BioFlockVR: Exploring Visual Entrainment through Amorphous Nature Phenomena in Bio-Responsive Multi-Immersant VR Interactives

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ABSTRACT
In this paper we present our bio-responsive virtual reality (VR) experience that explores visual forms of entrainment through amorphous nature-inspired phenomena that evolves and reacts to a tightly coupled real-virtual immersive space controlled through two immersants' physiological data. Multiple layers of real-time visuals inspired by nature phenomena are generated in 3D the experiential VR space which are controlled through two immersants' EEG, heart rate and gestures in real-time. In this paper, we present our system framework and setup and present our work-in-progress prototype.

CCS Concepts
• **Computing methodologies→Computer graphics→Graphics systems and interfaces→Virtual reality**

Keywords
Virtual Reality (VR); Biofeedback; Entrainment; Expressive-Arts Therapy; Meditative; Bio-Responsive VR; Neurofeedback; Heart Rate; Respiration; Multi-Immersant; Art Interactive; Amorphous Nature Phenomena.

1. INTRODUCTION AND MOTIVATION
The term virtual reality (VR) is rapidly becoming synonymous to TVs with the mass consumerization of VR, AR, MR and XR technologies. With this rapid growth into not only homes but also into the entertainment industry, content generation for VR and its related technologies is becoming paramount.

Currently, the projected revenue for the VR market in the US is estimated to be over $38 billion by 2026 and for the AR market, it is estimated to be $90 billion by 2020 [1].

Of the many application domains, health and wellness related applications is gaining a strong foothold in the industry. A quick search for meditative and wellness related applications on Google Play Store yields over 250 meditation apps. Coupled with commercially available physiological sensing devices (i.e. Apple Watch, FitBit, Spire, HeartMath's emWave), people are being tracked and monitored 24/7 while their every breath and movement are constantly being analyzed. Not only are users becoming much more hyper-aware of their health in relation to their physiological states, users are becoming much more reliant on the real-time feedback from these devices to track their health. At our research lab, one of the core areas of research focuses on the tightly coupled technological interplays between the human body (i.e. gestures, physiological data, facial expressions, speech) and various forms of digital entities (i.e. AI avatars, generative AI art, bio-responsive virtual environments). We have been researching and testing various immersive real-time environments created through computational systems that incorporate biological, cognitive as well as behavioral knowledge models.

In this paper, we present our current framework and installation setup for our multi-valent, multi-layered and multi-immersant bio-responsive VR system. Our current system is built and based on our previous framework we presented in 2017 [2][3]. Our lab has been critically examining the role of expressive arts therapies and biofeedback training in the context of building therapeutic and meditative environments in VR. In our tightly coupled real-virtual environments, the user's physiological data constantly evolves and reflects the immersant's bio-states into the immersive virtual spaces, extending the human body or the soma into the virtual space. The intersections between the immersants and the real-virtual experiential space has the potential for a variety of application spaces including stress reduction, emotional wellness, meditative and therapeutic applications as well as artistic interactives. The current system we present here is proposed as a VR art interactive. This paper is organized as follows. In Section 2, we present a brief background and related work on VR and biofeedback technologies and expressive arts therapy related concepts. In Section 3, we present our System Framework and installation setup. In Section 4, we present our current prototype implementation. Lastly, in Section 5, we conclude and present future work.

ICIGP 2019, February 23–25, 2019, Singapore, Singapore

ACM ISBN 978-1-4503-6092-0/19/02…$15.00
DOI: https://doi.org/10.1145/3313950.3313978

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2. BACKGROUND AND RELATED WORK

VR technology has been around for well over 80 years, with the first VR systems being developed as flight simulators in the early 1900s [4]. During the 1960s, Sutherland [5] pioneered graphics simulation and developed a head-mounted three-dimensional display. Since then, there has been a steady increase of VR applications in many application domains. During the 1990s, we started to see an increase in VR being used for art and therapeutic application spaces [6] with one of the first breath-controlled VR art installation piece Osmose [7] in 1996. Biofeedback-controlled meditative video games also started to appear on the market in the early 2000. Journey to the Wild Divine (now Unyte) had users' GSR (galvanic skin response) control the gameplay in real-time. It wasn't until the last 7 years that we have witnessed VR/AR/MR explode into the mass market with affordable consumer-grade head-mounted displays. Integrating bio-affective tracking for affective loop systems to study users' emotions and bio-states is a has been a growing area of research [8][9].

