part of the project, information from fish neurons grown over silicon wafers was sent to control a robotic arm programmed to draw pictures based on the real-time neural activity. Our involvement in the project entailed the development of a musical module that mapped the neural information to generate and manipulate digital music. In addition, we developed a graphical user interface that allowed users to browse and interact with different neural patterns datasets. By creating such a temporal "artist" that drew and controlled music in real-time, the project explored questions concerning art and creativity, such as how humans will interact with cybernetic entities with emergent and unpredictable behaviors and how society would treat notions of artistry and creativity produced by such "semi-living" entities. As part of the project, which was presented at the Ars Electronica Festival 2001, we used the audio representation of real-time electrical activity of fish neurons to generate and control electronic musical output based on the energy in different frequency bands in the signal. We also created a feedback loop, feeding the music back to the neural culture as external stimulus, allowing the algorithm to process the fed back information and produce second derivative output. The installation was featured as a laboratory set-up and included real-time generation of art and music as well as a set of pre-composed and pre-drawn examples.

Figure 1. A microscopic photograph of the neuron culture used for sonification in "Fish and Chips"

In an effort to depict the activity in the culture in a clear manner, we created a simple correlation between the energy in 25 frequency bands in the audio signal and the velocity of real-time generated MIDI notes. For each spike in each frequency band in the signal, a MIDI note was triggered, representing the center pitch at that frequency band at the appropriate loudness. To provide hands-on familiarization with the data we developed a graphical user interface in Max/MSP which depicted the 25 frequency bands, allowing users to choose between the output of live and recorded data, raw signals and filtered signals, pink noise for comparison, and the output from a live feedback loop (see Figure 2.)

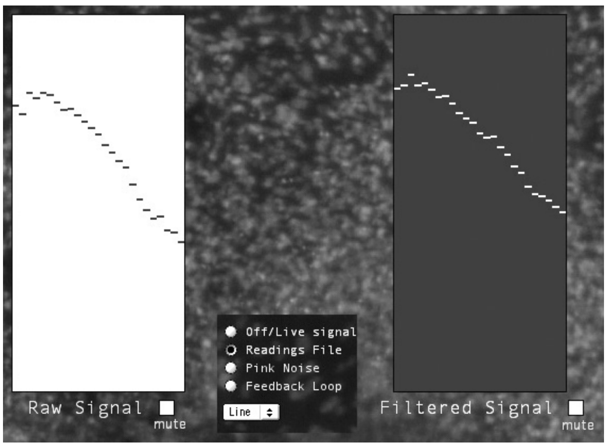

Figure 2. The graphical user interface in "Fish-and-Chips"

In the installation at "Ars Eelectronica" in 2001 hundreds of visitors interacted with "Fish and Chips" musical module. Most participants found the installation interesting and effective. A number of points for improvement, however, also became apparent. First, it was clear that the crude one-channel audio signal does not provide high-resolution spatial representation of the activity in the culture. The simple mapping strategy we used provided only a symbolic gesture for the possible richer musical outcome that can be generated based on detailed spatial neural data. Secondly, the graphical user interface that we designed allowed for only one person to interact with the data, and did not provide a tactile and immersive hands-on familiarization with the information at hand.

3. "BRAINWAVES"

In "BrainWaves" we attempted to address some of the deficiencies that were observed in "Fish and Chips". First, we were interested in representing the spatial propagation of neural activity in the brain based on accurate high-resolution data. In mature neural cultures, spatially localized bursts become common as groups of neurons generate spikes in clusters, stimulating other clusters to trigger in response. We decided to use spatial auditory patterns to represent the propagation of the neural patterns in space, aiming to create both aesthetic and functional merits. We believe that sonification can be more effective than visualization in such a spatial context due to the human auditory system's ability to perceive synchronous spatial stimuli from every point within the space, while visual perception is limited to the physical range of sight. In addition, we decided to provide players with tangible interaction with the data using newly designed percussive controllers. By allowing players to trigger neural spike propagations based on their natural occurrence, we hoped to encourage an active learning process of the interconnections and patterns in the culture. We, therefore, developed a system that allowed a group of players to collaborate in composing a musical piece using our new controllers. As part of the performance, neural spikes and propagation clusters were used to influence and prompt players to respond with actions of their own, facilitating the creation of a unique interactive experience. As players interacted by sending sound waves to each other in a manner that simulated spike propagation in the culture, they became a part of the system, reacting and interacting as the neurons do. The encoded neural information functioned, in a sense, as an equal-right participant in this process. In order to reinforce the functional goals of the system, we also complemented the auditory display with a video display (see Figure 3), which helped represent the information to players and viewers in a multimodal manner.

