

# BioRhythm: a Biologically-inspired Audio-Visual Installation

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## ABSTRACT

BioRhythm is an interactive bio-feedback installation controlled by the cardiovascular system. Data from a photoplethysmograph (PPG) sensor controls sonification and visualization parameters in real-time. Biological signals are obtained using the techniques of Resonance Theory in Hemodynamics and mapped to audiovisual cues via the Five Element Philosophy. The result is a new media interface utilizing sound synthesis and spatialization with advanced graphics rendering. BioRhythm serves as an artistic exploration of the harmonic spectra of pulse waves.

## Keywords

bio-feedback, bio-sensing, sonification, spatial audio, spatialization, FM synthesis, Open Sound Control, visualization, parallel computing

## 1. INTRODUCTION

Hemodynamics is the study of blood flow and circulation. Resonance Theory in Hemodynamics (RTH) [12, 7] provides scientific evidence of the relationship between harmonic peaks of blood volume change signals and visceral organs. The spectra and frequency selectivity of arterial beds in organs were found to change profiles following specific patterns with ligations of different arteries [7]. Three primary concepts summarize RTH. First is the measurement of a subject's physiological condition by palpation sensors and harmonic analysis of the resulting pulse waveform using objective signal processing techniques. Second is the perspective that there exists a direct relationship between the efficiency of the cardiovascular system and the development of meridians within a species. Biologically, meridians are pathways for the flow of qi (pronounced "chi"), the Chinese term for psychophysical energy. Finally, animal and clinical studies show the specific relations between visceral organs and pulse harmonics [7].

Five Element Philosophy (FEP) [11] provides a mapping from visceral organs to musical pitch, color, and cardinal direction. Table 1 combines Resonance Theory in Hemodynamics with FEP to create the mappings used in BioRhythm. We use FEP only as a metaphor for creating the artistic vocabulary and bio-audio-visual mappings

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Table 1: Summary of RTH and FEP

Harmonic	0	1st	2nd	3rd	4th
Organ	Heart	Liver	Kidneys	Spleen	Lungs
Color	Red	Green	Black	Yellow	White
Pitch	G	E	A	C	D
Direction	South	East	North	Center	West

within this work. BioRhythm is the first known attempt to establish a relationship between RTH and FEP.

## 1.1 Background

While the sonification of biological data for artistic purposes has a long history, the majority of projects have focused on electroencephalographic (EEG), electrocardiographic (EKG), electromyographic (EMG), or some combination of several sensors [10, 9]. In addition to aesthetic exploration, other studies have focused on biological sonification as a tool for diagnosis [5]. With BioRhythm the goal was to extract as many audio-visual mapping parameters as possible using a single fingertip photoplethysmograph (PPG) sensor. The unobtrusive PPG interface is also more conducive to audience interaction than other sensors.

## 1.2 Biological Sensor

A photoplethysmograph (PPG) is an optical sensor that measures blood volume changes by illuminating the skin with an LED and detecting the amount of light transmitted or reflected to a photodiode. The PPG used in BioRhythm takes measurements on the index finger and is used as the primary source to drive audiovisual generation. The spectrum of a PPG signal is characteristic of the harmonic spectra used in RTH. In addition, the optical PPG has the advantage of being easy to use for public installations.



Figure 1: PPG Sensor (BIOPAC Systems, Inc.) [1]

## 1.3 Harmonic Analysis of the PPG Waveform

The harmonic modulus is defined as ratio of amplitude of the harmonic to that of the fundamental frequency. BioRhythm uses RTH and FEP to map the harmonic moduli of a PPG signal (Figure 2) into five frequencies, colors, and directions that serve as the basis for sonification and visualization techniques.

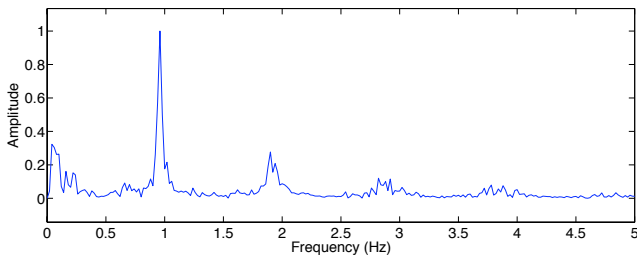


Figure 2: Spectrum of typical PPG Signal

## 1.4 System Integration

Real-time physiological signal acquisition to sonification and visualization is accomplished with parallel computing between three laptops via Open Sound Control (OSC) [13]. One laptop captures and processes the raw PPG data using BIOPAC software [1] then uses Max/MSP to send the raw data along with spectral information via OSC. Two other laptops receive OSC data and generate the sonification and visualization respectively.