Our lab's multi-disciplinary research draws broadly from the disciplines of expressive arts therapies (i.e. art, music and dance/movement therapies) as well as biofeedback research for designing VR interactives for therapeutic applications including stress relief, meditative and well-being. In this section, we briefly look at the above-mentioned disciplines.

2.1 Expressive-Arts Therapy

Expressive-arts therapy is defined as the therapeutic use of art, music, dance and movement, drama, poetry and writing. The four disciplines of therapy recognized in the UK are: Art Therapy, Music Therapy, Drama Therapy and Dance Movement Therapy [10]. Expressive-arts therapy has been linked to world healing practice traditions and cultural precedents where indigenous healers or shamans might sing, dance, make images, or tell stories in their healing rituals [11]. In these type of healing practices, it is important to recognize the paradigm shift of thinking of 'arts as therapy' to 'arts for health' and to put emphasis on the actual creative process of healing [12].

2.1.1 Art Therapy

Art therapy is built upon the premise that it is the most accessible form of communication for human experience using visual symbols and images [13]. There are many schools of art therapy. Of interest for our work is the school of depth-psychology oriented art therapy. Depth Psychology explores "the hidden or deeper parts of human experience by seeing things in depth rather than taking them apart [14]". Depth psychology involves a deep inquiry into the symbolic meaning of things—of symptoms, images, and emotions—that arise in one's life and influences the individuals with or without their awareness [14][15]. A depth approach may include therapeutic traditions that explore the unconscious and involves the study and exploration of dreams, complexes, and archetypes. One of the founders of modern depth psychology is Carl Gustav Jung, along with Alfred Adler and Sigmund Freud [15]. C. G. Jung developed Analytic Psychology and was pivotal in bringing forth concepts of the Self and dynamic individuation [16].

2.1.2 Music Therapy and Entrainment

The World Federation of Music Therapy (WFMT) [17] defines music therapy as "the use of music and/or musical elements (sound, rhythm, melody and harmony) by a qualified music therapist in a process designed to facilitate and promote communication, relationships, learning, mobilization, expression, organization, and other relevant therapeutic objectives, in order to meet physical, emotional, mental, social and cognitive needs." In the field of music therapy and ethnomusicology, many researchers and practitioners are researching the concept and application of rhythmic entrainment or entrainment to the therapeutic space [18][19][20]. Entrainment is a universal phenomenon where two or more independent rhythmic processes synchronize and "lock" into a common phase and/or periocity [20]. It was first identified in 1665 by a Dutch physicist Christian Huygens with the invention of his pendulum clock. In 1729, French physicist de Mairan first identified and studied photic entrainment (synchronization to the cycle of light and dark) in plants [21] moving from away from physics and mathematics to biological entrainment. Rhythmic entrainment has been established as a function for rehabilitative training and learning from the early 1990s by Thaut et al. [19]. Kret [18] describes rhythmic entrainment in music therapy as "a specialized practice used to assist in helping people become more 'in tune' to their own rhythm and the rhythms of the world around them."

2.2 Biofeedback

Biofeedback is the field of research where electronic recording equipment is used to obtain immediate and continuous information on physiological responses such as heart rate, skin response and temperature or blood pressure [22][23][24]. It has been recognized as a "therapy" and "intervention" from the late 1960s for physiological, emotional, social and self-regulation to improve one's health and physical performance [22][24]. Biofeedback training has positive non-invasive outcomes managing physical and mental health issues in patients including anxiety or stress, headaches, hypertension and ADHD and more [see 25].

