Development and Evaluation of Virtual Reality Heart Rate Variability Biofeedback Application

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Abstract

**Background:** Reduced heart rate variability is an important factor in evaluation of autonomic nervous system and diseases. Resonance frequency breathing is a non-invasive and effective training method for increasing heart rate variability. Turing this breathing exercise into a video game is an efficient way to reduce training time and vapidity. Though there has been a successful implementation in 3D game, the influence of virtual reality technology application and interaction elements still need to be explored.

**Objective:** The main objective is to build and evaluate the virtual reality game. Applying appropriate game design and interaction elements will also be discussed. The correct and efficient training should be ensured. Also, recognizing the relationship between game elements and efficiency is also included in the task. By evaluating the impact in heart rate variability biofeedback, the understanding of breathing training game design will be broadened and deepened.

**Methods:** A 3D virtual reality running game is designed with biofeedback framework. Development process is conducted in a user-centred way with interface test. The summative evaluation will be performed 10 participants in a controlled setting. (participant age and health state) Each participant will fill a post-test questionnaire about game experience. The sensor data will be stored on local device. Qualitative analyse of data will be done.

**Results:** VR environment game has shown more significant effects in helping increase heart rate variability than normal game (P<0.05). Both modes have shown more than 50% increase in standard deviation of heart rate variability. A high immersion and positive effects along was reported by a Game Experience Questionnaire.

**Conclusion:** The results have shown that the VR game has the potential to help increase HRV via the resonance breathing training. The game can also allow long-term study by increasing the motivation of participants. Evaluation with GEQ are presented, which will give insights about the usability of this game. Additionally, the new tracks for future study have been explored.
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Nomenclature

ANS     Autonomic Nervous System
BP       Blood Pressure
ECG     Electrocardiogram
HR       Heart Rate
HRi     Instantaneous Heart Rate
HRV     Heart Rate Variability
NN50    Number Of Pairs Of Adjacent N-N intervals That Differ More Than 50ms
OS       Operating System
VR       Virtue Reality
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1. Introduction

Heart rate variability (HRV) means the variation between successive heart beats during specific time interval, usually longer than 5 min. It could be used as an indicator of autonomic nervous system (ANS) function. Reduced HRV is believed to be related to some diseases, such as migraine, systematic inflammation. Biofeedback applications are aiming to improve the function of certain systems or organs based on specific routines or experiments. Via these methods, the function of human body and systems can be adjusted to optimal state. Biofeedback interventions have been considered effective in treating many medical disorders and are becoming popular among health care providers and payors as well as public.

There is an investigated method called resonant frequency breathing, which is applying biofeedback theory. It has shown the potential to be a non-invasive solution to increase HRV. In brief, this method requires the patients to follow instructions to meet the specific breath frequency, which will help increase HRV. There are relations between heart rate and breath rhythm, along with blood pressure. The previous research had shown that when people breathe at certain resonance frequency, HRV achieve maximum. This method has been suggested as substitute for antidepressant drugs by recent research.

Some research has been performed at the Royal Institute of Technology (KTH). These projects are operated in Android-based systems with application of resonance frequency breathing method. It has been shown that concentrating on the training could be the major problem due to the tedious contents and drowsiness, especially in long-term study. Thus gamification could be a helpful way to improve enjoyment. There have been several approaches which offer playful visualizations.

Virtual Reality is a computer technology which use headsets to offer the realistic images, which is usually 3D, sounds along with the simulation of the user’s presence in the environment. VR (virtual reality) technique has been applied in some cases among medical field, such as training for surgery in operation room and balance training for chronic stroke patients. Virtual reality is a potential tool to improve the usability biofeedback applications and thereby enhance the long-term engagement of users. Long term engagement is a necessary step for use of biofeedback as a part of recovery solutions.
Compared to other forms of games, VR technique can offer a better environment with more immersion and interaction, which will help the users remain in a more stable and normal state that can respond to the games in a more natural way. [4]. Also, VR technology can help the users to adjust to the optimal state faster due to its immerse experience, which can help improve the effectiveness of biofeedback game. A few examples of biofeedback game have been built by Somatic Vision. [18]

This thesis describes a VR game that was built and evaluated based on Android system. It is able to record necessary heart rate data for later analysis and make simple real-time analysis to determine biofeedback. The software will be used by non-professionals and unguided, which suggests high usability. It will be compared with existing projects. In the end, a discussion will be made on how these game elements influence the biofeedback training and the performance of VR techniques.
2. Aim and objectives

The aim of the thesis is to develop a biofeedback game based on virtual reality technology, which aims to help the users adjust their breath habit and gather data to evaluate the effectiveness of both the game and the sensors through experiments.

The objectives are:

1. Development of a game which will help breath training applying biofeedback method
2. Assessment the efficiency and game experience of the game based on the heart rate data and questionnaire
3. Materials and methods

This chapter will cover the hardware, the software platform and the method. The game concepts, realization and evaluation of the game will also be included.

