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Evaluation of virtual reality to stimulate human emotions; Fear and Contentment

IGNACIO PASCUAL FERNÁNDEZ

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ENGINEERING SCIENCES IN CHEMISTRY, BIOTECHNOLOGY AND HEALTH

ABSTRACT

The aim of this research is to evaluate how Virtual Reality can stimulate human emotions. In order to achieve quantification, this study will compare emotions between videos as it has been done previously in other studies and in Virtual Reality. Emotions chosen to be compared were one positive – Contentment – and one negative – Fear –. To compare emotions it is needed to extract quantitative indexes about them, so time domain analyses and frequency domain analyses as well as Poincaré plots were carried out in order to obtain information about Heart Rate and its variability. For time domain analyses, the mean and standard deviation of the heart rate recordings and time between beats were obtained. For frequency, power on low and high frequency bands was studied. The results showed an acceptable response and comparison in the time domain analyses and Poincaré plots that could confirm some initial hypothesis and serve as a starting point for future studies in virtual reality therapy.

KEYWORDS

Virtual Reality, Emotions, Heart Rate, Heart Rate Variability.

ACRONYMS

ACRONYMS	MEANING
VR	Virtual Reality
VRT	Virtual Reality Therapy
CNS	Central Nervous System
PNS	Peripheral Nervous System
ANS	Autonomic Nervous System
HR	Heart Rate
HRV	Heart Rate Variability
LF/HF	Ratio of low to high frequency power
IBI	InterBeat Interval
SDHR	Standard Deviation of Heart Rate
SDNN	Standard Deviation of NN interval

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1. INTRODUCTION

Technologies are leading the way in almost every field of the medicine. A field that highlights this situation is the case of Virtual Reality. VR is currently used to train professionals, to diagnose patients, to treat psychological disorders and even used in rehabilitation. More concretely, this study will focus on psychology and the physiology within it and the use of this technology to improve the psychological methodology currently used and in order to get better results in future studies.

Virtual Reality Therapy is becoming more and more important in the medical and psychological world as it can be a different way to diagnose and treat several disorders. The subject can experience different emotions in a trial of realistic environments, which simulates real situations and stimuli in order to reflect how patients would react without submitting them to a real pain or strong situation. As long as VR offers a controlled environment, it is easy to create stimuli very similar to reality since you can customize it at will, so therapies are more effective and directed to the target that should be evaluated.

Nowadays there are some studies which describe results for phobias, depressions, and traumas using the VRT. In this project, the grade of impact of VR caused on a patient will be examined and analyzed in order to clarify if this new technique is actually more effective than traditional methods. To compare VR with the traditional methods, the decision was to select some scenes/videos that will create in the subject the same kind of emotion that the specific environment provided, and differentiate both signals. Moreover, it would be important to discriminate if technologies are also an important change between emotions or if they respond differently. Contentment and fear will be evaluated and a comparison will be made between them and in different technologies.

Normally, literature shows us that emotions alter some physiological processes as sweating, heart beats and breathing. These factors have been studied in order to determine the grade of intensity of the emotions that the subject is experiencing. The HRV is currently one of the standards for analysis of the emotions. This technique is often complemented by devices that could store and manage the data from the subject. As physiological signals must be analyzed, normally the devices used for these researches are provided with ECG, EMG, EEG, sensors for breathing... In our case, it was decided to work with the heart signal, more concretely with an app and a device for tracking and analyzing the HR.

1.1. Purpose and objectives

In this section, the purpose and objective of this project will be explained. In order to clarify the content of the objectives pursued, they will be classified as academic/professional and personal objectives:

a) *Scientific*: As in every project developed in this academic context, the objective of this study is the experimentation and demonstration of a current issue found in a medical field. Emotions are very difficult to evaluate because of their subjectivity. Therefore, the test results can have a very high variability between them. This problem was found out during studies based on surveys after exposition to VR and when subjects were asked about their emotions and feelings. The limitations of these methods made clear that this kind of studies should be more objective and the analysis of the data cannot be only left to the expression of the subject.

   Instead, the goal of this study will be to compare emotions expressed by the subject but in a measurable way as it is his/her physiological response (Heart Rate). As time was the major limiting factor, the purpose of this study is to analyze the strength of the emotions in order to develop a bigger project about VR and the treatment of different disorders in the future, but this will be presented in Conclusions section.

b) *Academic/Professional*: The main goal is to develop a serious project as it should be taken in a professional way, exploring all the inconveniencies and possible problems and, finally, solving them in Chapter 5 through an analysis of the issue. In addition, another objective that could be achieved in this project is the learning and deepening in Unity, software used for videogames and simulations, which is the base of the virtual reality and many simulations of environments like surgeries, births, trainings… that could be interesting for a professional career in devices and Information and Communication Technologies.

1.2. Delimitations

All of the limitations found during the development of the project will be presented in the Chapter 5, but in the following part some of the delimitations are presented to understand why it was proceeded in that way:

a) Feelings studied: The used environments tried to make the subject feel both fear and contentment. In the case of fear, it is very difficult to know what every subject fears, so a research about fear had to be done in order to make it general. In the case of contentment, the situation is pretty similar. People tend to experience different emotions with the same stimuli, so the methodology should be general and for everyone in order to make the comparison possible.

b) Medical Approval: A wider experiment could have been done if some medical experts could support the project. When working with medical

issues, it is always important to count with medical help and permissions to work faster. In this case, as mentioned before in this chapter, time was a limiting factor and it usually takes a lot of time to get medical approval, so the methodology will not be supported by it and will be directed in another way.

c) Open Source: As it is a bachelor project it will only count with the help of the agreements that KTH could have with other entities and Open source resources. This means that the cost of the project will be reduced to the cost of the agreement between the University and already contracted services.

d) Availability of resources: Most of the study is developed and built with open source software and resources. Moreover, this project was carried out with the VR device of the School of Engineering Sciences in Chemistry, Biotechnology and Health in Flemingsberg, so the subject had to adapt to the established set up. No movement was allowed in order not to alter signals.

2. BACKGROUND

In order to get a better understanding of the goal of the project and why it has been developed, more information about medical technical knowledge and methodologies used in previous studies will be briefly introduced in this section.

First, it will be necessary to deepen in the physiology of the heart and how it is affected by our nervous system when emotions appear. The heart is the main organ of the circulatory system in our body. It is formed basically by muscles stimulated by our nervous system in order to contract and relax. Due to these contractions, beats take place and they allow blood to be distributed by the whole body through the circulatory system to irrigate organs and cells.