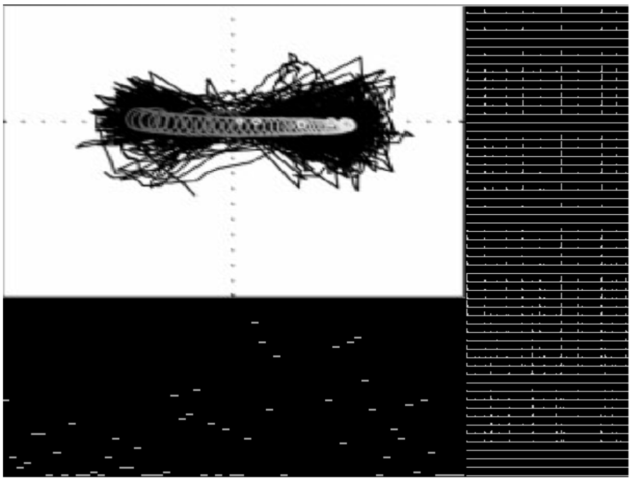

Figure 3. Real-time visualization of the data as projected to audience in "BrainWaves" performance. Top left - currently active spike propagation pattern. Bottom left - real-time data values from 60 electrodes. Right - sensor history

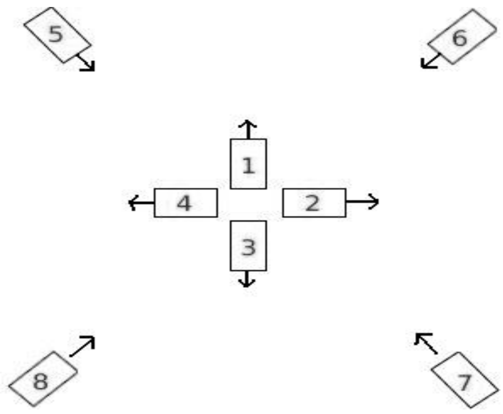

Figure 4. Speaker placement and sound projection in "BrainWaves"

The neural data used in "BrainWaves" was recorded and processed by a research group at the Laboratory for Neuro-Engineering at the Georgia Institute of Technology, directed by Steve Potter [11]. The data was captured from neuron cultures of a mouse cortex, grown over multi-electrode sensor arrays arranged in an 8 X 8 grid [15]. Two different sets of data were used for the project. The first was the raw recorded information from sixty electrodes, measuring the electrical activity in different areas of the culture. The second dataset was based on pattern recognition methods used to study the spatial propagation of spikes in the culture. Our system utilized nine of the most commonly occurring burst propagation patterns in the culture, simulating their trajectories as sound propagation in space. In order to provide effective spatial resolution for the representation of a sixty-electrode grid, we decided to use an eight speaker sound system. More speakers could have presented difficulties in interaction conveyance and sonic cancellation, while fewer speakers might not have provided high enough spatial resolution. Our goal was to represent the propagation in the culture as accurately as possible in a manner that would fit well with the performance space. We, therefore, divided the sensor arrays into eight different zones as depicted in Figure 4. Four outer zones extended from the corners of the grid towards the center, and four inner square zones were projecting sound from the center outwards. In mapping the data to the speakers, we used each sensor value per time sample to calculate an average of simultaneous values for each zone, testing it against a predetermined threshold. If the value exceeded the threshold, a spike was determined for the appropriate zone. We determined which spatial propagation pattern had to be triggered by using statistical data on each spike pattern probability given its spatial origination within the culture. The audio was then sent through the appropriate speakers, approximating the path of the propagation. When idle, the system played a soft drone sound-scape using long tones and pads of low frequency noise. When a spike was triggered by the encoded data, high frequency sounds were used to represent the propagation patterns. We also allowed users to trigger their own spikes, using a set of newly developed controllers (see Figure 5.). For these user-triggered spikes, we chose a set of loud and distinctive high frequency sounds with a noisier content. This timbre differentiation helped portray the interaction to users and to the audience by separating between the recorded data, the analyzed spike propagation, and the user-generated spikes.