3.1 Hardware

This section will introduce the compatible hardware.

3.1.1 Heart rate monitor

In this project the heart rate monitor requires Bluetooth communication to transfer data, which means most commercial products can meet the demand. In this case the Wahoo TICKR X is used.

The Wahoo TICKR X is a heart rate monitor produced by Wahoo Fitness. [20] It can provide many services, such as monitoring heart rate, calculating calories and recording data on or offline. However, in this case, only heart rate information is required.

![Wahoo TICKR X](image)

Figure 1. Wahoo TICKR X

3.1.2 Smart phone

To support VR mode, the smart phone requires at least Android 4.4 OS or iOS 7. [21] The hardware requirement is less important. In theory, the game can be operated on low specification phones, while it often comes with lower performance and programming language incompatibility. In this case, the used phone is Xperia Z C6603 manufactured by Sony.
3.1.3 Google Cardboard

Google Cardboard is a VR platform developed by Google for smartphone. It usually consists of lenses, cardboard body and fixation band, though the components could be different in different manufacturers. [22] To use this system, the users need to run the applications or images compatible with lenses and put the phone behind the lenses. Basically, it is a low-cost and easy-manufacturing system and highly compatible.

![Google Cardboard viewer](image)

Figure 2. Google Cardboard viewer

3.2 Software platform

Unity is a cross platform game engine developed by Unity Technologies. [23] Unity is used to develop both 3D and 2D games or applications for computers and mobile devices, including VR features. The applications built in Unity are usually convenient to switch to other platforms.
In Unity project development process, C# and JavaScript are two main programming languages used in editing. They are both object-oriented languages for general purposes.

Bluetooth Low Energy (BLE) is a wireless communication technology developed by the Bluetooth Special Interest Group (SIG). [24] BLE can operate on most devices with low energy cost while maintaining the data transfer quality. In Unity applications, Bluetooth plugins are required.

3.3 Evaluation

3.3.1 Test environment

The tests will be done in a controlled environment at KTH School of Technology and Health. A Xperia phone with the installed software and a Wahoo TICKR X are provided. The author is responsible as the moderator for explaining to put on the device and interviewing. The heart rate data will be stored on the phone and transferred to a private laptop, which will also analyze the data with Matlab. [25]

3.3.2 Game experience questionnaire

The questionnaire is based on the work of IJsselsteijn et al. [27], which is modified and listed in appendix B. This questionnaire concentrates more on the immersion and sensory feel of the users since the game will not provide a story and background.

According to the original definition [27], question 4 “I felt frustrated” lies in category of tension and question 6 “I had to put a lot of effort into it” lies in category of challenge. These two categories in this questionnaire are for the same purpose as the original ones to examine the experience. Though in this game the users need to do nothing but to follow the breathing rhythm, these questions can still demonstrate the experience to some extent.

Question 2, 5, 14 for immersion and sensory, question 1, 11 for negative effects and question 7, 8, 10 for positive effects are identical to the original design. These questions can reflect the direct feels of users in the whole experience.

Question 3, 9, 12, 13 were designed to estimate the flow of the game, usually about the motivation and reward [29]. These questions are mostly “forget things outside”, which can indicate involvement. In this biofeedback game, these questions can be easily confused with immersion questions since the VR environment can also make users ignore outside world. Despite the important role of game flow, the questions designed for it is out of date. Thus, in this case, these questions will still be taken into consideration but with low priority.
3.3.3 Study Protocol

Before the test, each participant needs to sign a participation contract to clarify the information usage of the recorded data.

The introduction is given through a PowerPoint presentation with automatic play back to avoid human interaction bias.

The test includes two parts: normal test and VR test. These two parts of test are conducted in the same way, with only difference in game mode selection.

First, the users need to be at rest and the HR data will be collected. This session lasts 5 minutes.

Then software will be started and pre-configured before the test. The real test will begin when the heart rate monitor is activated. The user can ask the moderator about the game usage. The game will be played 5 minutes.

After the test session is 5-minute HRV data collection when users at rest.

The normal test will use the normal mode in test while the VR test will use VR mode. After two parts of test are finished, the last step is to interpret the game experience questionnaire and let the user fill it. An interview will be performed depending on the will of participant, and the participant is encouraged to make comments.

3.3.4 Participants recruitment

For now, there is no specific requirements for recruiting participants. However, some young participants appear to be in sub-health state with indicator of higher heart rate and arrhythmia, even with no symptoms of diseases. The cause of this state could be sleep disorder or bad life habits. Considering this situation, these participants will be categorized as sub-healthy people instead of young healthy people.