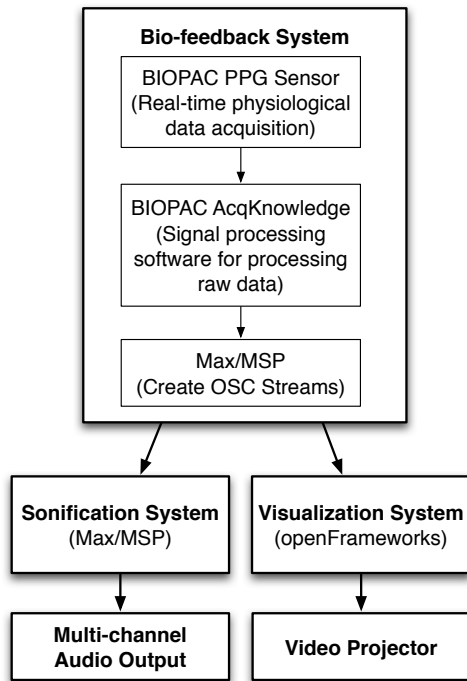


Figure 3: System Integration

## 2. SONIFICATION

The sonification for BioRhythm is composed of 3 separate sonic layers using an intricate combination of FM synthesis, spatialization, filtering, and delay lines implemented in Max/MSP. Parameters received via OSC are the raw PPG signal, heart rate (in beats per minute), interbeat interval (time between heart beats in milliseconds), and the amplitudes (0-1) of the five PPG harmonics. The sonification software also computes each user's average heart rate, thus, there is a brief learning phase for before the sonification begins for each new user. Figure 4 provides an overview of the sonification in BioRhythm.

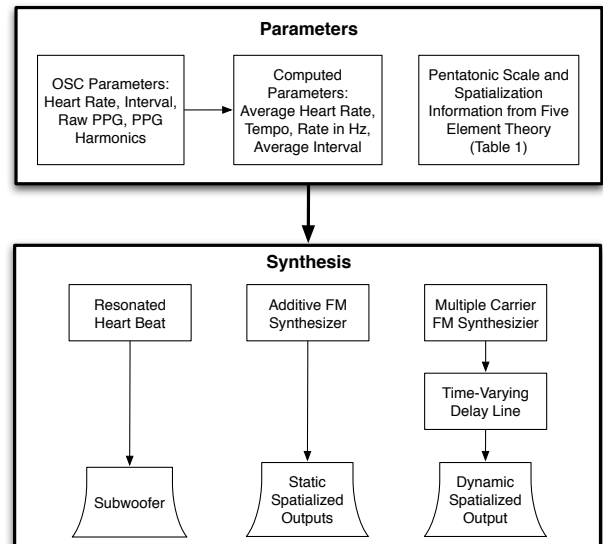


Figure 4: Sonification in BioRhythm

### 2.1 Heartbeat Layer

The first layer takes an iconic approach to sonification [6] by representing the user's heartbeat with a sound sample of a heartbeat triggered at each peak of the PPG signal. The sample is equalized with frequency peaks in the 40-80hz range corresponding to G, E, C, D, and A musical notes as defined by FEP. There is no sound synthesis or spatialization at this layer, but the heartbeat layer provides the user with a simple, clear biofeedback response while the other two layers contain more depth.

### 2.2 FM Synthesis

The second and third layers of sound use a unique approach to sonification that combines model-based and parameter-based methods [6]. If we think of the sonification software as an instrument, then the incoming data not only plays the instrument, but also defines and reshapes the instrument. This is accomplished through the use of frequency modulation (FM) sound synthesis. The basic elements of FM synthesis are a carrier frequency (the fundamental frequency), a modulation frequency (the rate at which the carrier frequency will vary), and the modulation index (the amount of frequency deviation from the carrier which directly corresponds to the number of resulting partials). When the ratio of the carrier to modulator frequency is an integer a harmonic sound results. For non-integer ratios the sound is inharmonic.

### 2.3 Additive FM Layer

The foundation of the second sonic layer sums five simple FM synthesizers, a technique known as additive FM synthesis. Each of the carrier oscillators is set to a frequency corresponding to one of the five notes of the FEP pentatonic scale specified in Table 1. The modulator frequencies begin at a 1:1 ratio with the carrier. The modulators continuously adjust themselves so that the ratio of the average heart rate to current heart rate matches the carrier to modulator ratio. Thus, the modulator frequency changes with each heartbeat. Due to the properties of FM synthesis, the sounds become more harmonic as the user's heartbeat closely matches their computed average. Large changes from the average heart rate will result in more inharmonic sounds. The amplitudes of the 5 harmonic filters are scaled

to a modulation index between 0 and 25 for their respective modulators. Thus, strong presence of a particular harmonic in the PPG signal produces a high modulation index that results in a harsher sound with more high frequency components. The output of each FM synthesizer is given a static position corresponding to a cardinal direction specified in Table 1.