As mentioned before, there is a strong relationship between our nervous system and the main circulatory system organ. Inside our complex neuronal network there are two main branches called Central Nervous System and Peripheral Nervous System. The CNS is formed by the encephalon and the spinal cord and is basically focused on the reception of stimuli and the emission of the adequate response. The PNS is formed by nerves and ganglia and its function is to carry the response of the CNS to the rest of the body. [Figure 1]

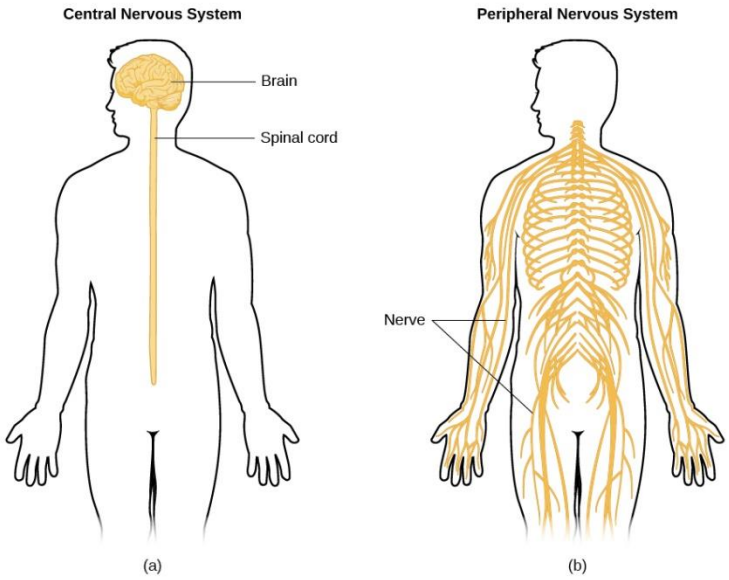


Figure 1. Anatomic description of CNS and PNS

It is important to differentiate between the two main systems because this project will be mostly focused on the PNS. The PNS can be divided at the same time in the Somatic System, where the cranial nerves and the spinal nerves can be found, and the Autonomic System, divided in the parasympathetic and sympathetic system Actually, the differentiation between the CNS and the PNS is only anatomic because some paths of the ANS and the Somatic Nervous System go through the

CNS, but even with this controversy, nowadays it is normal to find it classified as this.

During the procedure of this project, the Autonomic Nervous System will be analyzed because of its function. The ANS is supposed to take part in involuntary actions to regulate and to stabilize the well-functioning of the organs as breathing, heart rate, digestion… It can also be divided in two systems as was mentioned before. The parasympathetic system is responsible for the functions when the body is resting as it starts the digestion, gives the order about relaxation and activates some metabolism responses. The sympathetic system is related to the activation of the body signals such as breathing, sweating or heart rate. It prepares the body for a situation where mental or physical activity is required [1]. As mentioned in [5] the effects of both systems are different in time. While the effects of parasympathetic system are in the scale of milliseconds – it is possible to see differences between the beat-to-beat timing –, the sympathetic system is in the scale of seconds.

Previous knowledge was required to understand the aim of the project. As emotion's strength creation is going to be compared between devices, both systems, PNS and SNS are playing an important role in the comprehension of the results. As mentioned in [8], according to the review there is not a typical or generic explanation for all the emotions that can occur in an individual subject. The responses of the ANS and its strength are directly dependent on the emotion studied and even on the context (of the subject and of the experiment). In this mentioned review, information from some studies was recompiled and 16 emotions were analyzed categorizing them in six positive, eight negative and two without a clear valence. Among those emotions, two of them were selected to work with: fear and contentment (calmness).

Focusing on fear, many studies pointed out that sympathetic system activates when this emotion takes place. This resulted in acceleration of the HR, increased myocardial contractility, vasoconstriction and an increased breathing activity as presented in [3]. Conversely, Heart Rate Variability seems to decrease or be unchanged as concluded. However, every kind of fear has been found to cause different reactions in the ANS and a more detailed study should be done to know the specificity of any special type. Best results were found out in phobias, but this project will not go through this technique as will be commented in Chapter 5.

The other emotion that is going to be studied during this project is Contentment (also studied as calmness, peace or pleasure with similar results). In [3] is mentioned how nature scenes could help to reach this status easier. Contentment points to have a response related to the decreasing of the sympathetic system, but currently more analyses have to be done. Usually responses of contentment are decreasing acceleration or not changing in HR, unchanged or decreased HRV and lightly increased breathing activity in work, depth and rate.

However, there are also some studies which disagree with this previous idea, which makes it difficult to understand what type of measurement is required to find out how contentment emotions can be quantified.

Since every emotion is different to other, the responses are not equivalent and its way to measure should neither be the same. Although this could be a problem because a generic measurement is still being a discussion in the literature, some ECG analyses in relation to the ANS were made in order to clarify how a qualitative response can be studied in a quantitative way.

As mentioned in [3] Heart Rate Variability is commonly used as a relatively reliable biomarker to study when talking about measurements of the emotions. Although it is clear that the literature is not agreeing in every point of HRV around emotions, studies defend that it can be a great way to measure emotions but only when they are relatively strong [4].

Actually, when talking about HRV, literature shows that there are two ways to treat the information to extract from it [7]. Time domain analysis and the frequency domain analysis could be used. The time domain analyses usually go through: Average of all NN intervals and its standard deviation, square root of the mean of the squares of differences between adjacent NN intervals, standard deviation of the averages of NN intervals in all 5-minute segments of a 24-hour recording… among others. Frequency domain studies present Total spectral power of all NN intervals up to 0.04 Hz, up to 0.003 Hz, between 0.003 and 0.04, between 0.04 and 0.15, between 0.15 and 0.4 and ratio of low to high frequency power (LF/HF). Usually, time domain analyses do not shed really useful light because of its limitations and lack of information, but frequency domain analyses are still being studied to determine the relevance of the results.

Vagal activity in cardiac studies has been seen well described by HRV. Some articles based on using time and frequency domain have supported this idea as can be seen in [5]. It is well known that sympathetic activity results in an increase of the HR and parasympathetic activity, however, means a decreasing of the HR. This last system is represented in the spectrum of the HRV of the high frequencies and a mix of parasympathetic and sympathetic is related to the low frequencies. The range where both signals are considered is set to 0.04-0.15 Hz for low frequencies and 0.15-0.4 Hz for high frequencies, finding both sympathetic and parasympathetic activities around 0.15 Hz.

3. METHODOLOGY

3.1. Participants

In this study, seven volunteer participants were selected to take part in the experiment. They were four male and three female subjects who practiced sport or some kind of exercise at least twice a week in order to avoid an abnormal HR because of sedentary lifestyle. The range of age of the subjects was between 20 and 30 years old (20, 21, 22, 23, 24, 24, 26) with the average of 22.8.

All subjects replied negatively to questions about special illnesses or disorders who could affect the result of the study. Neither allergies nor sickness were reported during the initial survey, so seven healthy subjects will be analyzed.

3.2. Experimental Design

All of them were treated in the same way in order to reduce errors or variations connected to a change in the methodology. The seven subjects were exposed to an environment of fear and contentment both in VR and in videos.

3.3. Materials and settings

Here, all the devices and software used and needed to develop the project will be explained in order to make the project repeatable as it is one of the first assumptions of science and projects.

