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, Bio-Sensor, Interactive Music, Non-Verbal Communication, Affective Analysis/Display

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

Sharing Heartbeats Through Music
We can think of the heartbeat as the body's own music: organized sound that changes in rhythmic structure to express emotional information. Yet it is most often an unheard music. We learn to ignore our heart rhythm in most circumstances, and after birth we rarely have contact with the heartbeat of another. When we do experience another person's heartbeat, it is in a situation of intimacy, a close embrace. To know the heartbeat of another is to absorb their rhythm, to move inside the sphere of their bodily experience.

2Hearts is an amplifier for this latent heart-music. The rhythmic, changing heart signals are sensed electronically and translated into musical sounds of vivid pitch and timbre, audible to everyone in the room. The music becomes a new channel for non-verbal communication- players can move around and engage in conversation while still having access to the musical heartbeat information. This is a central theme of our work with 2Hearts: music as a communication channel, enhancing the intimacy of social interaction. Figure 1 is an illustration of the 2Hearts concept.

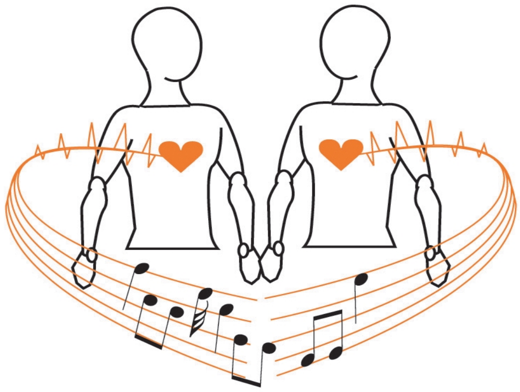

Figure 1. The 2Hearts Concept

The Human Becomes the Musical Interface
2Hearts can be contrasted with past bio-sensor musical controllers. For instance, David Rosenboom's piece Portable Gold and Philosophers' Stones utilized skin resistivity and temperature signals to control a sonic output [12]. Musical works have been performed with the BioMuse system, which allows heartbeat, brainwave, and other signals to control graphical and musical output [5]. The novelty of 2Hearts lies in its use of social relationships to moderate heart rate responses. Players of 2Hearts attempt to evoke responses in the other. In a sense, each player becomes a musical interface- players try to "play on each other's heartstrings".

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 [7]. As two or more users interact in an everyday setting, they can view the changing output and attempt to incorporate this information into their understanding of one another. Audible Distance, by Akitsugu Maebayshi, is an interactive VR piece in which multiple users wear heartbeat sensors and head-mounted displays [6]. 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 [9]. 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).

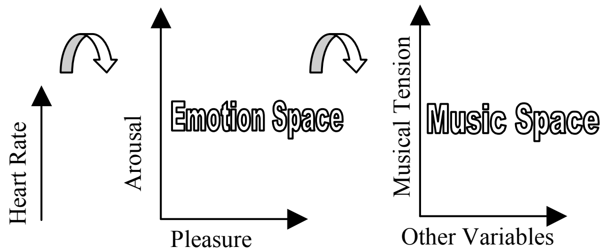

Figure 2. Mapping from Heart Rate to Tension

Studies have been done to determine the tension-producing quality of different musical variables [3],[8],[10],[11]. 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 NIME 1 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 infra-red conductance caused by each pulse of blood through the finger.

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 func-

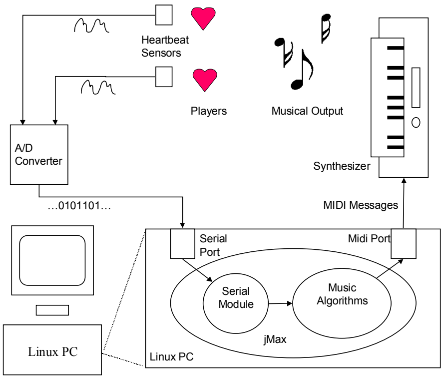

Figure 3. Components of 2Hearts-Gravity

-tions to generate a sequence of MIDI note and control messages. A Yamaha EX-5 synthesizer executes the MIDI commands.

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. The resultant value is scaled so that readings fall in the range [–64, +64]. Similar methods calculate the average heart rate of the two players, and the difference in rates.

Two Time Scales of Musical Variation

Developing the 2Hearts-Gravity system, we realized that another type of data could be extracted from the heartbeat 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 from the [–64, +64] range to the 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. The height dimension allows the composer to bias the ball's motion (see Figure 4).

