CardboardHRV: Bridging Virtual Reality and Biofeedback with a Cost-Effective Heart Rate Variability System

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ABSTRACT

We introduce CardboardHRV, an affordable and effective heart rate variability (HRV) biofeedback system leveraging Cardboard VR. Designed for easy access to HRV biofeedback without sacrificing therapeutic value, we adapted the Google Cardboard VR headset with an optical fiber modification. This enables the camera of the inserted phone to capture the photoplethysmography (PPG) signal from the user's lateral forehead, enabling CardboardHRV to accurately calculate the heart rate variability as a basis for biofeedback. Furthermore, we've integrated an engaging biofeedback game to assist users throughout their sessions, enhancing user engagement and the overall experience. In a preliminary user evaluation, CardboardHRV demonstrated comparable therapeutic outcomes to traditional HRV biofeedback systems that require an additional electrocardiogram (ECG) device, proving itself as a more cost-effective and immersive alternative.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Interaction devices**; **Ubiquitous and mobile devices**.

KEYWORDS

Human Computer Interaction, Heart Rate Variability Biofeedback, Virtual Reality, Photoplethysmography(PPG)

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1 INTRODUCTION

Heart rate variability (HRV) biofeedback has been proven effective in enhancing overall body performance [10] [9]. This effectiveness is attributed to balancing the sympathetic and parasympathetic systems [15], often facilitated by controlled breathing. During this process, individuals breathe at a specific frequency, commonly called the 'resonant frequency' [6]. It synchronizes heart rate and breathing, creating coherence: inhalation leads to an increase in heart rate. At the same time, exhalation causes it to decrease, ideally forming a sine wave pattern in heart rate.

Extensive research has demonstrated HRV biofeedback's effectiveness in several areas. Notably, numerous studies have highlighted its therapeutic effects on stress, anxiety, and PTSD, among others [5]. For example, Silva et al. provided evidence suggesting HRV biofeedback's potential in alleviating depressive symptoms [14]. There is also research about the effect of HRV biofeedback on sports performance. Mauro et al. [13] indicated that using HRV biofeedback during recovery after running improves cardiac variability and lowers recovery time. Their research also shows that the benefits are not only for athletes but also for the general population. These studies demonstrate the effectiveness of HRV biofeedback in treating a spectrum of conditions, encompassing mental illnesses such as anxiety, depression, and PTSD, as well as physical ailments.

The feedback mechanism is a crucial component of HRV biofeedback. Commonly, this includes a user interface with a sliding bar or animations reflecting breathing frequency. Some systems incorporate gamified feedback, which, while increasing costs, can significantly enhance user experience and engagement, especially during lengthy biofeedback sessions. Lots of research also demonstrates the effectiveness of gamified feedback. Thomas et al. [19] demonstrated the effect of gamified HRV biofeedback using an Android Flight game, proving that the gamified experience leads to more engagement in the biofeedback session. Shih et al. [17] designed a biofeedback game that proved that the game could potentially be utilized in clinical and self-care activities. Spillers et al. [18] also researched how to implement gamified elements in biofeedback sessions correctly.

In recent years, using virtual reality (VR) as a biofeedback device has also proved to provide a better user experience. Luddecke et al. [12] mentioned that VR biofeedback has advantages regarding involvement and attention focus. Kothgassner et al. [8] also demonstrated that VR biofeedback is beneficial for treating anxiety. The research also emphasizes that patients can benefit from VR combined with gamification and biofeedback. VR based biofeedback can also enhance therapeutic effect. According to Cuneo et al. [3], the use of VR in biofeedback decrease the depression in patients with chronic migraine. Overall, while the integration of VR with biofeedback does not ensure enhanced therapeutic outcomes across all treatments, it notably enhances user experience and fosters heightened user engagement.

Rockstroh et al. [16] highlighted that while both VR HRV biofeedback and traditional HRV biofeedback are equally effective in enhancing short-term HRV, VR HRV biofeedback demonstrates superior motivational benefits and aids users in maintaining attentional focus more effectively. Therefore, incorporating VR is crucial for optimizing HRV biofeedback experiences.

