Playing on Heart-Strings: Experiences with the 2Hearts System

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ABSTRACT
Here we present 2Hearts, a music system controlled by the heartbeats of two people. As the players speak and touch, 2Hearts extracts meaningful variables from their heartbeat signals. These variables are mapped to musical parameters, conveying the changing patterns of tension and relaxation in the players' relationship. We describe the motivation for creating 2Hearts, observations from the prototypes that have been built, and principles learnt in the ongoing development process.

Keywords
Heart Rate, Biosensor, Interactive Music, Non-Verbal Communication, Affective Computing, Ambient Display

INTRODUCTION
2Hearts is a computer-based system that maps two players' changing heart rates into a dynamic musical background. As the players interact by speaking and touching, they experience changes in mood, tension and arousal which impact on their heart rate signals. 2Hearts displays these signals as various musical parameters and state changes. In turn, the musical feedback affects players' emotions. Figure 1 is an illustration of the 2Hearts concept.

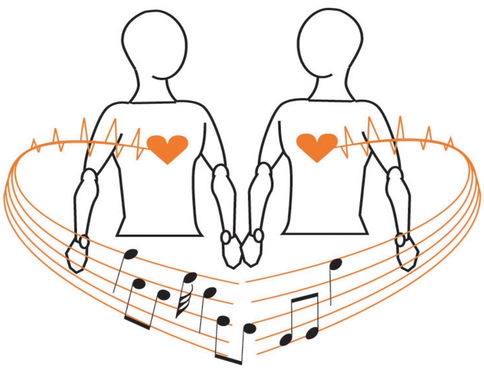

Figure 1. The 2Hearts Concept

Sharing Heartbeats Through Music
With appropriate biofeedback, individuals can learn to control their biopotentials, such as heart rate, to some degree. However, an individual's heart rate responds quickly to external events. More specifically, it responds to actions and events created by other people during communication. Thus, it is possible for one individual to intentionally influence another's heart rate. Normally, though, the heart rate of another is invisible and can't be heard. An effective method for providing access to the heart rate is mapping heart sensor data to musical parameters. In 2Hearts, we allow two people to interact with each other, verbally and physically, to control each other's heart rates, in turn controlling the music. Our work with 2Hearts depends upon two assumptions:

- Communicating the heartbeat signal can enhance the feeling of intimacy in human-to-human interaction.
- Musical mapping of heartbeat information provides a suitable display for the heart data as well as a mechanism for two people to express themselves musically.

The heartbeat we most commonly experience is our own, and it connects us to the fluctuations of our own body and emotions. Therefore to know the heartbeat of another is to absorb their rhythm, to move inside the sphere of their bodily experience. This thinking is supported by the success of artworks such as Christopher Janney's Heartbeat: mb, which audifies Baryshnikov's heart activity during a dance performance [5]. Using heartbeat in this way has been observed to create a strong feeling of connection between crowd and performer.

Music is an appealing medium for the display of biosignals because it has the ability to elicit emotional responses while remaining in the background, allowing the listeners to focus on each other. Past musical controllers have explored the use of biosensor data: for instance, David Rosenboom's piece Portable Gold and Philosophers' Stones utilized skin resistivity and temperature signals to control a sonic output [13]. Musical works have been performed with the BioMuse system, which allows heartbeat, brainwave, and other signals to control graphical and musical output [6]. The novelty of 2Hearts lies in its focus on two-way communication, and the use of social relationship to moderate the heart rate response. Users of 2Hearts effectively "play" each other.

The Human Becomes the Musical Interface

2Hearts extends traditional methods of musical collaboration. In a musical duet, each player directly controls a subset of the musical output parameters, and interaction occurs primarily through the *musical relationship* of these parameters. Using 2Hearts, the players focus specifically on their *human relationship*, and jointly control the music via social interaction.

We have attempted to design this emphasis on human relationship into 2Hearts' treatment of heartbeat data: in addition to mapping each player's heart rate to musical parameters, 2Hearts measures the differences and correlations in heart rate behaviour and maps these variables as well. Thus the relationship between players acts as a musical agent in its own right.