3.4 Ethical aspects

This game will be played by users without supervision of a professional medical worker, which indicates it is in the category of consumer health informatics (CHI) software. [26] By the definition of stages to categorize CHI solutions, level two means virtual only services without any interaction of a professional; level one means the solution is advise by a professional. In this case, level one or two depends on that if the user loads the app on his own or suggested by a professional. Only for level two there could be ethical problems since this game provides medical service without professional guidance.
In this case, if this software is provided in level one, it should be tested in functionality and to non-inferiority to existing methods. [26] The medical risk seems low cause there is barely medical intervention. In worst case the users can get bored or dizzy after long time test.
4. Results

4.1 Game principle and interface

Figure 3. Game interface: the button above shows the function of connection; the text below shows the information of status
Figure 4. Game interface: the text on the left shows the devices which can be connected; the button on the right can be used to select device.

Figure 5. Game interface: after successful connection, the left text will show the heart rate information; The button above is used to disconnect and the button on the right is for switching to VR mode.
The game principle is inspired by forever running game in Google Play store.

At the beginning, the player needs to connect to a heart rate monitor by pressing the buttons appearing on the screen. As soon as the device is selected and synchronized, the game will start, and the cat will run. There is also a button for switching between normal scene and VR scene, which will appear after the device is connected. The player can choose to stay in the normal scene or switch to the VR scene. Limited by the UI system in VR environment, this button can only switch from normal mode to VR model.

The player will control this cat running along this road forever. Coins will be spawned before the player as reward for completing the test. The obstacles will be built as markers on both sides of the road to simulate the real environment.

Background music and sound effects have been added.

### 4.2 Biofeedback framework

The key step of breath training method is to instruct the patient to breathe at certain frequency, usually 6 breaths per minute. However, it is not easy to achieve for untrained users. Since there is no breath monitor, the instruction of the breath in this game cannot be set to adjust automatically. In this case, the terrain will be set as curves so that the player will go up and down continuously. To follow the road up and down could help the users adjust the breath.
The speed of the cat is regulated by heart rate. The speed is calculated by following: \( \text{Speed} = \frac{\text{Heart Rate}}{70} + 1 \). At optimal situation, the heart rate is 70/min and the speed is 2/s, then the cat will finish one curve in 10 sec, which will follow the breath rhythm of 6/min. The resonance frequency is set as 6 breaths/min is based on previous studies [68], which can fit most people. The reason of using heart rate as the indicator of speed is that for most people without training, to breathe at such frequency is difficult. In real scenario, the users are encouraged to try to follow the rhythm or breathe as they feel comfortable to avoid hypopnea. Based on this design, the users can learn to breathe at a lower frequency and get closer to resonance frequency. Obstacles at both sides of the road can indicate the
speed of the player. The players can estimate the speed without knowing the HR. At higher speed, the users will slow the breath in a subconscious way, which will affect HRV.

Coins will be respawned with less time interval when the difference of successive RR interval is high, which usually indicates increased HRV. The calculation is based on: Time interval of coins=8-Abs(Difference/30); (Difference larger than 150 will be considered as 150). Collecting coins is a way to motivate the player to move on, which could be an important part of game flow.

4.3 Analysis

4.3.1 Data analysis

Table 1. Results of the 5-minute HRV study in 3 individuals before the test, during the normal mode test, during VR mode test and after the test respectively

<table>
<thead>
<tr>
<th>RR intervals</th>
<th>Before</th>
<th>Normal Test</th>
<th>VR Test</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean(ms)</td>
<td>582.03 (101.48)</td>
<td>616.84 (102.88)</td>
<td>630.05 (110.09)</td>
<td>650.42 (90.54)</td>
</tr>
<tr>
<td>RMSSD(ms)</td>
<td>10.20 (11.38)</td>
<td>4.07 (3.90)</td>
<td>41.75 (6.73)</td>
<td>46.96 (14.67)</td>
</tr>
<tr>
<td>PNN50(%)</td>
<td>0.72 (0.69)</td>
<td>0.70 (0.76)</td>
<td>3.64 (1.04)</td>
<td>3.35 (2.75)</td>
</tr>
<tr>
<td>LF(ms2)</td>
<td>484.28 (274.98)</td>
<td>787.02 (505.02)</td>
<td>1585.84 (1353.12)</td>
<td>901.42 (365.60)</td>
</tr>
<tr>
<td>HF(ms2)</td>
<td>153.64 (80.91)</td>
<td>108.91 (82.05)</td>
<td>664.42 (310.99)</td>
<td>1175.91 (882.47)</td>
</tr>
<tr>
<td>LF/HF Ratio</td>
<td>3.30 (1.94)</td>
<td>7.45 (2.30)</td>
<td>2.24 (1.54)</td>
<td>1.00 (0.63)</td>
</tr>
</tbody>
</table>

SD = Standard Deviation; RMSSD = root mean square of successive differences; PNN50 = portion of pairs of successive N-N intervals that differ more than 50ms; LF = low frequency; HF = high frequency; LF/HF Ratio = the ratio of power of low frequency and high frequency.