- *Hardware*:

In order to work with VR is necessary to have a device to visualize it. In this case, HTC VIVE device to reproduce the VR content was used. In the content of the device pack is included a helmet/glasses, two controllers, as shown in [Figure 2], to navigate around the interface manually, which will support the teleportation movement, and two tracking cameras to capture all the movements of the subject in order to transfer the information to the computer and translate it into the game, [Figure 3]. Also earphones were used in order to isolate the participant from the room and make the experience more immersive.

Figure 2. Glasses and controllers of VR

A computer able to handle Unity and the computational cost required to run VR was necessary for the developing of the environments and the experimentation with the subjects. Specifications are added in [Figure 3] for the VR device that was used in order to make it repeatable by any computer with the same characteristics.

Component	Recommended system requirements	Minimum system requirements
Processor	Intel Core i5-4590/AMD FX 8350 equivalent or better	Intel Core i5-4590/AMD FX 8350 equivalent or better
GPU	NVIDIA GeForce GTX 1060, AMD Radeon RX 480 equivalent or better	NVIDIA GeForce GTX 970, AMD Radeon R9 290 equivalent or better
Memory	4 GB RAM or more	4 GB RAM or more
Video output	HDMI 1.4, DisplayPort 1.2 or newer	HDMI 1.4, DisplayPort 1.2 or newer
USB port	1x USB 2.0 or newer	1x USB 2.0 or newer
Operating system	Windows 7 SP1, Windows 8.1 or later, Windows 10	Windows 7 SP1, Windows 8.1 or later, Windows 10

Figure 3. Requirements to support HTC Vive Virtual device used during the experiment

Polar band model H10 HR to measure the HR and synchronize it directly with an APP after recording was used during the experimentation. In that way recordings can be easily accessed and stored for its posterior analysis. The model number is H10 E7004818. This material was provided by KTH School of Technology and Health. [Figure 4]

Figure 4. Polar Band device used to record HR

- *Software:*

All the study was developed in Unity. Unity is a platform used to make games, apps and simulations for 2D, 3D, VR and AR as it is described in its own webpage. This platform offers three different modes: Open Source (Personal), Plus and Pro. Those last two products are for professional developers and a payment to acquire its service is required. In this study, Personal mode was obtained – as it is Open Source - and performed during the whole work. Unity 2017.3.1f1 (64-bit) was the version used, but nowadays a later version exists which accepts all of the implementations of previous versions.

As it is compulsory to have environments for both fear and contentment, a study about the offers of Unity was made. Assets are the main packs that can be added into a project in Unity, from multimedia to characters, or a whole environment all in 3D and 2D. For this project, an asset of an environment to create the emotion of contentment was downloaded (Nature Starter Kit 2) and some assets needed to make a homemade development of the horror environment to create fear was obtained (PBR – Hospital Horror Pack). Both can be found in the Asset Store of Unity.

To complement the fear environment, a Zombie asset (from PLXTIGER group) was obtained that included some creatures and animations that could be added to confer them the ability of moving, walking, attacking or falling.

Unity also is provided with Monodeveloper, an inner interface to program in C# and Java some scripts that are instantaneously attached to the application and examined in order to find any error when running the project. Both of them are the main programming languages used in this software.

The third asset required for this experience is SteamVR, as it is optimized to work well with HTC VIVE. This pack contains all the prefabs and scripts needed (setup for players, cameras, tracked controllers, teleportation…)

On the other hand, the app of Polar was also required to store all the data and form the experiment recordings. Polar Beat, a free app from Polar, which allows you to synchronize in real time the information of your polar device recordings (in this case, the band H10 which was described previously) was used.

To analyze what a participant was seeing in each second of the experiment, a software tool was used to record the sight of the screen. Wondershare Filmora was selected based on its friendly interface and ease to edit the video in order to select the period required for the posterior analysis of the sign.

3.4. Experiment

First of all it is necessary to deepen into the procedure of the creation of the environment. To create contentment it was commented before that a nature asset was downloaded. By adding some effects and environmental music, it was intended to create an atmosphere of tranquility and calmness as was described in literature in order to make the terrain presented in [Figure 5]. Moreover, to implement the movement of the subject, SteamVR asset provided some teleporting code and areas.

Figure 5. Contentment environment developed with Unity

It was different in the case of the horror environment for creating fear. Only some objects were available in the pack from Unity, so it had to be developed right from the start. The objects included some beds, rooms, lamps and windows with several textures and colors to impress the subject with a look of an abandoned hospital. They were used to build a scene where the subject has to escape from a room while something strange happened around it. Some scary creatures similar to zombies are walking and screaming around them and some others are trapped in cells. At the end of the scene, the subject faces the creature in a no way out corridor as shown in [Figure 6]. Moreover, some previous research about horror in films was made in order to know which kind of effects were more used and could shed light to this issue (such as playing with lights, waiting time to create stress, environmental music or sound effects in high volume to increase the attention of the viewer).

Figure 6. Zombie attacking a subject in Fear environment

In both contentment and fear environment, a scene was created, where the subject can explore the whole scenario and experience occurring events, but it does not interact with them. As it is easy to understand, the more movement and interaction you add to the scene the more immersive the experience is. If the subject can move freely or grab and throw things, the HR would be affected and would vary because of the exercise. As a study where only emotions are taken into account was tried to be developed, the movement was reduced to teleporting by holding and pressing a touchpad in the VR controller. The explanation about teleportation is based on [6] the principle of motion sickness. If locomotor sensors are not being stimulated but you have the sensation of movement by what you are seeing, the subject will experiment motion sickness and will start to feel dizzy, what automatically will produce physiological responses which would contaminate the recordings of our study.

Seven subjects were selected for the study. All of them were treated in the same way and followed the same protocol. The experiment consisted of the exposure to four experiences, two in VR and two videos of the same environment as VR. As it is shown in [5], emotions are normally studied with the IAPS system, but just like emotions are different between subjects and contexts, they are also different between methods or stimuli. So, although knowing the limitations of showing an environment twice (VR and video), it was decided to show a video with the same scenario of VR as there was no point found in comparing two different stimuli.

The participants of the study were informed of which type of data was going to be recorded and where it was going to be stored as well as the purpose of the study. Everybody signed to accept the responsibilities and agreed to provide their data for only academic purposes.

The HR of the subjects was monitored during the whole experiment. Also they were recorded in video as well as what they were seeing in order to clarify some effects in the HR when analyzing the results. Also, but not described here,

there was a “Think aloud” methodology carried out in order to improve the experiment in the future and to listen to how the subjects said that they were feeling. By comparing both results, it could be seen if what the subject was saying corresponds to the physiological signal.

These subjects were studied in four experiments each of around 15 min. Five minutes of HR were recorded for every VR experiment and five minutes for both video experiments. Moreover, the signal was recorded before and after each experiment during five minutes to capture the baseline of the subject. At the same time, every event that happened was noted manually in a notebook to understand outliers or strange responses in the signal, for example: lost signal, lag in the scene, hitting against some object in real life… As this could result in a different response in HR, it was noted in order to delete the information recorded in this time as it is not truthful. Baseline was recorded while these subjects were standing to reduce the difference in HR due to the position of the body (in VR they should stand).