Feature Extraction: Our Approach to Heartbeat Analysis

In creating a system to communicate bio-sensor data, we had to decide how the system should translate the data into a useful format for human comprehension. Existing systems provide a range of different approaches to this issue. IBM's Emotion Mouse research is an example of the classification approach [1]. This system obtains a vector of physiological signal values, and attempts to infer the user's emotional state (categorized into basic emotions such as happy, sad, scared, etc.)

An alternative approach is to directly map the raw signals into human-perceptible form. The Galvactivator consists of a partial glove containing an LED, with light intensity controlled by skin resistance [8]. Audible Distance, by Akitsugu Maebayshi, is an interactive VR piece in which multiple users wear heartbeat sensors and head-mounted displays [7]. While the users walk through a common physical space, they are presented with a graphical representation of each user's position and heartbeat.

Considering the aims of 2Hearts, we decided that the appropriate scheme for extracting heartbeat data lay somewhere between the two extremes of the classification approach and the direct mapping approach. Discrete classification schemes do not convey enough information to do justice to the subtle, continuous changes of heart rhythm. However, direct mapping does not necessarily allow for the best comprehension of the heart signal. After all, heartbeats are not communicated in most of our social interactions; there has been little pressure to learn or evolve techniques for interpreting the raw heartbeat signal.

The 2Hearts software derives variables from the heartbeat signal that we hypothesize to be especially relevant in two-person social interaction. These variables include the raw beat times, the measured heart rates, the changes in heart rate, and the relationship between the two heart rates. Emphasis is placed on representing the output variables in a compelling, affective way to enhance the degree of intuitive interpretation.

Mapping from Heartbeat Space to Music Space

While schemes of emotion classification can be very complex, one well-known theory uses a two-dimensional emotion space [10]. Arousal forms one axis of this space, the other being pleasure. Directed by the autonomic nervous system, the heart rate changes according to rising and falling levels of arousal [4]. In other words, a person's heart rate may be high either because they are happy and excited (high arousal, high pleasure), or because they are scared (high arousal, low pleasure).

Music is often discussed in terms of the rise and fall of tension. Thus, a strong link between emotion space and music space is the affinity between arousal (in emotion space) and tension (in music space). Completing the chain, we can map increasing heart rates into musical parameters that convey increased tension (see Figure 2).

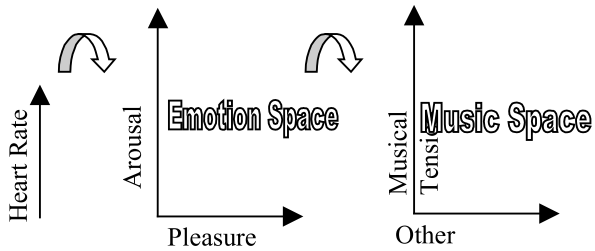

Figure 2. Mapping from Heart Rate to Tension

Studies have been done to determine the tension-producing quality of different musical variables [3],[9],[11],[12]. It has been established that tempo and timbre correlate strongly with tension, while pitch level, dissonance, ornamentation, and volume also have an influence. This presents a candidate list of variables to manipulate.

The scheme still leaves questions: How do we pick the correspondence between heartbeat variables and tempo, timbre, etc.? And, importantly, how do we traverse music space along the non-tension-related dimensions? In the 2Hearts prototypes discussed below, several different techniques are implemented for comparison.

THE PROTOTYPE: 2HEARTS-GRAVITY

Our first iteration of the 2Hearts design was completed in January, 2001. Its version-name, Gravity, ties together elements that distinguish this prototype from later versions of 2Hearts: the inertia-based control metaphor, the Techno style music employed in its interactive score, and (unfortunately) the finger-clip heart beat sensors which made it necessary for the players to sit in chairs. 2Hearts-Gravity has been demonstrated to the public on several occasions, including the ASI Exchange technology fair in Vancouver, (March 13, 2001) and the NIME01 demo event at the Experience Music Project in Seattle (April 2, 2001).