Table 1 shows the results of HRV of 3 individuals. Some data seemed to be abnormal, for example, extremely low pNN50 or RMSSD, which is not likely to happen in young healthy people. The causes of abnormal values can be considered as unhealthy but still acceptable. All other values can be considered in normal values, though some are out of the normal range [28]. However, considering the HRV data could differ significantly for different people, it is still acceptable. Before the analysis, some error data caused by devices need to be discarded. In this project, the NN intervals more than 1500ms are considered errors. The RR interval numbers of each group has been conducted t-test with p<0.05, which indicates great significance of different mean values. This can indicate that the changes of HRV features, like pNN50 and RMSSD, are caused by the changes of heart rate instead of the randomization.

Based on the analysis above, the results have shown that the test can improve HRV significantly. The SD, RMSSD, PNN50 all show positive response. The VR mode shows much greater potential in
improving HRV compared to normal mode. The effects of game could last after the test finishes based on the analysis of data before and after the test.

More detailed analysis is listed below.

Table 2. PNN50 of three tests

<table>
<thead>
<tr>
<th>Different sessions of test</th>
<th>PNN50 of three samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>pnn50</td>
</tr>
<tr>
<td>normal test</td>
<td>pnn50</td>
</tr>
<tr>
<td>vr test</td>
<td>pnn50</td>
</tr>
<tr>
<td>after</td>
<td>pnn50</td>
</tr>
</tbody>
</table>

Table 3. RMMSD of 3 tests

<table>
<thead>
<tr>
<th>Different sessions of test</th>
<th>RMSSD of three samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>before</td>
<td>rmssd</td>
</tr>
<tr>
<td>normal test</td>
<td>rmssd</td>
</tr>
<tr>
<td>vr test</td>
<td>rmssd</td>
</tr>
<tr>
<td>after</td>
<td>rmssd</td>
</tr>
</tbody>
</table>

From these two tables above, it is obvious that HRV has increased significantly during and after VR tests, which confirms the effectiveness of this game. However, some results have showed that the effects after the game are even better than during the game.
From the tables above, we can see that the total power of heart rate is increasing during and after VR mode. There is growth in normal game mode but not significant as the VR mode.

**4.3.2 Questionnaire results**

Basically, the results can show that the goal of designing a training game is achieved. It seems there is no tension and challenge in this game, little negative effects and good immersion experience.
Table 5. Results of three main categories

The blank space of negative effects means both average and standard deviation are zero. The standard deviation of immersion experience is kind of abnormal (mean: 0.89, SD: 0.93) and for positive effects (mean: 3.33, SD: 0.71) is fine.

The participants made good comments on the immersion and environment. The VR environment provides better immersion experience which makes people relax and reduces distraction.

However, some complained that the game itself is not interesting. The reward is not much attracting and no fun to solve or explore. Also, there is no fun of manipulation in the game since the player cannot control the game objects with their mind or action. Compared to other training projects which are usually defined as boring, this game is interesting. After all, this application is not literally a game designed for fun while the main purpose is still helping breath training.
5. Discussion

5.1 Results analysis

The results have shown that this application has great potential in increasing HRV. Compared to other similar projects [11] [32], the results seem effective and efficient, even unexpected. Overall, the game system proved to be efficient and interesting.

The residual effects after VR game mode are out of expectation. There is no related study about the effects after HRV biofeedback training. Usually, it is believed that the autonomic nerve systems will react after these methods in several seconds. I assume that the after effects are caused since the users will try to follow the rhythm even after game tests.

The after effects can cause doubt about the effect of different game modes. However, HRV growth in VR mode are always much higher than in normal mode. Some features indicate that after the VR mode, HRV growth decreases, which can be a proof for VR mode effects. Considering the complexity of HRV features which differs quite much for different people, these results can prove that the effects are reliable.

Though there could be explanation for the residual effects, there are still some other abnormal data in the tests. Some zero points in RMMSD should mean extremely small numbers, however, it is quite unlikely to appear. The assumptions are that the differences of RR intervals are all small, which can cause this situation. Since there is no actual standard for HRV, these data are all kept.

5.2 Limitations of the study

For the game itself, sometimes there could be drift problems caused by the sensor errors, which could be a problem for the users. This problem may differ in different situations, which can be affected by the phone and the outside environment. Fortunately, it will not always happen.

The participants recruitment does not meet the demands since HRV is usually related to some chronic diseases, though increased HRV should be positive for every person. Large samples of study could help assess the correlation of the game and HRV features. In many HRV study cases, age and gender are important factors. More participants allow to split into control group and test group, which will increase internal validity. Though HRV features could differ much with persons, more samples could still show patterns.
For the game performance, there are some disadvantages. The UI system in VR scene still needs to improve. Due to lack of input devices, no buttons are displayed in VR scene. The terrain and environment are other potential components in game design, though they are usually limited by the resources of graphics processing in smart phones. Compared to other similar games (Introduction section), the game elements and game flow are still not enough.