3.5. Analysis of the method

The procedure of the analysis was divided in two parts as commented previously. Normally, HRV can be studied in the frequency-domain or in the time-domain. Both studies were conducted with the aim of finding a significant difference between emotions and usage of technologies, but first it is important to highlight the acquisition, storage and treatment of the data to extract conclusions. Before deepening in the analysis, data had to be filtered in order to delete false ones.

First, HR was recorded as was mentioned in Chapter 3.3 with a Polar Band attached to the chest of the subject. Data was sent via Bluetooth to a mobile device, where an app collected all the recordings and synchronizing instantaneously with the Polar website. The data was stored in the database of the Polar account and exported to Excel in order to work easily with HRs.

In this point, all the notes taken during the experiment were important to find incorrect results in the table of HRs and to stay with only truthful data. During the filtering procedure, time periods where the subject was moving, drinking or acting abnormally were manually erased following the notes. So, as a result of the filtering, a table with refined data that was useful for the followed purposes could be achieved.

After filtering the data, both analyses in frequency and time domain where used:

a) *Frequency Domain*: A study in the frequency domain tries to find a distribution of the signal power in bands. HRV is usually studied based on a ratio which compares two of them: Low Frequencies (LF) and High Frequencies (HF). This ratio is called LF/HF ratio and, as mentioned before, it theoretically relates the sympathetic system responsible for physiology of fear to the parasympathetic system responsible for contentment. As described in [7], there is a range where different responses can be studied according to the frequency. Parasympathetic responses can be found in the HF power of the signal, from around 0.15 to 0.4 Hz. However, LF is highlighting the sympathetic (and parasympathetic in a minor way) in a range between 0.04 and 0.15 Hz.

b) *Time Domain:* Time domain analyses are focused on the information that can be found in the signal in relation to time. To measure the HRV, indexes used were:

- Mean HR: Indicates the mean of the HR captured in a period of time.
- Mean IBI: Mean of the time for the period between two beats.
- SDNN: Dispersion of the intervals between beats in relation to their average in ms.

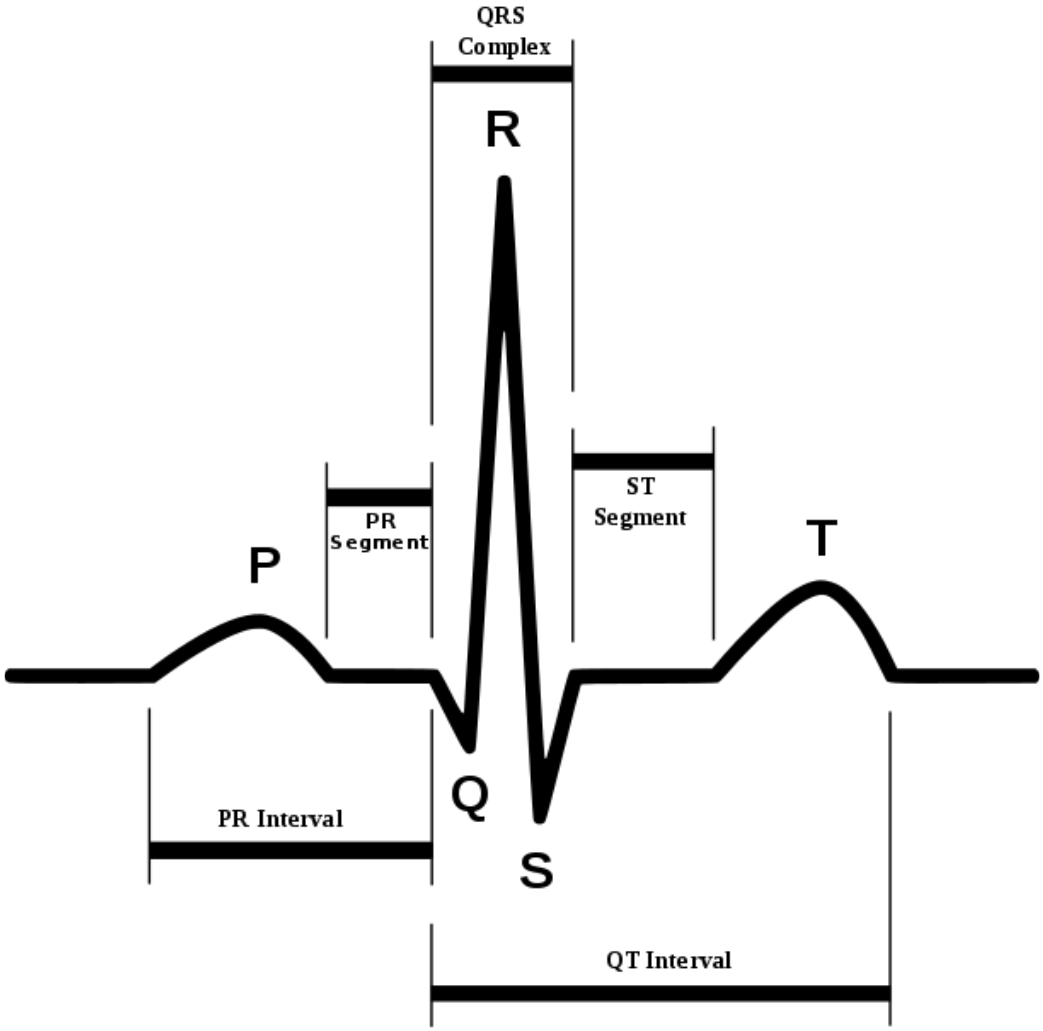
- SDHR: Dispersion in beats per minute of the HR recorded in relation to its average.

Apart from common frequency and time domain analysis, Poincaré plots were obtained to represent HRV. They plot the IBIs in relation to each previous IBI. In an ECG signal, waves related to the polarization (relaxation) and depolarization (contraction) of the auricles and ventricles of the heart are represented as shown in [Figure 7.a]. P wave represents the depolarization of the atria while QRS complex and T wave represent the depolarization and repolarization of ventricles respectively. QRS complex has the R wave which symbolizes the beat in terms of heart rate. Therefore, R wave in ECG represents a beat in terms of heart rate and RR interval is the same as IBI. Then, Poincaré plots show how a RR interval, and accordingly IBI, predicts the next one as presented in [Figure 7.b] so that the relation between the time of the beats and its variability (HRV) can be observed. If values are spread, the HRV is high, but if they are more concentrated, the HRV is lower [12]. As mentioned in [11], "HRV may be analyzed quantitatively by fitting an ellipse to the plotted shape. The center of the ellipse is determined by the average RR interval". SD1 means the standard deviation of Poincaré plot perpendicular to the line-of-identity, while SD2 represents the standard deviation of the Poincaré plot along the line-of-identity, and a graphic example is presented in Appendix A. By comparing the value of SD1 and SD2 of the recordings, HRV can be compared between experiences and baselines.

Other time-domain analytic methods were carried out, but here are only presented which were used to the conclusion extraction after all. The other results, including frequency and time domain graphics, are presented in appendix.