System Architecture

Figure 3 shows the major components of 2Hearts-Gravity. Attached to each player is a finger-clip blood-flow sensor that works by measuring the change in infrared conductance caused by each pulse of blood through the finger.

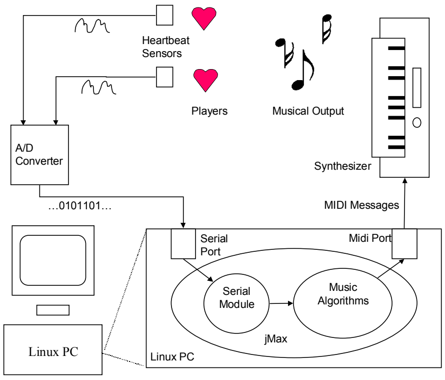

Figure 3. Components of 2Hearts-Gravity

Sensor outputs are digitized and sent to the serial port of a Pentium II computer, running the jMax music programming environment [2]. The jMax program sends a sequence of MIDI note and control messages to a Yamaha EX-5 synthesizer.

Figure 4 shows an example of heart rate data as obtained from two users in a test session. The notable increase in both rates at around 100s corresponds to the enabling of audio output and the onset of physical touch between the users. Some of the sharpest peaks represent noise from poor sensor contact.

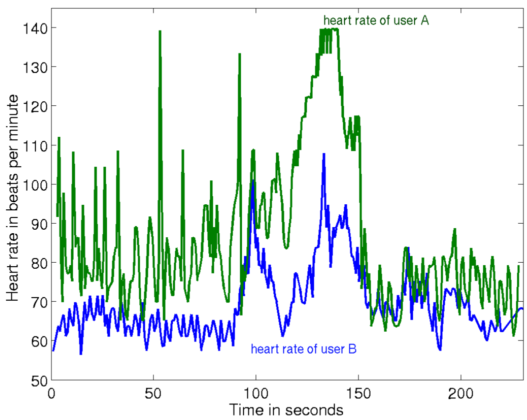

Figure 4. Sample Heart Rate Data

Heartbeat Feature Extraction

Within jMax, peak-detection is performed on the heartbeat signals and heart rates are calculated. Rate values are averaged over the last four beats to filter out small, random fluctuations. Since every person has a different range of heart rates, heart rate is subtracted from a centerline that slowly tracks the current rate.

Two Time Scales of Musical Variation

Developing the 2Hearts-Gravity system, we realized that another type of data could be extracted from the heart beat signals: their cumulative behavior over time. To take advantage of this information, we built 2Hearts-Gravity as a musical state machine.

Gravity's heart rate-to-music algorithms function on two levels: first, moment-to-moment changes in heart rate control immediate modifications to a predefined loop of notes; second, the two heart rates steer progress through different loops using a Musical Terrain metaphor. The immediate musical feedback for each change in heart rate is critical to the experience of shared heartbeat.

Immediate Heartbeat-Music Mappings

Facing the issue raised above of mapping heart variables to musical tension, we took a simple first approach for the immediate mappings. We chose to modulate tempo, timbre, and pitch level, due to their strong and well-understood effects on tension. We also used rhythmic ornamentation to occasionally increase tension.

2Hearts-Gravity uses two instrument tracks (A and B) and a drum track. As the music cycles through a repeating note sequence at the current score position, the following musical parameters are continuously altered:

- The tempo is changed with each new heartbeat to equal the players' average heart rate adjusted by a constant scaling factor. The scaling factor allows us to use various styles of music at their natural tempi, and to explore the effect of increasing or damping feedback.
- An increase in the first player's heart rate modifies the timbre of Instrument A to a harsher sound. A decrease in heart rate produces a more mellow sound. Likewise, the second player's heart rate is linked to Instrument B. Calibration tables monotonically re-map the control signals to MIDI control values, to create an intuitively "linear" progression in timbre.
- As a player's heart rate signal crosses a low or high threshold, the notes played by the matching instrument change to lower or higher chord inversions.
- When the difference in players' heart rates exceeds a certain threshold, an echo effect is applied to the instrument sounds. This creates a multiplicity of off-beat notes, which portrays the loss of emotional "synchronization" between players.