5.3 Future work

The summative study only evaluated the effectiveness and game experience of the developed project, there are still potential for additional improvements.

More participants are needed in this project to evaluate the effectiveness and limitations. The application of VR environment seems positive, but it still requires long-term study to understand the effects on human. Also, since this game is aimed to improve the enjoyment in breath training, long-term and multi-time tests need to be performed to evaluate its effectiveness. More tests are required to determine the target group, since playing mobile application games do not fit the habits of everyone. It seems that game is a useful tool for breath training, which makes long-term HRV study possible. To study long-term effects on HRV will help understand the correlation between HRV and ANS function.

The respiratory signal is not available in this project, which will lead to inaccurate automatic resonance frequency. Despite there is no gold standard for resonance frequency, the rough estimation can also work in biofeedback framework. To achieve optimal performance, the biofeedback system based on respiration signal and automatic resonance detection should be added, which requires both software and hardware building. A visualized real-time feedback could help improve the efficiency of training. Based on these components, game mechanisms could make better performance.

Comparison with other similar applications focus on resonance breathing training will help improve the quality of game. The existing research of game elements has shown that the relationship between game design and motivation [19], could be useful in modifying the game.

Despite resonance frequency breathing, there are some other methods which are believed to increase HRV in a non-invasive way, such as joga, mindfulness, music and acupuncture [30, 31, 32, 33]. To make deep understanding of biofeedback methods, comparison between all these methods should be made.
6. Conclusion

In this thesis a biofeedback game with VR settings is developed. The gaming concept and design have been implemented based on the user-centered principle. The resonance breathing method has been applied in the game design.

The results have shown that the VR game has the potential to help people in the resonance breathing training. Especially, VR display has much more effect than normal graphic display. With limited elements shown in the game scene, the application still demonstrates the success in immerse experience. Since there is little difficulty for using, it can be expected that this game could have a potential user base. Also, the application can be used without guide of a professional medical worker, which allow the users to perform breath training at any time and any place.

The results can contribute to the field of HRV biofeedback by increasing enjoyment during the training process, which will allow long-term study by increasing the motivation of participants. Evaluation with GEQ are presented, which will give insights about the usability of this game. Additionally, the new tracks for future study have been explored.
Appendix

A. Literature Study

A.1 Biofeedback

To be simplified, “Biofeedback is a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance.” [34] This definition is approved by: Association for Applied Psychophysiology and Biofeedback (AAPB), Biofeedback Certification International Alliance (BCIA), and the International Society for Neurofeedback and Research (ISNR), which are three main professional biofeedback organizations.

Basically, biofeedback can be simply considered as a process of gaining awareness of physiological functions and activities and changing or improving performance and health. [34] Another important factor in this definition is instruments. The instruments monitor the physiologic process and transform or process the data into understandable feedback continuously. The understandable feedback does not imply the presentation of all the data or information gathered during the process, which can be confusing and annoying especially for the users without medical knowledge, but will be shown in a more ergonomic way, such as encouragement and guide.

The aim of biofeedback can be varied in different methods; however, it can be generalized as improvement of physiological performance and health. Through the development of techniques and methods, biofeedback can be applied in many cases, including muscle pain, cardiovascular system, urinary incontinence, stress reduction etc., which covers both mental and physical applications.

The physiological changes which biofeedback method desire are usually caused by the changes in emotions, thinking, motion, while the mechanism of some certain methods are still not clear, which will make it hard to assess the efficacy. Like physical training and language learning, the double-blind protocols and sham training are often not feasible. Despite the difficulty of assessment of effectiveness, biofeedback interventions have been considered effective in treating many medical disorders since many methods have stood the test of time, and outcomes and are becoming popular among health care providers and payors as well as public. [35]

A.1.1 Biofeedback of heart rate variability

Heart rate recordings can gather the information needed for heart rate variability (HRV), which is an important assessment of autonomic nervous and cardiovascular systems function. [50] HRV could be important when human face changes and challenges. Throughout the recent year researches, low HRV can be an indicator of cardiovascular problems, generalized anxiety disorder, panic disorder and post-traumatic stress disorder. [51]
HRV can also be used to measure resilience. [48] Resilience refers to a phenomenon that someone can protect himself from mental health problem even under adversity, which can be considered as mental recovery ability. The resilience has now gathered more focus since it can possibly prevent illness through active adaptation mechanisms, which indicates a potential therapeutic path for depression treatment and even other dysfunctions caused by mental illness. [49]

Biofeedback breath training could be applied in many treatments and some results have been reported, including helping treat hypertension and chronic heart failure, better cardiovascular and cardiac nervous function, help treating anxiety and depression. [53]

A.2 Heart Rate Variability

The heart rate variability (HRV) illustrates the changes of the time intervals between heart beats. In this section, the basics of heart rate physiology, the use of HRV, and biofeedback method in HRV will be introduced.