However, HRV biofeedback technology, especially VR biofeedback, is not easily accessible. Most devices are designed for professional use, require medical supervision, and are complicated to operate. While commercial HRV biofeedback devices like HeartMath[7], MUSE Handband [2], Apollo Neuro [1], and Elite HRV [4] exist, they are costly, ranging between 100 to 300 USD, and require additional hardware. A VR headset like Oculus Quest or Pico usually costs around 500 USD. Consequently, a low-cost HRV biofeedback device could broaden access, particularly for those with limited medical resources or low income.

CardboardHRV distinguishes itself with its immersive VR environment, offering a unique, user-focused biofeedback experience. Using cardboard VR and fiber head mount, we can acquire accurate heartbeat signals and calculate HRV. The immersive environment provides interactive visualizations and auditory cues corresponding to physiological changes, making biofeedback more accessible and engaging. Our fabrication design enables users to enjoy gamified VR biofeedback at a lower cost, thereby making the experience accessible to more people.

Our comparative study indicates that CardboardHRV matches the therapeutic efficacy of higher-priced HRV biofeedback systems, such as biofeedback rings and finger clips. This underscores its potential as an affordable and effective tool for self-treatment and early heart health interventions.

2 SYSTEM DESIGN AND FABRICATION

The objective of this study is to develop an economical VR HRV biofeedback system. This system aims to deliver immersive experiences comparable in quality to those offered by high-cost HRV biofeedback devices yet at a significantly reduced expense. To achieve this, the study will explore the potential of integrating mobile phone functionalities to minimize the need for additional sensors. By harnessing the capabilities of Google Cardboard VR, the proposed system aspires to be both cost-effective and widely accessible, thereby democratizing the availability of advanced HRV biofeedback technology.

2.1 System Description

Our software will be an Android application that is converted into cardboard VR format. In our development process, we used a SAMSUNG Galaxy S10 smartphone as our Android device. Since it is hard to implement complicated signal processing techniques in C Sharp, we use a MacBook Pro with an M1 chip as our signal processing device. The data will be transmitted to the laptop for calculation in Python, which has more signal processing tools. To maximize the sensors and functions of the phone, optical fibers are used to conduct the light signal. The camera system, including the back camera and flashlight of the mobile device, works together with the optical fiber and head mount we designed, serving as a photoplethysmography (PPG) sensor of our system. The system will be further described in the fabrication part.

2.2 System Design

As we aimed to create an affordable device accessible to a broad user base, it is crucial to leverage the computing power and sensor systems available in mobile devices. Accurate heart rate signals are essential for computing HRV values and providing breathing feedback in HRV biofeedback. For mobile devices, heart rate measurement typically involves using the back camera and a flashlight. Users place their fingers over the back camera while the flashlight provides external illumination for photoplethysmography (PPG) measurements. The average value from a specific color channel (red or green) is calculated for every frame, transforming the video stream into a one-dimensional data stream, which we refer to as the raw PPG signal. Recent research has explored the potential of remote PPG (rPPG) [11]. However, rPPG demands significant computational resources from a mobile phone, which can lead to overheating and may not be as accurate as traditional PPG for HRV calculations. Therefore, contact PPG remains our preferred method.

In our setup, the mobile phone is placed in a cardboard box in front of the user, laid horizontally. This positioning makes it impossible for the user's skin to reach the back camera without structural modifications. The primary goal of these modifications is to transmit light so that it is equivalent to the skin touching the camera. In this context, using optical fibers is the most effective method for transmitting data.

To achieve this, we designed an optical fiber mount in front of the cardboard VR. The fiber mount is at the exact position of the phone's back camera. So when the phone is inserted into the cardboard, the fiber is attached to the back camera. The other end of the fiber is attached to the skin, making it possible to read PPG signals from the fiber. Another fiber is also connected to the flashlight of the phone, providing extra light to the measurement process.