The Musical Terrain Metaphor

The Musical Terrain metaphor was our solution for mapping the players' exploration of each other into a journey through musical space. In the Musical Terrain metaphor, musical state is modeled as the position of a virtual ball rolling across a three-dimensional surface. Different portions of the surface area are assigned to different sections of music, which loop until the next section is reached (see Figure 5).

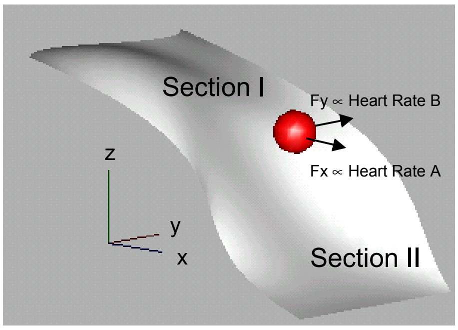

Figure 5. The Musical Terrain Metaphor

The ball is pushed by forces in the x and y directions, corresponding to the calibrated heart rates of the two players. Thus, to progress in a diagonal direction, players must co-operate to affect both heart rates in a certain manner. The elements of inertia, friction and bias through terrain slope help to compensate for the imprecise control signals, and so stabilize ball motion.

We deliberately scored the Musical Terrain to generate a narrative of each player's changing tension, using the musical dimensions of volume, chord progression and rhythmic density. This proved to be a difficult compositional task. The prototype Gravity score employs electronic pad and bass sounds for Instruments A and B, in a Musical Terrain with four main sections. The drum track is configured to increase in excitement along the diagonal increased-heart-rate axis. The melodies for A and B become more agitated with increasing heart rate. The sculpting of terrain height is minimal, consisting of upward slopes near the terrain edges.

Evaluating 2Hearts-Gravity

At the demonstration events, volunteers were seated in two chairs and instructed to attach the blood-flow sensors. Players were instructed to provoke each other by asking embarrassing questions, telling jokes, and so forth, in sessions lasting about 5 minutes.

Players appeared to understand easily the timbre/inversion changes of each track and their relationship to heart rate changes. The echo effect was noticeable during some moments of sudden change, but many players did not notice it or link it with events in their interaction. Our use of an all-or-nothing threshold technique, as well as the fact that the threshold was too low, meant that this correlation signal did not play as important a role as we had hoped.

We noted that most players interacted in a mainly verbal, tentative manner. Those players who were more experimental, interacting in a more touch- or dance-oriented manner, seemed to achieve more interesting, interpretable results. Calibrating and maintaining the finger-clip sensors was difficult in the demo setting. Often when players moved around, the sensor contact was broken, triggering false heartbeat readings.

We observed that the Musical Terrain functioned as designed, providing musically coherent changes of melody and dynamic. However, it was unclear whether players noticed most of the musical effects related to Terrain position. One reason was that the virtual area of each Terrain section was too large; a change of section only occurred about once every 20 seconds. Another problem with the Musical Terrain was the repetitiveness of the music. The scripted melodies became tiresome before long, and seemed to impart a sameness to the mood of each interaction.

The three most serious problems of 2Hearts-Gravity can be summarized:

- The heartbeat sensors were unreliable and physically limiting.
- The heart rate difference signal was often not expressed in the musical output.
- The Musical Terrain was not rich enough, leading to lack of output variation.

Improving on the Musical Terrain Metaphor

Given the third point listed above, a potential solution would be to compose a more detailed Musical Terrain. However, composing in two dimensions while attempting to portray cumulative tension levels of two players was a mind-bending task. It was not intended that the system require such a demanding compositional effort. We also noted that the simplest mappings to tempo and timbre had been easiest for players to interpret, in agreement with the research [9],[11].