Different types of biofeedback measures include: brainwave frequencies through sensors place on the forehead/scalp using EEG (electroencephalogram), electrical activity of the heart (heart rate, heart rate variability) measured through EKG/ECG (electrocardiograms) skin electrodes and blood volume pulse (BVP) measured through PPG (photoplethysmograph) light sensors; respiration which measures breathing rate and amplitude through abdomen bands; electrical activation of the muscles measured through EMG (electromyography); activity of sweat glands and changes in perspiration of the skin measure through sensors on the finger, inner palms or the wrist through EDG (electrodermograph); and changes in skin temperature measured through sensors that detect blood flow to the skin (i.e. forehead, fingers, wrist, feet, armpit) [24]. There are many biofeedback devices for research as well as for consumer use today on the market. Of the main ones for research are: Thought Technology Ltd., Muse EEG, Empatica, Heart Math, NeXus and BioPAC Systems Inc.

2.2.1 Heart Rate and Respiration

For biofeedback training, it is preferable to use PPG light sensors to measure cardiovascular activity as it is easier to administer than ECG. PPG measures the blood that passes through the tissues in a localized area with each beat or pulse of the heart. With this BVP data, heart rate can be derived by measuring the distance between the peaks of the waveform called the inter-beat interval (IBI). With the IBI data, the heart rate variability (HRV), which is the measurement of how much variation there is between each beat given a timeframe, can also be derived. Having a high HRV (i.e. the distance between each beat is varies a lot given a timeframe) and a low HR is optimal sign of good health [26].

There exists a strong correlation between breathing cycles and HRV called the Respiratory Sinus Arrhythmia (RSA). RSA is the HRV in synchrony with respiration where during inhalation, the heart rate increases and during exhalation, the heart rate decreases. [27]. Sleep studies across three universities have shown that breathing rate affects the heart rate but not the other way around during deep sleep [28].

2.2.2 Neurofeedback
Neurofeedback is a type of biofeedback training for a multitude of conditions (i.e. depression, anxiety, posttraumatic stress disorder (PTSD), personality disorders, addictions, and unresolved emotional issues) that uses brainwave activity [29]. It has been well established as a therapeutic modality since the 1960s. The 5 common brainwave frequency bandwidths are: Delta, Theta, Alpha, Beta and Gamma. See Table 1. for the classification.

Table 1. Common brainwave frequency bandwidths [29]

Bandwidth Name	Frequency Range (Hz)	Description / Characteristics
Delta	1-4	Sleep, repair, complex problem solving
Theta	4-8	Creativity, insight, deep states
Alpha	8-12	Alertness, peacefulness, readiness, meditation
Beta^	13-21	Thinking, focusing, sustained attention
SMR*	12-15	Mental alertness, physical relaxation
High beta	20-32	Intensity, hyper alertness, anxiety
Gamma	38-42	Cognitive processing, learning

^ Beta is further classified as Low/SMR (12-15), Mid (15-18) and High
* SMR: Sensorimotor Rhythm
Note: Table has been modified by the author

Studies on neural oscillations during 4 different types of meditations (1. focused attention (FA); 2. open-monitoring (OM); 3. transcendental meditation (TM), and 4. loving-kindness (LK) meditation) on meditators and meditation-naïve adults showed increased oscillatory activity in the meditators in different regions and bandwidths [30].

3. SYSTEM FRAMEWORK AND SETUP
Our VR system can be broadly categorized into 3 components: 1) Immersants' Physiological Data and Real-time Sensor Devices; 2) Amorphous 3D Forms and Environment; and 3) Bio-responsive Experiential Space. These components are described in detail below.

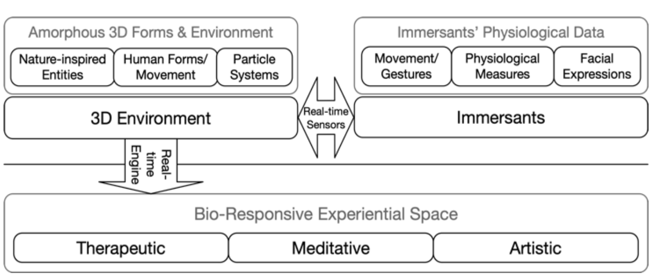

Figure 1. System framework.