Moreover, before all the analysis, a Kruskal-Wallis test was performed in order to clarify quantitatively that there was no relation between the baselines and the experiment. This test compares if any of our groups studied come from the same distribution. It means that the baselines and the experience will be compared in order to know if they present statistical differences between them. Kruskal-Wallis works like an ANOVA - which determines whether different treatments show significant differences or their population means do not differ - but taking into account that data cannot have a normal distribution. If the significance is enough to reject the null hypothesis, then it can be said that statistical differences between the groups exist.

a)



b)

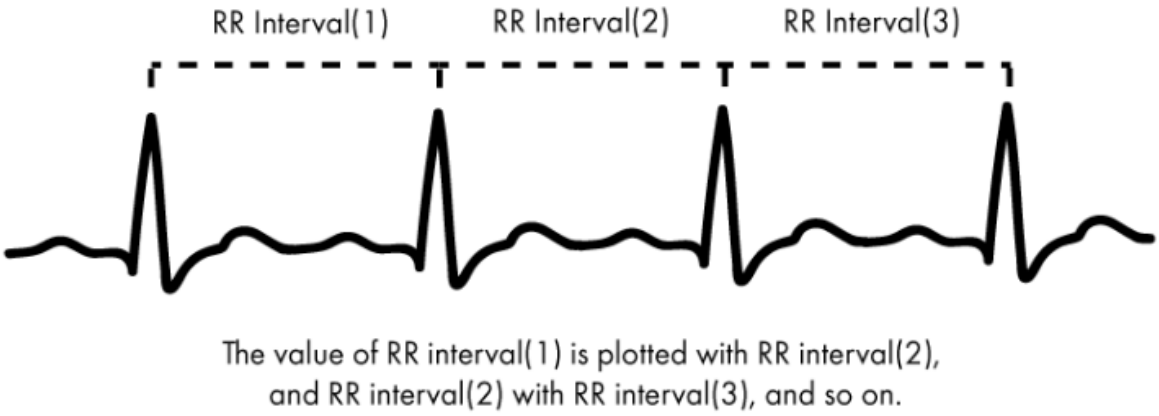


Figure 7.a) Graphic of a typical ECG waves representation and intervals between them .b) Graphic explanation of how Poincaré plots explain predictions and interbeat deviation

4. RESULTS

In this section, all the results from the previous analysis mentioned will be presented. Kruskal-Wallis test was showing significance under 0.001 in 26 of the 28 experiments -four experiences in seven subjects- [Figure 8]. Here is an example of the results of one experiment. Significances in table will be added in the appendix.

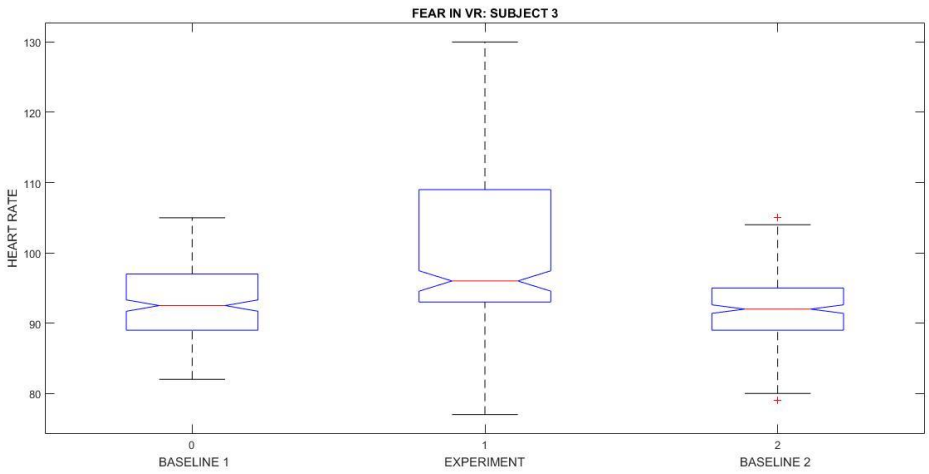


Figure 8. Box and whiskers graphic from Kruskal-Wallis Test for Fear in VR in patient 3

Time and frequency domain indexes are reflected here. Interesting Poincaré results are presented here while plots are presented in the appendix. They will be represented in a way which simplifies the comparison between the emotions and the technologies, but it will be apportion by subjects:

Table 1. Results of time and frequency domain analysis for subject 1

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	596.3	26.1	100.8	4.4	2.66
	Environment	589.9	21.1	101.9	3.7	2.28
	Baseline 2	583.5	33.2	103.2	5.8	5.18
Video Fear	Baseline 1	568.4	31.3	105.9	5.5	5.45
	Environment	593.9	23.0	101.2	3.9	2.70
	Baseline 2	584.7	32.9	102.9	5.8	4.48
VR Contentment	Baseline 1	817.8	44.0	73.6	4.0	4.23
	Environment	641.0	26.1	93.8	3.8	3.68
	Baseline 2	823.0	79.3	73.7	8.1	3.94
VR Fear	Baseline 1	773.0	43.9	77.9	4.3	7.59
	Environment	656.3	23.7	91.5	3.4	3.70
	Baseline 2	702.3	64.4	86.1	7.2	3.55

The results of the first subject can be summarized in some statements. During the VR experiment which tried to create contentment, the HR was even

higher than during the recording of baseline. Moreover, the time between beats and the standard deviation also decreased.

During the fear environment in VR, HR increased as supposed and its deviation too. Regarding the time between the beats and its dispersion, it was clearly reduced during this experience.

During submitting the subject to videos, big differences in HR in comparison to VR even in the baseline could be seen, which will be discussed later. There were no significant differences between the baselines and the experience. However, the dispersion in time and beats during both environments seemed to be reduced.

LF/HF ratio decreased during video experience and lightly increased or stayed stable in VR. During contentment experiences, the ratio decreased and during fear environments decreased in video but increased in VR.

The analysis of HRV by the Poincaré plots showed that it decreased in the video of contentment (in comparison to the baseline) and in fear. Also it could be seen a decrease of the HRV in plots for VR.

Table 2. Results of time and frequency domain analysis for subject 2.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	772.7	28.9	77.8	3.0	8.39
	Environment	763.6	29.9	78.7	3.3	6.74
	Baseline 2	746.8	30.2	80.5	3.4	2.49
Video Fear	Baseline 1	749.9	28.3	80.1	3.1	5.78
	Environment	787.9	38.6	76.3	3.9	8.45
	Baseline 2	745.2	24.1	80.6	2.6	8.02
VR Contentment	Baseline 1	680.5	31.0	88.4	4.3	12.06
	Environment	665.1	28.1	90.4	3.9	5.38
	Baseline 2	657.5	31.4	91.5	4.3	2.92
VR Fear	Baseline 1	657.5	29.8	91.4	4.1	8.28
	Environment	668.3	2.4	89.9	2.8	5.28
	Baseline 2	657.8	254	91.3	3.5	4.30

Examining the second subject, it is possible to see that during the VR contentment experience, HR was not reduced as in subject 1. Its HR was increased with time but the dispersion of the beats was reduced. The time between beats had no significant changes but the dispersion was also reduced. During the Fear environment in VR, HR was very similar to its baseline with slight reduction. Due to that, the time between beats increased. Dispersions of both time and beats were decreased.