These findings suggest it would be wiser to de-couple high-level chord progressions and melodies from a specific tension-parameterization. We thought of two schemes for accomplishing this, while still increasing the amount of musical variety:

- Keep the Music Terrain architecture, but compose an arbitrary 1-D or 2-D score without regard to a specific meaning of each dimension. This would still require the development of tools to facilitate the Terrain creation.
- Abstract away from Musical Terrain, by eliminating traditional melody, creating different bundles of heartbeat-to-tempo/timbre/pitch/volume mappings, and moving randomly between bundles.

Elements of the two schemes could also be combined.

Regarding the rolling-ball metaphor, it presented too much of a conceptual leap as a control mechanism. Yet, the metaphor gave satisfying results in terms of musical progression and pacing. We believe the element of inertia is the key aspect of the metaphor, and continue to experiment with this element in the 2Hearts control system.

THE SECOND VERSION: 2HEARTS-AURA

The second iteration of 2Hearts is currently under development. It is named "Aura" because we have added the element of graphical display to the 2Hearts concept. Heartbeats are visualized as glowing, pulsing auras surrounding each player in the CAVE virtual projection environment.

2Hearts-Aura follows our idea of abstracting away from Musical Terrain and traditional melody. It also incorporates a superior heart sensor technology and many other improvements and ideas. Figure 6 shows the 2Hearts-Aura prototype.

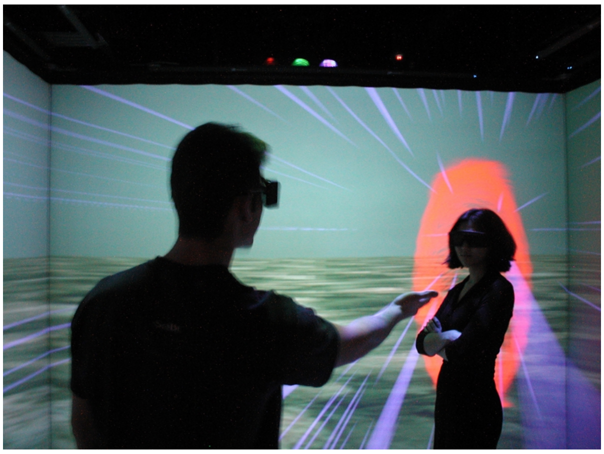

Figure 6. People interacting in 2Hearts-Aura.

A Graphical Element for Heartbeat Display

We were interested in adding graphics to 2Hearts to compare the effectiveness of the two output modalities, and to see if graphics could reinforce the musical output. 2Hearts-Aura employs the imagery of auras that surround each player, pulsing in time with heartbeat and changing colour in connection with heart rate.

When used in the standard way, the CAVE VR system presents advantages and disadvantages for the 2Hearts project. The 3-D graphics help create the feeling of a shared heartbeat-continuum which envelops the players, but the 3-D glasses hide the eyes, hampering non-verbal communication. The current ultrasound/inertial head-tracking system is bulky and tethers players with wires, repeating the problem of restricted motion. We are still changing the graphical content and sensor/display technology to solve these problems.

Improved Heartbeat Sensing System

2Hearts-Aura uses Polar™ brand heartbeat sensors that employ chest straps to detect the electrical activity of the heart. The sensors wirelessly transmit signal pulses to receiver units. Transmission range is limited to 1 meter, which we intend to increase through customization. We find the chest-strap sensors to be reliable, producing fewer false or missed beats than the finger-clip type. The chest-straps do require skin contact, so they are less appealing to many casual users in the demo setting. For committed players the sensor placement is good since it directs attention to the physical heartbeat, supporting the 2Hearts objective. An I-CubeX™ voltage-to-MIDI converter is used in place of the custom A/D converter. It is less fragile, and simplifies input to jMax.

Improvements in Heartbeat Feature Extraction

There are several advancements in the heartbeat feature extraction algorithms of 2Hearts-Aura. Instead of using a floating centerline to adapt to each player's natural heart rate range, Aura maintains a lifetime mean and variance for heart rate. This allows a player to experience a long stretch of raised heart rate and have it continue to register as high.