Each of the eight 3 feet percussive controllers was installed next to a speaker around the performance space. Each controller contained a piezoelectric sensor to detect hits and an electric circuit to drive two sets of LEDs, offering spatial visual representation of sound propagation in space. An elastic chord connected the hitting surface to the controller's frame, providing haptic and expressive hit response. The system was designed to provide tactile familiarization with the network topology and the high-level structures in the culture. In order to engage players and provide a long lasting musical experience, we designed the interaction as a game. Players could trigger a propagation pattern by hitting their respective controllers. A spatial wave of sound then propagated from the nearest speaker to other speakers in the space, simulating the neural propagation in the culture. When the pattern ended, the player positioned at that receiving station was prompted to respond with his or her own spike trigger, and so on. By allowing players to send waves of sound to a stochastically chosen destination (the propagation cluster was chosen based on its statistic occurrence in the culture) we added an element of surprise to the system which encouraged players to follow the propagation cluster more closely and to try and surprise their co-players. Free-play interaction schemes were also experimented with, which often led to shorter, less engaged play sessions. In January 22, 2005 the "BrainWaves" system was presented in a performance at the Eyedrum Gallery in Atlanta, GA. The performance began with a brief explanation of the project, followed by a demonstration of the system in idle mode. We then played the recorded neural data accompanied by a visual representation of sensor history, real-time sensor activity, and a visual representation of spike propagation each time a spike occurred (see Figure 1). The system ran the recorded data for several minutes, giving the audience the opportunity to become familiarized with the information and its representation. After several minutes, a group of six performers started triggering spikes and propagating sound waves according to the game rules as described above. The performance proceeded in this manner, eventually involving all performers up to a point where the activity lessened and the system returned to play in an autonomous manner, fading out slowly. When the performance ended, audience members were invited to interact with the system in free play mode (see Figure 5).

Figure 5. A player interacts with the "BrainWaves" controller, triggering sound patterns in space based on probabilistic occurrence of neural spike in the brain

4. DISCUSSION AND FUTURE WORK

The "BrainWaves" performance was well received, leading to positive responses from audience and participants who found the tactile interaction and detailed spatial information useful and aesthetically interesting. This constituted a notable improvement in comparison to user reactions in "Fish-and-Chips". The observations and discussions with participants and audiences also led to a number of suggestions for further improvement and future work. While the environment was intriguing and immersive to most users, the relationship between the data and the sounds, particularly in the interactive sections, were not apparent to everyone. While the projected visualization did help the audience to better understand the activity in the culture, for some players the graphics became the main focus of attention. For the next version of the project we plan to experiment with less distracting visualization schemes that would complement and augment the auditory artistic experience, rather than dominate it. Another manner in which we plan to improve the auditory display is to conduct further experimentation with speaker placement and mappings. The sounds we chose for the performance worked well and created the aesthetics that we aimed for, but the system can benefit from experimentation with other timbres sets that are further separated from each other perceptually. This would hopefully improve group interaction, since at times, players found it difficult to follow the sound propagation. The game interactions were well received and encouraged participants to follow the sounds that they created in space, adding an element of tension and surprise. Some players, however, were prompted to interact more than others due to the fact that many patterns in the data ended in the same few stations. To address this problem we plan to explore other spatial datasets that may show a larger variety of propagation patterns. We will also investigate and explore other interaction schemes using non-spatial patterns in the data. This may involve implementing new pattern recognition methods, using tools such as neural networks to discover new and potentially meaningful patterns in the culture. Finally, we aim to improve the musical mappings by focusing on elements such as rhythm and harmony, utilizing perceptual concepts such as rhythmic stability and harmonic tension [4, 12], which may lead to richer and more interesting musical results.

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