In relation to the videos, Contentment does not seem to change significantly neither the HR nor the time IBI during the experience. Deviations neither show a

big impact in their values. Fear, like contentment, does not shed much light to the study as its values are not very different between baselines.

LF/HF ratio did not shed much light as it was not responding following a clear pattern. The ratio was higher in video than in VR.

Poincaré plots showed that HRV was mainly stable during videos and contentment in VR. However, they presented a significantly decreased HRV in fear in VR.

Table 3. Results of time and frequency domain analysis for subject 3.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	671.3	50.8	89.9	6.6	6.66
	Environment	663.9	36.3	90.6	4.9	8.27
	Baseline 2	665.8	46.7	90.5	6.1	10.36
Video Fear	Baseline 1	649.3	39.1	92.7	5.6	5.34
	Environment	606.2	73.7	100.5	12.5	4.71
	Baseline 2	652.4	38.5	92.3	5.3	9.56
VR Contentment	Baseline 1	652.4	52.8	92.6	7.5	6.37
	Environment	642.4	40.5	93.8	5.8	5.72
	Baseline 2	649.7	45.1	92.8	6.3	10.08
VR Fear	Baseline 1	649.3	39.1	92.7	5.6	5.34
	Environment	612.8	68.9	99.2	11.9	6.69
	Baseline 2	654.2	397	92.0	5.5	11.30

During VR environment of contentment, the HR was more or less stabilized (little increase) but dispersions were reduced both for time between beats and for HR.

For fear in VR, HR was significantly increased and IBI was reduced as a consequence. However, standard deviation of HR and time between beats increased, so it means that HR was changing a lot during the recording.

About the videos, in contentment the HR and IBI did not change too much but the deviations of both were reduced. Nevertheless, HR and IBI were drastically modified in the fear video and even the deviation was significantly increased.

In videos, LF/HF ratio increased in contentment in relation to Baseline 1 but it is lower than baseline 2. However, the ratio for fear is decreased as it theoretically should be. For VR, the ratio is decreasing in contentment and staying between baseline values for fear.

Poincaré pointed on a decrease in the HRV during the contentment in video and an increasing in fear. In VR, contentment did not present any significant change of HRV but increased drastically in fear.

Table 4. Results of time and frequency domain analysis for subject 4.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	1018.8	53.7	59.1	3.4	10.28
	Environment	994.9	56.4	60.5	3.7	13.40
	Baseline 2	946.6	58.2	63.6	4.0	11.83
Video Fear	Baseline 1	957.4	36.9	62.8	2.5	8.44
	Environment	996.4	81.7	60.7	5.5	9.34
	Baseline 2	-	-	-	-	-
VR Contentment	Baseline 1	833.8	44.7	72.2	3.8	18.45
	Environment	929.8	47.2	64.7	3.4	6.21
	Baseline 2	890.3	49.2	67.6	3.9	16.47
VR Fear	Baseline 1	865.4	50.7	69.6	4.3	17.57
	Environment	922.3	42.1	65.2	3.1	6.68
	Baseline 2	896.3	26.7	67.0	2.0	11.26

For this subject, VR contentment experiment showed that HR was decreasing as expected but fear was also reducing it. Deviations were not shedding much light because they did not vary following an explainable pattern.

In the case of videos, both contentment and fear showed that HR did not differ much from the baseline. One point that had to be highlighted is that SD in the case of fear, for HR and IBI, was considerably high. For the baseline 2, the recording was corrupted during the acquisition of the signal and uploading to the database, so it could not be used for the study.

In videos, contentment and fear showed an increasing LF/HF ratio. Oppositely, for VR the ratio was significantly reduced.

Contentment in videos did not show any interesting change when studying HRV with Poincaré plots while fear was increasing it. In VR, contentment and fear stayed stable.

Table 5. Results of time and frequency domain analysis for subject 5.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	826.3	46.3	72.8	4.1	27.43
	Environment	845.8	32.0	71.0	2.7	10.17
	Baseline 2	795.2	48.9	75.7	4.6	13.73
Video Fear	Baseline 1	846.4	56.8	71.2	4.9	15.98
	Environment	829.7	59.8	72.7	5.4	26.41
	Baseline 2	921.2	42.2	65.3	3.1	10.01
VR Contentment	Baseline 1	1004.5	35.6	59.8	2.2	5.28
	Environment	868.6	55.3	69.4	5.1	16.80
	Baseline 2	998.1	92.5	60.7	6.4	10.58
VR Fear	Baseline 1	1016.2	39.6	59.1	2.4	3.86
	Environment	857.1	55.9	70.3	4.9	14.85
	Baseline 2	997.3	75.7	60.5	5.2	12.86

Studying VR experiences, it is clear that both of them increased HR in subject 5. Both also showed a very elevated standard deviation in Baseline 2, so the signal varied quite a lot after experiencing the VR.

In videos, Contentment did decrease the HR and the fear environment increased it. While the deviation in contentment of HR and IBI was reduced, the deviation of the signal during the fear was increased, although it was not really drastic.

LF/HF ratio decreased in contentment video experience, but increased significantly in fear. In the case of VR, it increased in both environments.

Poincaré plots presented that in videos, both contentment and fear showed a decrease. HRV in contentment did not change a lot in VR, but it seemed to be decreased in fear.

Table 6. Results of time and frequency domain analysis for subject 6.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	831.8	25.8	72.2	2.3	6.12
	Environment	860.6	39.5	69.9	3.1	7.43
	Baseline 2	826.3	42.4	72.8	3.7	8.09
Video Fear	Baseline 1	792.8	24.7	75.8	2.4	10.51
	Environment	870.9	25.6	69.0	2.1	4.40
	Baseline 2	836.8	41.2	71.9	3.6	9.01
VR Contentment	Baseline 1	819.4	36.6	73.4	3.3	11.07
	Environment	822.0	25.5	73.1	2.4	11.18
	Baseline 2	866.2	55.9	69.6	5.0	11.35
VR Fear	Baseline 1	815.5	64.9	74.0	5.7	11.56
	Environment	859.6	30.0	69.9	2.5	10.40
	Baseline 2	836.7	27.6	71.8	2.3	8.47

Subject 6 showed a stabilized HR during contentment in VR getting lower after it. Deviations during the experience were low, so the intensity of HR and the time between beats did not change much. Even for fear, deviations had low values, so VR in this subject did not suffer from severe modifications during the experiment.

However, for fear in VR, HR was decreased and this is not typical.

In videos, contentment got to decrease the HR but fear also decreased it. Deviations for both fear and contentment did not follow any pattern that can allow us to highlight any result.