A.2.1 Cardiac physiology

The Heart pumps blood through the vessels by repeated contractions, [57] the number of contractions per minute is heart rate. The rhythm of contractions is controlled by a complex nervous system, and in general, regulated by an impulse conduction system. [58] During the process of impulse conduction, tiny electrical changes will happen on the skins. [59] Using electrodes on the skins can measure the electrical activity, which is also known as electrocardiogram (ECG). Usually it has several waves and peaks in one beat (Figure 1), which will suggest different phases of the depolarization and repolarization cycle. The time interval between two heartbeats is determined by two R peaks, which is also known as R-R interval. When the R-R interval is measured between two regular or normal heart beats, it is named as N-N interval. The instantaneous heart rate then can be calculated: \( HR = \frac{60}{RR} \), where RR is the time interval between two R peaks.

![Figure 9. The sketch of ECG in one heartbeat. [60]](image-url)
The variations of R-R intervals determine HRV. The variations are regulated by the autonomic nervous system (ANS), which controls involuntary actions. The ANS includes sympathetic (SNS) and parasympathetic (PSNS) part [29]. SNS are related to the increase of heart rate and blood pressure while PSNS is the opposite.

A.2.2 Heart Rate Variability Features

The definition of HRV is variation of instantaneous heart rate over time. However, most parameters and features are calculated based on R-R intervals or N-N intervals. There is a set of recommendations for measurement and physiological interpretation of the HRV set by European Society of Cardiology and the North American Society of Pacing and Electrophysiology [61]. According to Malik et al, HRV measurements can be categorized as short-term (≤5min) and long-term (24h) [61]. In this thesis, only short-term recordings will be used.

Basically, most analysis methods for HRV can be grouped under two categories: time domain and frequency domain. For the time domain, the standard deviation of N-N intervals (SDNN), the number of pairs of successive N-N intervals that differ more than 50ms (NN50), the portion of NN50 divided by the total number of N-N intervals (pNN50), and the square root of the mean of the squares of the successive differences between adjacent NNs (RMMSD) [61]. These features can indicate several different aspects of cardiovascular status.

Some most widely used frequency-domain methods are based on power spectral (PSD). To measure PSD, one of the most common methods is the discrete Fourier Transform (DFT). The N-N intervals can be converted into signals with different frequencies and then be classified into different bands. According to Malik et al, there are three important bands: high frequency (HF) from 0.15 to 0.4Hz, low frequency (LF) from 0.04 to 0.15 Hz, and the very low frequency (VLF) lower than 0.04 Hz [61]. To calculate and compare the PSD of different bands can help understand the cardiovascular activities and the nervous system activities. The HF component can be induced by vagal stimulation, which indicates parasympathetic activity. The LF component is assumed to be induced by sympathetic activity or by both parasympathetic and sympathetic activities [61]. These features can help reflect human physiological and mental health.

A.2.3 Existing protocols

One of biofeedback methods related to HRV is resonance frequency training [52]. Through this training, people can with exercise expand their HRV by increasing the amplitude of respiratory sinus arrhythmia (RSA). [52] During training, people slow the breath to certain rate where resonance occurs between respiratory-induced oscillations and oscillations that naturally occur. The baroreflex could be triggered by the baroreceptors due to the changes in heart rate, given that heart rate will rise and fall along with breath rate while the blood pressure will fall when heart rate rise.

There are some existing protocols that focus on performing resonance frequency training. Lehrer et al. introduced a 5 and 10 visit therapy, which has been widely accepted. [52] The 5-visit therapy is used to test personal resonance frequency and the 10-visit method is for assessment of effects.
Another protocol was developed by Lindskog at KTH [63], which was tested in a master’s thesis by Sjödahl [61].

Most protocols are performed in the same pattern. Firstly, 5 minutes of relaxation should be performed to decrease the stress influence caused by the device and experiment. Second, the baseline measurement will be done through 5 minutes of blood pressure and HRV recordings. Next, 20 minutes of HRV training should be followed and then the blood pressure should be measured, along with a rest of 30 minutes. The last step is 5 minutes of HRV measurement for analysis to confirm HRV change.

A.3 Signal Processing

In this section several common methods for signal processing will be introduced, which will be used to process the medical signal captured by sensors and integrated in the frame work.