3.1 Immersants' Physiological Data and Real-time Sensors
We examine a variety of immersants' physiological data including immersants' movements/gestures, physiological measures as well as facial expressions. For this work, the immersants' physiological data is obtained through two devices, the Empatca E4 and the Muse 2016. The Empatica E4 (Fig. 2. left) is a medical grade wearable biosensing wristband capable of reading blood volume pulse (BVP), galvanic skin response (GSR or EDA), peripheral skin temperature and 3-axis acceleration data. The raw data is sent over BLE (bluetooth low energy) to the Empatica BLE Server that then processes the data to be streamed over to Unity3D. Currently, we are using BVP and 3-axis acceleration data for our VR system. The Muse 2016 is a 4-channel EEG headband (Fig. 2 right). It has 7 sensors – 2 forehead sensors (AF7 and AF8), 3 reference sensors and 2 behind the ears (TP9 and TP10) – that detect brainwave activity of the following bandwidths: delta, theta, alpha, beta and gamma. Muse has multiple ways to connect to devices and computers for real-time data processing. Currently, we are streaming the brainwave data into Unity3D through the MuseMonitor and the MuseLab. Unity3D is a real-time game engine.

Figure 2. Empatica E4 wristband and muse EEG headband.

3.2 Amorphous 3D Forms and Environment
Our lab's (iVizLab.sfu.ca) main research domain is in generative AI art systems and real-time behavioral systems for empathetic AI avatars. We have been experimenting with different real-time 3D particle systems to visualize the generative art into the experiential spaces controlled through the user's physiological input such as gestures, biofeedback, facial expressions and voice.

In designing the 3D environments for our system, we have taken inspiration from nature phenomena and structures to visualize and extend the internal bio-states of the immersants into the virtual environment. Our goal is to create amorphous experiential spaces that can organically move and continuously respond and react to the immersants' physiological states. Our 3D environment consists of a larger than life Voronoi web cell structure that provides the breathing cues and a real-time particle-based flock of bird system to visualize the heart rate. The Voronoi cell structures was based on Voronoi diagrams that can be observed on a giraffe's skin and a dragonfly's wings (Fig. 3, left, middle). The flock of birds were inspired by the beautiful patterns created by Starlings (Fig. 3, right).

Figure 3. Voronoi structures on a giraffee (left), dragaon fly wings (middle) and starlings flocking behavior (right). (*images from pixabay*).

3.3 Bio-responsive Experiential Space
Using the physiological data from one's own body as an extension into the experiential space can create meaningful embodied experiences. However, if at any time during the experience there is a disconnect in the mapping of the biosensor data to the visuals, it will leave the immersant disconnected and break the immersive

experience. It is imperative to ensure proper mapping and scaling of biosensor data to the virtual as well as real space. Our project is being developed in four phases. In Phase 1 of our project, we have implemented a scalable mapping system in Unity3D where we are able to map multiple biodata sets to multiple parameters affecting the visuals. In Phase 2, all channels of Empatica E4' and Muse's data sets are being integrated into the system. In Phase 3, we will be testing the full system with the proposed installation set up (Fig. 5) described below. In Phase 4, we will be moving our system to a public art installation Our VR interactive system is designed to be fully experienced with head-mounted display. Currently, it is running on the Oculus CV1 head-mounted display (Fig. 4).

Figure 4. Oculus CV1 head-mounted display (HMD).

3.3.1 Proposed Installation Setup

Figure 5. is the proposed installation setup for our VR system. The EEG data from Immersant 1 (right) is streamed into Unity3D, where it is mapped to the breath cues for Immersant 2. Immersant 2's blood volume pulse (BVP) and acceleration (ACC) data then streamed back into Unity3D where heart rate (HR) and gestures are interpreted and mapped to the bird flock simulation's multiple parameters. The combined visuals created through the flock simulation and the Voronoi cell structures create a complete yet constantly evolving virtual experiential space for Immersant 2.

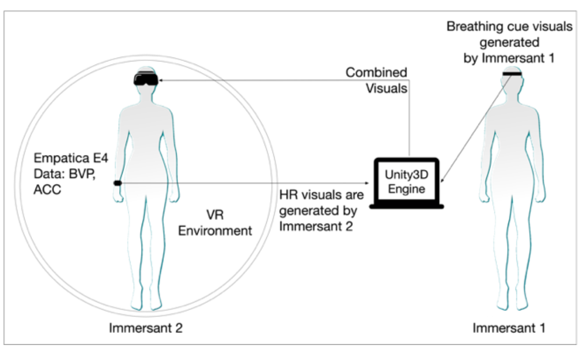

Figure 5. Immersant 1 (right) and immersant 2 (left).