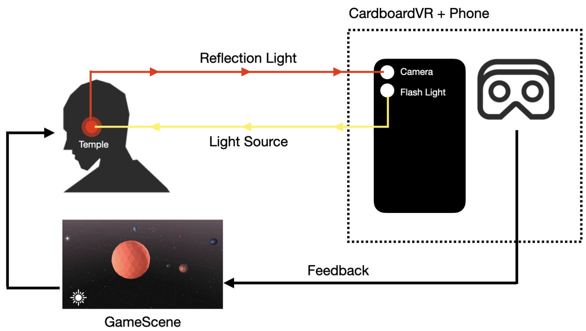

Figure 1: System Design. Using fiber as the light transmission medium

3 GAME DESIGN

Our goal is to provide a gamified experience during biofeedback sessions. This approach aims to enhance user engagement with the biofeedback task, making the sessions more enjoyable and interactive. The gamified experience offers users directive and interactive virtual feedback.

We designed a scenario based on space travel. Users will experience an immersive space scene, complete with stars and planets. The game's background will feature a sky filled with shining stars and interactive planets. The primary game elements are two planets: one representing the resonant frequency and the other symbolizing the user. The planet linked to the resonant frequency will orbit at a rate matching this frequency.

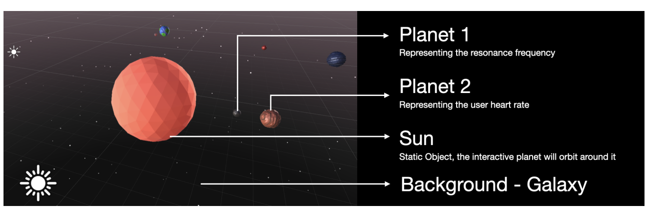

Figure 2: Game Scene Design. The primary game elements are two planets: one representing the resonant frequency and the other symbolizing the user. The planet linked to the resonant frequency will orbit at a rate matching this frequency.

Data will be transmitted to a PC via WiFi, with heart rate calculations performed every 0.5 seconds. A real-time peak-finding algorithm will identify the highest heart rate values. The time intervals between these peak heart rates will then be calculated and transmitted to the user's phone, influencing the orbital speed of the user-representing planet.

If the user achieves 'heart rate coherence'(which means the heart rate coherence with the breathing) by breathing in sync with the resonant frequency, the two planets will orbit around the sun at the same speed. If not, their orbital speeds will differ, signaling the user to adjust their breathing pace. This mechanism aims to guide the user in achieving breathing patterns that resonate with the target frequency.

4 EVALUATION

The main evaluation was divided into 2 parts. The first part would be evaluating how our fabrication and design can capture accurate heartbeat signals compared to using ECG. The second part would evaluate how our system can effectively improve the HRV performance of the participants and how well the therapeutic effect is compared to other products or equipment.

We recruited 6 participants among college students, ages 20-30($M = 24.33, SD = 2.3825$). Each participant was informed about the procedure of our study and possible actions they needed to take. After the evaluation process, each participant was rewarded with a gift card or cash deposit.

The evaluation process took place in a serene, comfortable laboratory environment where participants can relax on a plush seat. An instructor was presented to offer necessary support, including providing evaluation instructions, assisting with device setup, and addressing any software issues.

Figure 3: Evaluation setup. Participants were guided to sit in a comfortable laboratory environment with CardboardHRV or Polar H9 wear on.

4.1 Signal Accuracy Evaluation

We compared our signal with the Electrocardiogram(ECG) benchmark signal, which is considered the most accurate way of measuring heartbeat signal, heart rate, and heart rate variability. As for the ECG signal, since we had limited resources for medical ECG devices, our ECG will use the currently most popular home ECG product, Polar strap H9. It has already been proven to have significant medical effects regarding heart health, and the ECG measurement is also in the acceptable accuracy range. Thus, it is meaningful to use these devices as benchmarks.

In our endeavor to ensure that our system can precisely detect a broad spectrum of heart rates, selected participants were requested to engage in mild physical activity prior to the testing session. This exercise was designed to elevate their heart rate so we could receive heart rate samples from different ranges. Following this, participants were situated in a tranquil environment conducive to relaxation, with arrangements allowing them to comfortably rest their arms. Subsequently, they were instructed to wear both the CardboardHRV device and a benchmark Electrocardiogram

(ECG) device concurrently. The duration of each testing session was set at 30 seconds, aligning with the standard length for HRV measurements. Data from the CardboardHRV will be transmitted in real-time via WiFi and captured locally in a CSV format for analysis.