## 2.4 Multiple Carrier FM Layer

The third layer of sound implements multiple carrier FM synthesis (MCFM), multiple carriers sharing a single modulator). Again, each of the carrier frequencies corresponds to a note in the FEP pentatonic scale. However, in this layer the user's current heart rate is converted to Hertz and used as the single modulation frequency. The raw PPG signal is scaled to an index between 0 and 25 for the modulator. Higher amplitudes of raw PPG data indicate higher blood pressure for the user and will raise the modulation index of the sound, resulting in more high frequency components. Likewise, users with lower blood pressure will experience a calmer sound with less high frequency components.

## 2.5 Spatialization and Movement

Further interpretation of the third layer lies in the timing and spatialization of the synthesized sounds. The output of the MCFM synthesizer connects to a delay line with a variable delay time set by the interbeat interval. Thus, slower heart rates produce longer delays that echo the dry sound. If the heart rate suddenly increases it will be echoed by several short time-delayed versions of the sound. The time varying delay lines shift the frequency of the sound, which produces an effect similar to Doppler shift. This delay line implementation makes apparent subtle changes in heart rate that cannot be interpreted by simply listening to the heart-beat of the first layer. Lastly, this layer is highly spatialized as a single point source moving rapidly around the user. A direction (azimuth) and distance is computed from the weighted average of harmonic levels that correspond to cardinal directions. The panning algorithm used is original but similar to distance-based amplitude panning (DBAP) techniques [8].

## 2.6 Sonification Summary

To summarize the sonification, we have a simple heart beat sound providing the underlying rhythmic interpretation and deep bass frequencies, a second layer that represents change through tonal timbre and chord formation, and a third fluttering treble layer that focuses more on time delays and dynamic spatialization to represent change. Due to the extreme sensitivity of the PPG, a static sound cannot be achieved even in the user's most restful state. Thus, users are not required to elevate their heart rate or dramatically change their physiological state to hear interesting results (though many have fun doing so). Each individual produces their own unique choreography of sounds due to parameters of their unique heart beat or biorhythm.

## 3. VISUALIZATION

The visualization consists of a single abstract organic form produced by algorithmic methods focused on distorting of a perfect sphere. As with the sonification, the incoming bio-signals are mapped according to RTH and FEP, which leads to an extremely coherent synchronization between auditory and visual cues in the installation. The visualization receives the same parameters as the sonification via OSC and runs as a C++ OpenFrameworks [4] application.

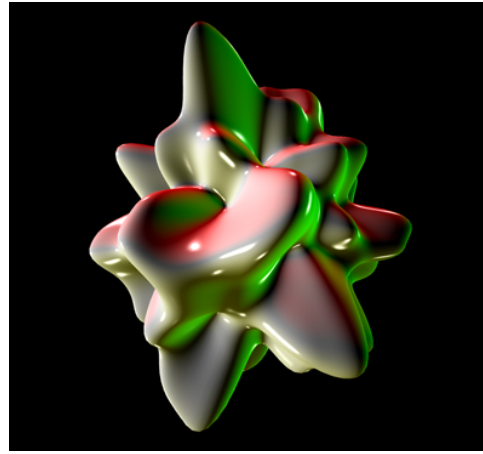


Figure 5: BioRhythm Visualizaton

## 3.1 Aesthetic

The development of an organic aesthetic was pursued because of the biological nature of the research. This organic form steers away from traditional data graphs and plots, so to engage the installation's audience in a deeper and more anthropomorphic manner. The blob-like extrusions in the visual aesthetic help to emphasize the human body, its organs and their fluctuations, as described in RTH.

## 3.2 Mapping

The base radius of the sphere reflects the amplitude of the raw PPG data and thus the overall form appears to "thump" in unison with the user's heard beat and sonification. A 3D Perlin noise function distorts the vertices of a sphere as the user's heart rate departs from equilibrium and the sonification produces more inharmonic sounds. If the user can steady their heart rate, then they will be able to replicate a pseudo-perfect sphere along with a harmonic sonification. Otherwise, as with the sound, the form will fluctuate and warp according to the blood pressure in the user's finger.

Four lights add color to the visual scene. Green, red, black (absence of light), yellow, and white lights are placed according to the cardinal directions given by FEP. The presence of any color varies with the amplitude of its harmonic along with the presence of a FM carrier frequency in the sonification.

## 4. PUBLIC INSTALLATIONS

BioRhythm has been publicly exhibited at MindShare Los Angeles [3] and at the Media Arts and Technology End of Year Show at the University of California, Santa Barbara (UCSB) [2]. Both events regularly draw hundreds of artists, engineers, scientists, and others interested in new media at intersection of art and technology.