A.3.1 Lomb-Scargle Periodogram

Lomb-Scargle periodogram is a method for estimation of power spectrum density for uneven sampled data, based on least squares fit of sinusoids to data samples [65, 66]. It could mitigate the problem of long-periodic noise in long gapped records, which Fourier method could boost [66]. Also, it can estimate the PSD without resampling in HRV analysis. [67]

\[
\tau = \tan^{-1} \left( \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j} \right)
\]

\[
P_x(\omega) = \frac{1}{2} \left( \frac{\left( \sum_j X_j \cos 2\omega(t_j - \tau) \right)^2}{\sum_j \cos^2 2\omega(t_j - \tau)} + \frac{\left( \sum_j X_j \sin 2\omega(t_j - \tau) \right)^2}{\sum_j \sin^2 2\omega(t_j - \tau)} \right)
\]

Figure 10. Lomb-Scargle Periodogram [65, 66]

In these formula (Figure 10), \( t_j \) is the sampled times and \( \tau \) is the time delay calculated.

A.3.2 Hjorth Parameters

Hjorth parameters are statistical properties of signal and are originally used in EEG processing for feature extraction [54]. To be simplified, the Mobility represents the mean frequency and the Complexity represents the frequency change (Figure 4) [54], which indicates how complex the signal is or whether it is signal.

\[
Activity = \text{var}(y(t))
\]
\[
Mobility = \sqrt{\frac{\text{var}(\frac{dy(t)}{dt})}{\text{var}(y(t))}}
\]

\[
Complexity = \frac{\text{Mobility}(\frac{dy(t)}{dt})}{\text{mobility}(y(t))}
\]

Figure 11: Hjorth parameters

### A.4 Virtual reality

Virtual Reality (VR) is a computer technology which uses headsets to offer realistic images, which is usually 3D, sounds and other sensations along with the simulation of the user’s presence in the environment. Usually the virtual environment is projected by a head-mounted goggles which provides two individual images with a specific angle for each eye but can also be achieved by specially designed large screen and glasses. Combined with the interaction with virtual items, VR environments can create a lifelike experience which is hardly different from the real world. In most VR systems, the interacts with the virtual features and items rely on specific systems, including haptic sensors, motion capture and game controller.

VR technique has been applied in some cases among the medical field, such as training for surgery and balance training for chronic stroke patients. [35] [36] Virtual reality is a potential tool to improve the usability of biofeedback applications and thereby enhance the long-term engagement of users.

Compared to other forms of games, VR technique can offer a better environment with more immersion and interaction, which will help the users remain in a more stable and normal state. [37] In this way, the physical features, such as heart rates and heart rate variation, will be more similar to them in the real-life experiences. Also, VR technology can help the users recover faster due to its immerse experience, which can help improve the effectiveness of biofeedback game.

On the other hand, VR environment could cause some symptoms and effects, including sickness, visual disturbances and etc. Though usually these effects are mild and subside quickly, it still needs to be taken into consideration [13]. To design a VR environment should be followed in a user-centred way.

Nowadays, Virtual reality (VR) systems have become popular in rehabilitation and medical practice due to its unique interactive and realistic environments. The systems applied can be varied from immersive experience with head-mounted goggles to commercial game consoles. Two examples of rehabilitation and medical practice will be introduced.

#### A.4.1 Application in rehabilitation

In this case, the clinicians developed a VR system called Rehabilitation Gaming System (RGS) which aims to help the rehabilitation training of stroke patients. [55] The interface consists of background, a model of a human torso with arms in the first-person view. The goal is to intercept the spheres that
move towards the user and one point will be rewarded to the user if the sphere is successfully intercepted. The user’s arms’ movement will be captured to move the virtual arms to complete the task.

The difficulty of this game can be modulated via setting the velocity of the sphere, the interval of two consecutive spheres and the range of dispersion of spheres. In game, there is an automatic adjustment system to modulate the difficulty based on the successful rate of catching the spheres. The results have shown that the automatic difficulty adjustment and the whole training are both working well, and there is no significant difference between the performance of two hands. Overall, it is a successful application despite its rough algorithms and interface. Future work could be designing of two angles for both hands training and for specific arm motions, like lifting or waving.

A.4.2 Application in medical practice

One typical example is MIST VR (Mentice AB, Gothenburg, Sweden) simulator diathermy task, which aims to train the new residents that usually lack experience. A prospective, randomized, blinded study had been done by Neal E. Seymour, Anthony G. Gallagher to compare the outcomes of actual training and VR training. [56] The VR device contains monitor to simulate the environment in tissues and kinetics sensors for the users to control as the instruments to perform surgery. Before the test, all the students will have to pass the VR training in certain level to establish the baseline. The results have shown that after VR training the students are more likely to succeed and less likely to make errors.