4.2 HRV Therapeutic Effect Evaluation

We also demonstrated the therapeutic effect of CardboardHRV compared to other HRV biofeedback equipment. Most commonly used at-home HRV biofeedback devices cost around 100-200 USD; some reached 300 USD, which consist of an ECG device and some biofeedback guidance. There are some well-known products in the market, including HeartMath, MUSE Handband, Apollo Neuro, and Elite HRV. Based on our resources, we will use Elite HRV combined with Polar H9 to make a comparison.

Participants were divided into 3 groups. The first group were using CardboardHRV, and the second one were using Polar H9 and Elite HRV for comparison. And since we had limited time, we tried to evaluate the short-term effect of our system. For every evaluation session, participants were asked to fill out a questionnaire about their body performance. Participants were asked to measure their 1-minute HRV before starting the test. After the measurements, participants were guided to do a 10-minute HRV biofeedback, during the session we measured their HRV at the same time. After the session, they re-did the questionnaire once again. We also asked the participants to fill out a short survey about the experience of the system. The questionnaire about subjective body performance and subjective user experience is also listed in the appendix.

For complete comparison purposes, we also evaluated the therapeutic effect when we combined Polar H9 and cardboard VR. That is, we still used cardboardHRV for the feedback device, but the heart rate data source was provided by Polar H9 rather than our own fabrication and algorithm. As a result, we will have 3 groups of evaluation in total.

5 RESULTS

5.1 HRV Estimation accuracy

The 30-second Heart Rate Estimation shows the accuracy of our system compared to ECG. The heartbeat data of each of the participants were recorded and stored in a local device.

We chose one of our participants as an example and plotted the overlap of heartbeat data. The orange lines represent the benchmark using Polar H9 ECG, and the blue one represents the measurement.

Since the heartbeat data is acquired using different methods, we need to normalize and re-scale the data for better visualization purposes. As the figure shows, the 2 data align well with each other, demonstrating the effectiveness of the fabrication design and the system design.

For HRV analysis, the most important thing is to measure the RR intervals of the signal. The result of the RR intervals can be seen from the figure. The test data aligns well with the benchmark data, further demonstrating the system's ability to detect various heart rate variability.

We calculated the MAPE of the RR intervals compared to the benchmark, which is 4.27. The low MAPE of the data indicates that the HRV measurement is accurate enough for HRV biofeedback visualization.

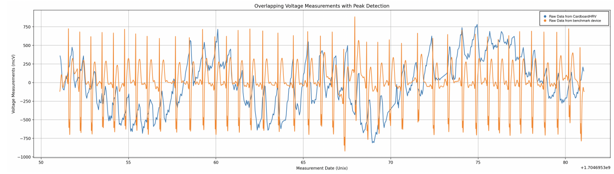

Figure 4: Raw heartbeat signal from participant 1. Signals are re-scaled for visualization purposes

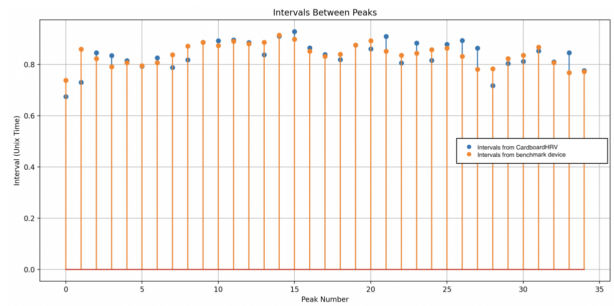

Figure 5: Beat-to-beat Intervals from Raw Signal and Benchmark Signal measured from Participant 2. The overall MAPE of the Interval data is 4.27.

5.2 Effectiveness on improving HRV

Compared to other commercially available products, our system shows similar therapeutic effects. Compared with commercially available products(Polar H9), all of the participants showed HRV gain during the training session. And it also demonstrated that using Polar H9 and cardboard VR did not bring a significant difference in improving HRV, indicating our system is cost-effective. The average percentage gain is shown in the table below. However, due to the limited number of participants and the bias between the participants, it is still not statistically significant that our system has better therapeutic effects than the commercially available product. But it at least indicates that the biofeedback mechanism works and provides a certain level of therapeutic benefits.