2Hearts-Aura also uses a different type of correlation measurement: instead of taking the difference in calibrated heart rates, it takes the difference in heart rate derivatives. This measure has the potential to be more interesting, since it expresses information that is not so obviously related to the two heart rates considered separately.

Interestingly, heart rate rises slightly with each inhalation, linking the heart rate signal to breathing. Time averaging filters out this effect, but in 2Hearts-Aura the instantaneous rate signal is also maintained, to let the breath cycle enter the shared feedback space.

Improvements in Heartbeat-Music Mappings

In the change from 2Hearts-Gravity to 2Hearts-Aura we wanted to keep the elements that worked well (direct mappings to tempo, pitch and timbre) while avoiding the feeling of being stuck in a repetitive loop. We abandoned the use of an established musical genre and removed the scripted melodies and chord progressions.

2Hearts-Aura uses two similar ethereal, pad-type voices, which play notes synchronized with the heartbeats of each player. There is no common tempo; rather, two parts that come in and out of phase depending on the phase difference in heartbeats.

For each voice, the pitch and timbre of notes are linked to the heart rate of a particular user. Pitch is not changed through chord inversion, but rather is free to wander through the notes of a major scale. Timbre ranges from a smooth, glassy sound to a harsh, fiery sound. Pitch is controlled by the average of the last three heart rates, while timbre is controlled by the instantaneous rate. Thus, pitch is more stable while timbre expresses the breath-related heart fluctuations. A variable reverb effect is applied that makes the voices blur together. It is increased when the difference-of-derivatives correlation signal increases.

When the heart-rate-derivative of a player crosses a threshold, the corresponding voice shifts up a semitone in pitch. This expresses a moment of temporary urgency, and also creates musical discord if the second player's heart rate does not also change rapidly.

Preliminary Evaluation

Our experiences with the system so far have been positive. The music seems to reflect heartbeat changes, and is aesthetically pleasing. The reverb effect works well, in the sense of being noticeable and frequently changing. The presence of the raw time-of-beat information in the music increases a player's feeling of connection with the system; the experience can be eerie at times as one hears one's heartbeat projected outside the body.

We have noticed a tradeoff in the move away from a stereotyped musical genre- removed from the context of a known musical language, the changes in pitch and timbre seem less strongly suggestive.

Future Work

In order to complete the 2Hearts-Aura prototype, we are developing additional voice-plus-mapping sound sets. The music will mix smoothly between different sound sets as controlled by an inertial metaphor similar to Musical Terrain. This will add musical variation which is controlled by the players' arousal signals, but is not specifically parameterized in terms of musical tension. We hope that this will create an interesting musical "inkblot effect": the shifting sound sets will add different moods to the players' interaction, and the players may in fact interpret each mood as suiting their interaction in a meaningful way.

Once we complete the sound design and find a satisfying combination of graphics/sensor technology, we will begin user testing of 2Hearts-Aura. We plan to record heart rate data along with video to obtain quantitative results about the system's interaction with heart rate.

CONCLUSION

We have presented the 2Hearts system, which uses music to express heartbeat information. We have described our experiences from the two versions developed so far. Summarizing, here are the principles we have developed in our work with 2Hearts:

1. Arousal indicated in the heartbeat signal can be effectively mapped to musical tension through the variables of tempo, timbre and pitch.
2. Higher-level musical structure, being difficult to analyze and less effective as output, can be treated in a more arbitrary manner. However, it should vary by some means, to avoid repetitiveness.
3. Expressing the raw time-of-beat information is important to create a connection between player and music.
4. Interesting variables can be derived from the relationship between the two heartbeat signals.
5. There are tradeoffs involved in employing a known musical genre: the structural requirements limit the choice of output variables but aid the interpretation of musical tension.

2Hearts is both an artwork and a communication augmentation system. Through this work we develop general techniques for transmitting affective data through music. Future technologies may follow the 2Hearts concept by leveraging the expressive power of music to enhance human communication.

ACKNOWLEDGMENTS

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