A.5 Game design

Before the introduction of game design, the development of game itself needs to be mentioned since the game design is highly related to the aim and means of the game. A typical definition of game by Salen and Zimmerman is “a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome” [38]. Based on this definition, a game can usually be identified by three key elements: rules, play, outcomes. This definition could be important since there are several different terms which can be confusing: game, play, gamefulness [39], gamification [40]. According to some researchers, the only distinction between game and play is that play includes game and game is tied to rules. [41] The term “gamefulness” is introduced by McGonigal, [39] which denotes the qualities of gaming, while “playfulness” denotes qualities of playing. Although according to Deterding [41], the distinction between game design and “gamification” is that gamification means the design strategy of using game design elements. Whereas gameful design the indicates design goal of designing for gamefulness, it still needs to stand the test of time and judge of users, mostly game players, which makes the definition blur for now.

For game design part, there are different opinions about the essential elements in game design, especially considering that the game industry is growing rapidly, which is developing new game techniques and methods every day. After surveying the existing literature on game design, this review will divide the elements into two parts: game mechanics and interface. The mechanics will cover how this game is played, including if it has stable logic judgement under different circumstances, such as mission chain issue, and if it is easy for the user to understand the rules, and if
it is too easy or too difficult to achieve the goal. The interface will cover the game environment, the interaction with other items or players.

A.5.1 Game elements

The game design theory is still evolving rapidly, which suggests that it will be hard to tell what are essential elements of making the most popular game. Reeves and Read had introduced “Ten Ingredients of Great Games”: three-dimensional environments; narrative context; feedback; reputations, ranks, and levels; marketplaces and economies; competition under rules that are explicit and enforced; teams; parallel communication systems that can be easily configured; time pressure. [42] However, these ten elements are still not enough to identify a successful or great game: some elements would be missing in a great work, or some games with all these ten ingredients are not considered great at all. Basically, only rough estimation can be made based on some important elements in game design, where the elements themselves are not so clear.

Deterding et al. have categorized some elements on different levels of abstraction. [41]. Though this kind of category might not be perfect, it includes most common elements. The first one, game interface design patterns, mainly indicates the achievements in a game, for example level, ranking or reputation, which could be the most driven factor in a game. The examples of game design patterns and mechanics level are mostly time pressure, which will drive the player to complete the task in limited time. The game design principles mainly relate to long-term experience, which is highly dependent on context of game. The game modes are more detailed than game design principle and related to the background context and the story, which can be identified as “narration”.

Mechanics-Dynamics-Aesthetics (MDA) are more like elements for the whole structure. The mechanics refer to the rules and algorithms and the dynamics refer to the interaction when the user act. The aesthetics refer to the emotional response of the user, which can be triggered in varied ways, such as environment and story. Core Elements of the Gaming Experience (CEGE) contain two elements: Video-game and Puppetry. Video game usually means the environment and the gameplay, while puppetry indicates the ownership and control that the user can acquire in the game. These two elements can produce enjoyment according to researchers, [44] though it is not clear whether these two elements are the only factors that can produce enjoyment or they are responsible for main enjoyment.

A.5.2 Game engine

Unity is a game development tool with a set of resources for rapid development of 3D or 2D applications using C# or JavaScript [47], which makes cross platform convenient. It also supports the toolbox to convert the 3D game into VR environment by adding extra camera in game setting.

A.5.3 Usability

According to ISO 9241-11, usability is defined as the product of effectiveness, efficiency and satisfaction of a system [46]. Effectiveness describes if the user can achieve the goals and efficiency
describes how difficult it will be to achieve the goals. Satisfaction describes the user's perceived ease of use [46].

To test the usability the questionnaires could be quite useful. There are many different questionnaires designed to cover certain purposes. One example is Core Elements of Gaming Experience (CEGE) questionnaire.

In CEGE model introduced by Eduardo et al., the researchers have developed a questionnaire to measure the satisfaction of the players. [43] The questionnaire consists of 38 questions and 10 scales, where the participants should choose the most suitable one based on their feelings and experience. The question are mainly about how they feel and what they feel, which will be rated by 7-point Likert scale. In the experiment performed by Eduardo et al., the participants were asked to try to forget they were in a lab and imagine in the place they usually played video game.

For some games designed for teaching or training, game experience could not be appropriate. Brooke had introduced System Usability Scale (SUS) to measure the overall usability. [45] The questionnaire consists of 10 questions with Likert scale, which can be summed up to the SUS score [44]. It rose to a useful tool for usability testing.

### B. Game Experience Questionnaire

Please indicate how you felt while playing the game for each of the items, on the following scale:

0: not at all; 1: slightly; 2: moderately; 3: fairly; 4: extremely

Questions:

1. I felt bored
2. I found it impressive
3. I forgot everything around me
4. I felt frustrated
5. I found it tiresome
6. I had to put a lot of effort into it
7. I felt good
8. I thought it was fun
9. I was fully occupied with the game
10. I felt happy
11. It gave me a bad mood
12. I was deeply concentrated in the game
13. I lost connection with the outside world

14. It was aesthetically pleasing

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