Studying the HRV via frequency domain, the LF/HF ratio seemed to decrease in fear while the subject was exposed to video but it remained stable or

not far from the baselines for the rest of experiments. Ratios in videos were lower than in fear.

In videos, HRV was showed by Poincaré with increased values for contentment and decreased for fear. HRV decreased in contentment for VR and stayed close to the baseline in fear.

Table 7. Results of time and frequency domain analysis for subject 7.

Experience		Mean IBI (ms)	SDNN (ms)	Mean HR (bpm)	SDHR (bpm)	LF/HF ratio
Video Contentment	Baseline 1	723.0	27.5	83.1	3.1	15.46
	Environment	748.6	28.9	80.3	3.1	7.30
	Baseline 2	825.3	36.3	72.8	3.4	2.65
Video Fear	Baseline 1	731.2	25.2	82.2	2.8	11.80
	Environment	809.4	51.2	74.4	5.1	30.10
	Baseline 2	776.5	33.0	77.4	3.3	13.09
VR Contentment	Baseline 1	708.9	25.1	84.7	3.0	14.41
	Environment	745.8	23.6	80.5	2.6	9.24
	Baseline 2	715.4	29.2	84.0	3.4	13.58
VR Fear	Baseline 1	714.9	27.7	84.1	3.2	16.06
	Environment	736.0	27.4	81.6	3.1	9.37
	Baseline 2	713.7	25.3	84.2	3.0	7.69

As made with previous subjects, VR and Videos will be differentiated. In both VR experiments it was found that HR was decreasing although not drastically, so the IBI was increased. Deviation was reduced in contentment but it was stable for fear.

In relation to videos, contentment did not show a reduction in the HR of the subject with respect to baseline recorded before the experience but it showed it after the experience. Fear in videos reduced the HR in comparison to baselines, which will be discussed later because a pattern could be seen in all subjects. Deviation was more or less stable for contentment but increased its value for fear.

Frequency analyses showed that LF/HF ratio did not change too much except for fear in video where it was increased significantly and in contentment in VR where it was reduced.

Eventually, in the last subject, for videos the HRV showed by Poincaré plots stayed close to the baselines in contentment but increased for fear. In the case of VR, in contentment the HRV decreased and in fear it was very similar to its baselines.

To conclude, summarizing all the data acquired before, some conclusions from the results obtained in the time domain analysis are introduced and they will be discussed in the following chapter. Dividing the results in three statements, it is

possible to differ between the comparison between baselines and the experience inside of the emotion, between technologies and even between emotions:

a) For videos, with respect to the baseline, contentment showed that three out of seven subjects were reducing the HR (and then increasing the IBI) and the deviation of the time between beats and the number of beats was also decreased. Fear, showed that three out of seven were experiencing an increase in HR but two experienced a decrease. It also presented that four out of seven increased their deviation of IBI and HR while only one was reducing it. Subjects not mentioned did not present significant variations.

   For VR, in comparison to baseline, contentment environment was reducing the HR in three subjects but increasing in two. Six subjects out of seven (almost all of them) presented a lower SD for HR and IBI. However, Fear showed an increase of the HR in three subjects whereas two subjects decreased it. Deviation in time between beats increased significantly in one subject and decreased in four while deviation in number of beats decreased in three subjects and increased in two.

b) Also studying the significant differences between technologies it is possible to find out some important information. For contentment, HR was reduced in both technologies in three subjects, but only in VR it could be found that two subjects were increasing it. Also both technologies showed that for the deviation of the time between beats and the number of beats, it was clearly reduced in comparison to baseline, but it was presented by more people in the VR.

   For fear, the same number of subjects showed an increase and a decrease in HR (three and two respectively) in both technologies. Important differences are obtained when deviation is analyzed. Deviation in time and beats was increased by four subjects and decreased by one in videos while, in VR, four subjects decreased the SD of time between beats and three the number of beats, and one increased the time between beats and two the number of beats. So SD is not as clear in VR as it is in videos.

c) The last point that can be compared is differences between emotions. At the end of the study, it can be confirmed that contentment environments (VR and Videos) reduced the HR in comparison to the baseline of the subjects. For fear, it was more competitive and increase in the HR was presented as majority, but there are also some decreases (two out of seven) in both technologies so HR in fear should be analyzed in Chapter 5.

Talking about the deviation of the data, contentment showed predominance in low values of deviation of time between beats and number of beats, so it is normal that the signal changed a bit during the whole recording for contentment. However, in fear the predominance is to show high levels of SDNN and SDHR in videos, although in VR it is more complicated because three subjects were reducing the levels of deviation while two were increasing them.

In the frequency domain analysis, HRVs from subjects have responded differently to the emotions and it will be approached in the next chapter.

Poincaré plots showed a decreased HRV in fear in three subjects out of seven both in video and VR, but video also showed to increase the HRV in two subjects. On the other hand, contentment created decreases of HRV in video in three subjects but only in two for VR, having no significant effect on HRV of subjects.

5. DISCUSSION

In this section, important points that needed to be approached during the study will be presented in order to understand the results and compare it to our first hypothesis.

- **Discussion of the results:** As mentioned in the Chapter 2, a review of many studies carried out in [8] showed that contentment presented decreasing acceleration or no change in HR, unchanged or decreased HRV and lightly increased breathing activity. However fear showed acceleration of the HR while the Heart Rate Variability seemed to decrease or be unchanged.

  Studies that analyze VR are normally too specific (about specific disorders, diseases or controlled scenarios), so general information about VR in comparison to other methods is needed. In relation to the comparison between both technologies, it is established in literature that the response of the emotions depends directly on the presence and immersion of the experience. Stronger emotions are developed in immersive environments where the presence that the subject or patient feels is higher [9]. So it could be expected that if fear or contentment is expressed correctly, the physiology will be reflected in the values of HR and HRV.

  In comparison to our results, contentment showed similar responses to what was expected. Both in video and environment, the HR usually decreased. SD of IBI and HR was significantly reduced in video by fewer subjects (three subjects) but decreased in VR by five. This response could be due to the presence experienced in the forest environment which made the subject calm down and to vary less the signal of HR what meant a smaller variation in time between beats. This theory could confirm that in the experiment of VR, emotions were stronger than in video. Moreover, in some results as video in subject 7 or VR in subject 5 and 6, contentment showed a decrease in the HR acuter in B2 than during the experiment. These values revealed some important information and it could be interesting to find out if with longer recordings it could be known if calmness is more effective when experiencing it for a long period. Poincaré plots showed that HRVs were decreasing in three subjects in contentment while seeing videos and almost not modifying HRVs in VR, as was expected.

  Fear, however, showed different results to what was expected based on the theory. HR was clearly increased in both experiments (video and VR) for three out of seven, but also decreased in two. Fear, as mentioned before, should have increased HR. SD in IBI and HR was the most unexpected

result. It was supposed to be decreased, but it was only decreased in three subjects in VR while it was increased in two subjects. In case of fear in video, the HR was increased in four subjects, while is a really interesting aspect to discuss. Poincaré plots presented good results in VR in comparison to the literature as HRVs were decreasing in three subjects and remaining stable in the other three (only one HRV increased). However, fear in video showed an increase of HRVs possibly linked to the reduction of fear created in this environment by reasons that will be discussed in the following paragraphs.