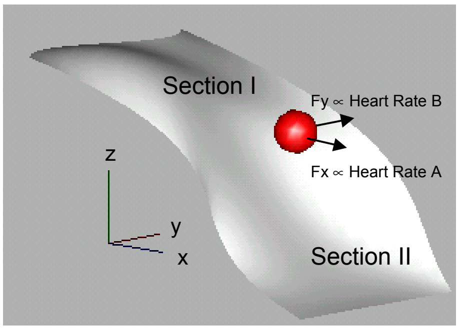

Figure 4. The Musical Terrain Metaphor

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 ball-pushing metaphor was thought to be especially suitable since a conversation can be thought of as a series of verbal pushes and responses. 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 verbally provoke each other by asking embarrassing questions, telling jokes, and so forth. The sessions were usually short (approx. 5 minutes), meaning that learned interpretation of the audio output was minimal.

Players appeared to understand easily the timbre/inversion changes of each track and their relationship with heart rate changes. The global tempo variation was also deemed successful. Particular success was noted when moments of sharp heart rate increase resulted in clear musical changes, which were also perceived by the crowd and found to be entertaining.

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. Many factors could explain this, including the nature of our instructions, the public nature of the demo (giving the feeling of being on display), and the fact that most pairs were strangers. Those players who were more experimental, interacting in a more non-verbal, 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. Variations in skin thickness had to be compensated by turning a variable resistor. Often when players moved around, the sensor contact was broken, triggering false heartbeat readings. This inhibition to free movement was another factor limiting the range and intimacy of player interaction.

We observed that the Musical Terrain functioned as designed, providing musically coherent changes of melody and dynamic. However, as a control metaphor it was difficult to conceptualize: the concepts of heartbeats, rolling balls, and music are difficult to link. 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 [8],[10].

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 proved too much of a conceptual leap for casual players to learn. 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 5 shows the 2Hearts-Aura prototype.

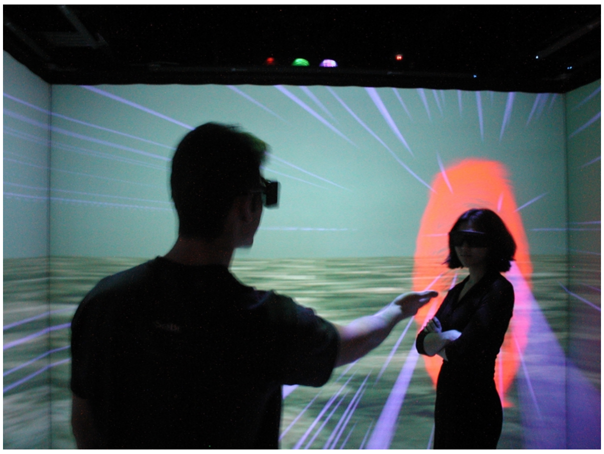

Figure 5. People interacting in 2Hearts-Aura.

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. The auras are controlled by most of the same heartbeat variables as the music, and the music is meant to suggest a harmonious sound effect caused by the auras themselves.

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. The results from the graphical side of 2Hearts-Aura will be discussed in detail in another paper.

Improved Heartbeat Sensing System

2Hearts-Aura uses Polar™ brand heartbeat sensors that strap around the chest, next to the skin, and detect the electrical activity of the heart. The sensors wirelessly transmit signal pulses (one pulse per heartbeat) to small receiver units. Transmission range is limited to 1 meter, but we intend to customize the hardware to increase this range.

We find the chest-strap sensors to be very reliable, exhibiting fewer false or missed beats than the finger-clip type. They fit snugly but comfortably, allowing natural movement. The chest-straps do require skin contact, so they are less appealing to many casual users in the demo setting. For committed players, (or 2Hearts owners in the future…) 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 expressed information that is not so obviously related to the two heart rates considered separately.

Interestingly, heart rate rises slightly with each inhalation and falls with each exhalation, so the heart rate signal is linked to breathing. Time averaging over subsequent heartbeats 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. The pitch and timbre mappings differ in that 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.

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.

A variable reverb effect is applied that makes the voices blur together. It is increased when the difference-of-derivatives correlation signal increases.

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 do feel there has been a certain 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. It will also be possible to disable the graphical component of Aura, while retrofitting the chest-strap sensors to Gravity, for a direct comparison of the music algorithms.

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.
6. Sensors in a heartbeat-to-music system should not inhibit the free movement of players.

2Hearts is a compelling artwork that resonates with people's ideas about music and relationships. 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

We thank the New Media Innovation Centre (Vancouver, Canada) for financial sponsorship of the 2Hearts project, and for the use of the CAVE facility.

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