4. PROTOTYPE IMPLEMENTATION

We are well underway for the prototype implementation and Phase 1 and 2 of the project is almost complete. The Voronoi cell structures have been created using Grasshopper3D. Grasshopper3D is a visual programming language and environment that runs inside Rhino3D CAD application. It uses scripts and to generate parameterized 3D objects. The flocking particle system was created using PopcornFX. PopcornFX is a 3D real-time particle system that allows for finer customization of parameters that can be accessed in the Unity3D engine. In Phase 1 and 2 of the development, our prototype integrates all streaming data from the Empatica E4 wristband and the Muse headband. Empatica E4's data consists of multiple channels – 3-axis acceleration and BVP. The acceleration data is interpreted as hand gestures and further drives the spread of the flock. As the user raises or lowers their hands the flock behavior begins to separate or converge into the attractor volume. The flock simulation's speed, color as well as size is also driven by the data collected through the Empatica E4 wristband (Fig. 6). We are currently testing the different EEG data sets (bandwidths) from the Muse headband and mapping them onto the Voronoi structure's open/close states (Fig. 7).

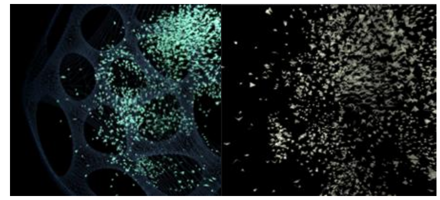

Figure 6. Parameterized flock simulation controlled through Immersant 2's heart rate and gestures.

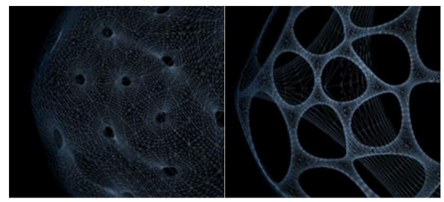

Figure 7. Voronoi cell structure for breathing cues.

Figure 8. shows the setup of two immersants with the biosensing devices and the Oculus CV1 HMD. Immersant 1's (left) EEG neurofeedback data is mapped to the environmental Voronoi cell structures providing breathing cues for Immersant 2 (right). As Immersant 2 begins to regulate his/her breathing patterns to the breathing cues, Immersant 2's heart rate generates the constantly evolving aesthetics of the flock of birds simulation inside the Voronoi cell structure displayed through the Oculus CV1 HMD for Immersant 2.

Figure 8. Immersant 1 (left) with Muse EEG headband. Immersant 2 (right) with Oculus CV1 HMD and Empatica E4 wristband

5. CONCLUSIONS AND FUTURE WORK

In this paper, we present our work-in-progress prototype of BioFlockVR, a multi-immersant VR art interactive to explore the notion of visual entrainment through amorphous nature phenomena coupled with two immersants' real-time biofeedback data. Biofeedback research has shown positive results on neurofeedback and breathing on heart rate and heart rate variability. Moreover, most VR biofeedback systems are designed to process one immersant's biofeedback data to create an affective-loop for therapeutic, training and visualisation purposes. Our system proposes to extend the experiential bio-responsive VR space to integrate two immersants' biofeedback data. This starts to create interesting paradigms of how different immersants' biofeedback can be used in the domain of wellness and therapeutic purposes. One such scenario could involve a therapeutic or meditative guide as Immersant 1 and their client as Immersant 2 where Immersant 1's deliberate and controlled biofeedback visualisations can be used for Immersant 2's biofeedback training. Over the next couple of months, we will be exploring a full art installation of a multi-immersant scenario where the biofeedback of one immersant alters the visual representation of the second immersant in virtual space.

6. ACKNOWLEDGMENTS
We would like to thank Simon Fraser University's Michael Stevenson Graduate Award for funding the equipment in this research as well as SSHRC. We would also like to thank PopcornFX for their continued support.

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