Gain / Metric / Device	RMMSD	SDNN	pNN50
Mean(Polar H9)	69%	36%	156%
Mean(CardboardHRV)	88%	59%	195%
Mean(H9+Cardboard VR)	81%	75%	230%

5.3 Evaluation on user experience and subjective feedback

For the subjective feedback, most users showed an improvement throughout the experiment. Since it was a short-term experiment, users could't improve their overall performance in a short period. However, most users agreed that they experienced a relaxing biofeedback session and they felt more relaxed after the session.

The evaluation also shows our system performs well in terms of immersiveness, and experience. Participants highly recommended

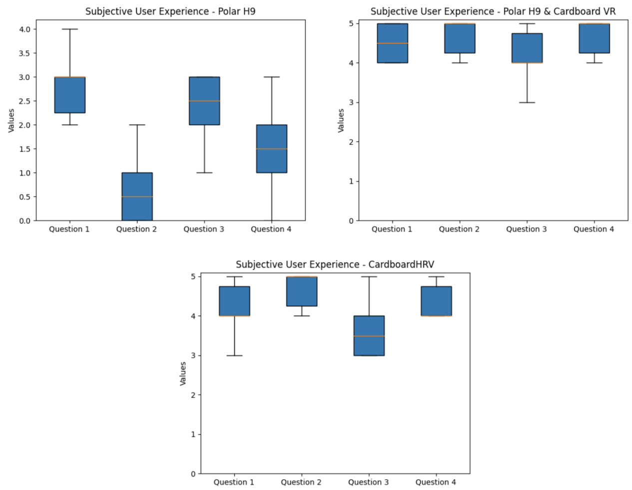

Figure 6: Subjective User Experience Feedback result. The questions in the graph are - Question 1: The experience you get with the products, Question 2: Can the product provide sense of immersiveness? Question 3: Can you focus on breathing adjustment? Question 4: Can you stick to the habit easily?

the immersive virtual environment and said it was a much better experience compared to the commercial product they used. The median of the total evaluation score of CardboardHRV was $16.5(IQR = 1.75)$. And the median of the total evaluation score of Polar H9 was $7.0(IQR = 2.25)$. They were also statistically significant according to a Friedman test ($\chi 2(1, N = 6) = 6, p = .01431$). Specific statistical results also indicate that CardboardHRV better helps with habit forming, providing immersiveness and helping users focus on the task. Participants also talked about the discomfort of using a chest band, saying that it is inconvenient to use in public environments. It's also freezing when used in winter since the material of the chest band needs to be directly in contact with the skin, and the user even needs to apply some water to moisture the electrodes. This further demonstrates the discomfort of the current wearable system and the advantage of our device.

6 APPLICATIONS

6.1 The significance of low-cost medical solutions - equality, inclusive.

Despite the application on HRV biofeedback, CardboardHRV also has lots of potential applications. We demonstrate the phone camera lens and optical fiber can be used for HR and HRV measurement and can acquire good signal quality. This can be a low-cost solution for medical devices if there are limited resources. Future development can focus on designing a more stable mount so it can dramatically reduce motion artifacts.

6.2 Possibility on Mobile Cardboard Game

The Mobile cardboard VR game represents an affordable, user-friendly solution in the realm of virtual reality. CardboardHRV is envisioned as a versatile toolkit that can expand the potential of mobile VR gaming. By integrating the CardboardHRV system, mobile VR/AR games will be equipped to capture heart rate signals. These signals can be utilized for various interactive elements within the games, elevating the gaming experience to a new level.

This integration not only lowers the cost of heart signal acquisition but also introduces a unique dimension of dynamic experience. Games can adjust their difficulty, narrative, or visual elements in real-time according to the change in heart rate, creating a more engaging user experience. Furthermore, the use of heart rate or HRV data can open avenues for more health-focused applications despite gamified biofeedback. This brings great potential in aiding various health problems or fitness training. In essence, CardboardHRV could bridge the gap between entertainment and wellness, transforming how we interact with mobile VR/AR gaming.