### 4.1 Hardware

The original BioRhythm installation at UCSB used a video projector and accompanying array of 32 speakers in an upwards-pointing semi-circle on the floor around the user. A stereo version has also been implemented for venues where larger surround setups are not possible. The fingertip PPG sensor hangs from the ceiling by a thin wire.

### 4.2 Interactivity and Feedback

The public feedback we receive is generally positive, and users are often comment on how well the sounds match the visuals. Typical behavior after waiting for the 15 second learning phase is that people either attempt to remain

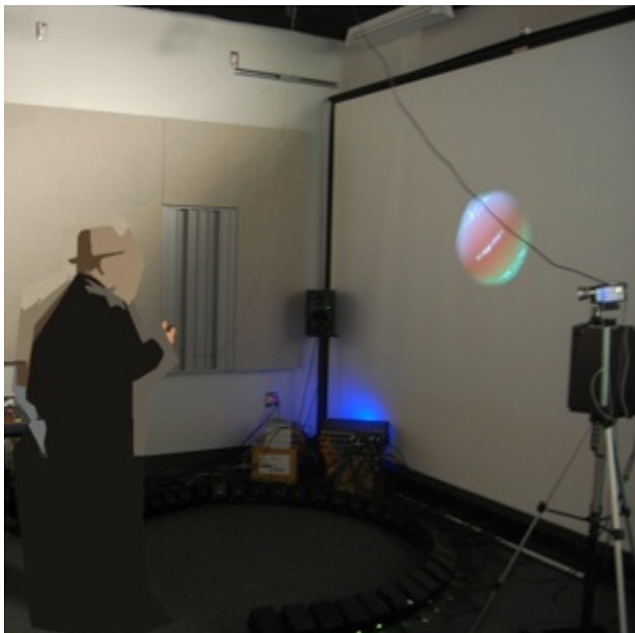


Figure 6: 32 Channel Installation at UCSB

calm to settle the system, attempt to elevate their heart rate through movement to provoke dramatic changes, or attempt some “hack” of the system. For instance, realizing that blood flow is being measured in the finger, some users trigger audio-visual reactions by clenching their finger or fist. In fact, one man attempted to cut off circulation in his girlfriend’s hand, and when he released her wrist there was indeed a dramatic change in timbre and spatialization with an explosive warping of the visual form (similar to Figure 7). Other users realize the extreme sensitivity of the PPG sensor and squeeze or rub the sensor to produce extreme effects. Though these hacks are quite interesting, we find that each individual produces interesting time-varying results when remaining still. The sensitivity of the system is such that the user would have to be laying down nearly unconscious to achieve a constantly harmonic sound with spherical shape.

## 5. CONCLUSIONS

BioRhythm explores the use of a biofeedback sensor for an interactive audio-visual installation. The simple velcro fingertip sensor makes BioRhythm suitable for public installations with hundreds of users. The sonification involves dynamic changes in pitch, timbre, rhythm, and spatialization most notably through the use of FM synthesis, delay lines, and multichannel panning. The visualization projects concurrent movements of shape and color. Users are able to observe audio-visual reactions in the installation corresponding their unique physiological states.

Future work involves improved sensor calibration, searching for patterns within pulse spectra, and the use of alternative sound synthesis methods. RTH and FEP have provided one mapping from biological data to sound and visual domains, but they are only a starting point, and we are excited to explore newly proposed mappings from artists and scientists alike.

## 6. ACKNOWLEDGMENTS

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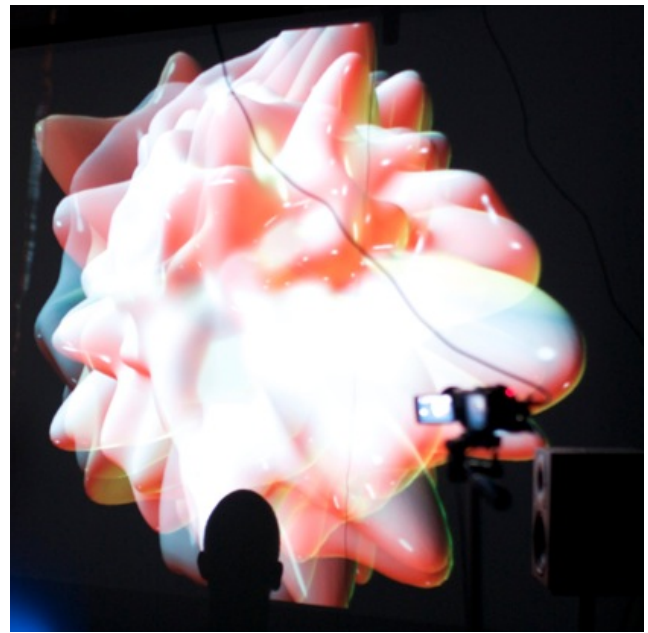


Figure 7: Dramatic Change in BioRhythm

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