7 DISCUSSION

Our research demonstrates the potential for developing a low-cost and widely accessible HRV biofeedback device. Within our laboratory environment, we have successfully reduced the building cost of the CardboardHRV system by utilizing various tools, such as laser cutters and 3D printers. This has significantly facilitated the construction of our system components, including the cardboard VR and fiber mount. However, we still believe the system is cost-effective despite the tools we use. With the prospect of mass production, cardboard cutting becomes more efficient, with the cardboard VR costing only approximately 5 USD on platforms like Amazon. Additionally, while we utilized 3D printing for the fiber mount, its simple structure allows for easy replacement with materials like plastic or wood, maintaining cost-effectiveness at scale.

The associated skills for assembling CardboardHRV are also pivotal in promoting accessibility and inclusivity. Currently, CardboardHRV requires a brief adjustment period for proper fitting, as the fibers need to align with the phone's camera. In response, we have conducted experiments involving suction cups to enhance stability, thereby ensuring a secure alignment with a diverse range of phone cameras.

There are also limitations to this work. Due to the limited access to medical devices, we did not involve medical HRV biofeedback Device in our user evaluation process. Thus, we are not able to say that our system has a therapeutic effect compared with medical devices. The sample size of the user evaluation is also not large enough to have statistical significance, since there are biases among the users. The majority of recruited participants fall within the 20-30 age range, thus not representing all age demographics. We remain uncertain about the system's performance in older individuals, whose skin conditions may differ significantly.

There are also some problems with the experiment design due to time limitations - we only compared CardboardHRV and Polar H9. However, we need to further demonstrate the necessity to use cardboard VR instead of other VR products like Oculus Quest. Only in this way can we prove that our device has a comparable therapeutic effect to a commercial VR-HRV device even if the device is cost-effective, and the use of an additional VR device will be redundant.

8 CONCLUSION

This work demonstrates the possibility of using low-cost cardboard VR to implement HRV biofeedback. It turns out that using optical fiber and Cardboard can read accurate heartbeat data for HRV calculations. And the use of Cardboard HRV also brings immersiveness to HRV biofeedback. Among our participants in the research, most showed a positive increase in short-term HRV values, indicating that the system can have a therapeutic effect.

It also opens the possibility of using optical fiber for signal transmission in low-cost devices. The system gives us the possibility of using cheap optical fiber to acquire skin signals. Based on this design, we can produce lots of applications. Games can use heartbeat signals to enhance the experience for multi-modal interaction, and other apps such as fitness trackers can also be implemented in cardboard VR. There will be endless possibilities for building new interactions in a cost-effective way.

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A USER EVALUATION QUESTIONNAIRE

The 2 subjective user evaluation questionnaires will be used to measure the overall body performance and the user experience based on users' subjective feedback. Each question can be rated from 0 to 5, of which 0 is completely not agree and 5 is completely agree. Figure 5 shows the questionnaire we will be printed out to the users.

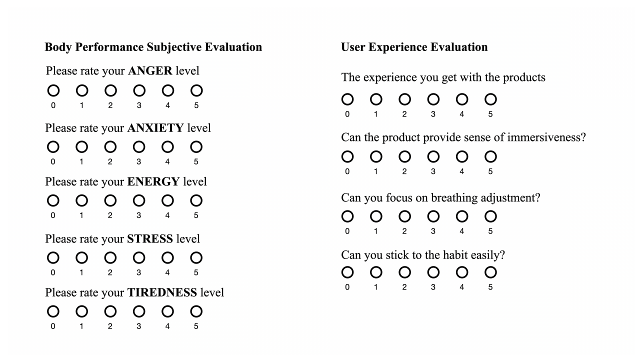

Figure 7: User evaluation questionnaire including body performance evaluation and user experience evaluation.

B ANDROID APPLICATION

The cardboard VR game was built as an Android application. Google Cardboard VR Unity Package can transform the game scene into this 2-view layout, so when the phone is inserted into the CardboardVR Mount, the user will be able to see 3D virtual reality.

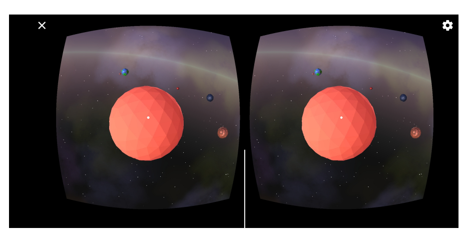

Figure 8: Screenshot of the Android cardboard VR game scene.