Talking about frequency domain analyses, HRV could not be really explained by them in this project because there was not a strong pattern followed by the results. A wider analysis with longer periods should be taken into account to differentiate better frequency bands and, as mentioned later, ensure that fear and contentment are being created in the subject.

To understand the results obtained, some limitations of the study should be analyzed, which could bring an error during the methodology and the extraction of conclusions from the recordings.

- **Strength of the emotions**: First of all, as was mentioned before, VR is supposed to have more impact in the subject as the presence in the environment is higher. Feedback from the subjects thanks to the Think Aloud (which means that the subjects give oral feedback while experiencing the situation in order to help the designer to understand them and improve the methodology) test was obtained and they confirmed that felt high levels of presence in both environments, but more in fear than in contentment. Maybe with more immersive technology [10] the arousal of the emotions could be higher and the response of them would be reflected strongly on the paper. Immersive VRT can be achieved with the use of the technology and resources in order to reduce consciousness of the subject and could shed more light to the strength of the emotion.

- **Resources**: One of the limitations of the project was the amount of resources available. Fear responses are quantified better when arousal of the emotion is higher, but it can hardly be achieved only with a VR desktop device. Earphones to avoid external stimuli were given to the subject but currently CAVEs (environments where the visual stimuli are projected directly on the walls of a room) are also used in some experiments to increase the presence of the subject in the experiment. Moreover, the weight of the VR device (glasses) is quite high, so it makes the subject being uncomfortable, which can have repercussions in the HR and the HRV. It could be the explanation for the increasing HR in subject 1 and 5 in the VR contentment because both of them propose via their feedback to study the

ergonomics of the glasses if contentment is wanted to be created. As a whole homemade environment for fear had to be created from nothing (only the assets available in Unity), there could be some mistakes carried out during the creation of the environment. Although research was done about fear effects and conditions to increase the presence of the patient, it is difficult to build up a scary scenario without professional resources (workforce, assets, ideas…).

- **Time of the experiment:** Another aspect that has to be highlighted is the time spent in the experimental part. Five minutes were necessary to measure the HR and HRV in the VR and video experiences as it was necessary for the study of the frequency domain due to the range of frequencies studied [0.04-0.4 Hz]. As shown in [12], short-term HRV analysis do not show the same information that long analyses of 24 h. As studied from [11], five minutes of recording should be enough for the HRV, but even a lot of changes can happen in five minutes for the HR and a realistic average will not be shown. Moreover, there are differences in some results due to the difference in time where they were obtained. For example, for subject 1, VR experience and Video experience were recorded in different days due to personal reasons. Differences in Means of HR and IBIs between both technologies are also appreciable even in the baseline, showing a result that could be pathogenic as it is not between 60 and 90 bpm while resting. Stress of the subject in the day of the experiment could bring exaggerated results.

- **Status of the patient:** Linking with the previous paragraph, one of the most important aspects when considering studying emotions is the status of the subject. In this study it was tried to minimize the effect of the difference between subjects by bringing them to the same status. An interview was made first of all to calm them, the device was showed and they could interact during some minutes with the interface and another environment, they could speak during the recording of baseline in order to simulate a real situation and to eliminate the difference between the VR because they could Think Aloud and talking can change HR. Almost all differences were tried to be minimized, but the personal context of the subject and the way they experienced the experiment cannot be conditioned. Subject 1 for example suffered from some stress that day, subject 2 showed little variations between technologies maybe due to the hours that he spent playing videogames and even VR during the week as he indicated, subject 3 was very sensitive to fear and it was reflected on the results. Emotions are different depending on who is developing them, so even that results show some similarities, to ensure the confirmation or declination of the hypothesis, a wider study with more people should be taken into account in order to

reduce the difference that can be found with only seven subjects. Also it is important to understand that VR can increase the HR only by facing this new technology and by the motivation of using a known unreal environment which indeed seems like reality. That could be another explanation to the higher HR found in contentment mentioned before.

- **Order of the experiences:** Order of the inputs given to the subject is also important. As differences between subjects wanted to be minimized, the methodology always followed the same order. Contentment and fear, in this order, were shown in VR and later, contentment and fear were shown in videos. As comparison between technologies should be the most similar possible, videos had the same content, environment and effects as the VR, but instead of a controller they consisted of a camera walking by the environment and looking at all the important points. As video was also after VR, the subject could know what was going to happen and the effect of fear for example could be less intense or contentment could be turning into boredom. Even considering that, results between technologies do not seem to reveal several effects due to this limitation.

- **Fear and Suspense:** However, the most important point could be the differences between the results obtained in fear and the theoretically expected ones. Far from a clear change in HR during the experiment, only five subjects showed significant changes and they mixed increases and decreases. One explanation could reside in if fear was created or not. As mentioned before, the environment was not professional and the effects and methods to create fear were homemade, but the biggest problem was how to make the subject deepen into fear for five minutes. It was considered at first to go for phobias and studying it in some subjects with diagnosed fear to some stimuli. The problem found was the time requirements for medical approval. Most of the studies about fear are related to phobias. As phobias were not introduced in this study, a different fear had to be achieved. Looking at the results and based on the literature, it is possible to deduce that the environment was not creating fear but suspense. The subject woke up in an asylum and some effects and events were taking place, but to feel fear for a long period, some pauses were introduced between the events. As known from the review in [8], suspense tends to decrease HR and increase the IBI, just like results from this study were showing. The increasing SD of IBI and HR is normal since all the subjects confirmed that they did not experienced fear in video due to that they knew already what was going to happen already in the scene.

5.1 Future work

Once the limitations and the results of this study carried out were known, some new future lines can be improved in order to get the final aim. This study could become the basis of a master thesis about diagnosing or treating disorders of fears and sleeping disorders if fear and contentment could be quantified in an effective way. To achieve this objective, fear should be classified as real fear using phobias as shown in literature, avoiding suspense or anxiety emotions. To do that medical approval would be needed.

As status of the subjects cannot be modified, it is important to make the presence the highest possible. Immersive Virtual Reality as mentioned before should be considered in posterior experiments in order to stimulate stronger emotions. Time is a secondary aspect to improve because theoretically it can respond well to HRV, but a comparison between the results of longer recordings could also be considered in order to examine significant changes in the variability.

6. CONCLUSIONS

In this project, an evaluation of virtual reality to stimulate emotions of fear and contentment in subjects was carried out. In order to achieve quantitative results for the comparison, some indexes were studied in the time domain and the frequency domain, as well as non-linear methods. These indexes studied in seven volunteers were compared in virtual reality and in videos in order to know if the emotions were stronger with any of those methods.

The evaluation showed significant results in the time domain analysis and non-linear methods as Poincaré Plots. However, frequency domain analysis was not as useful as the previous ones because its behavior did not follow a determined pattern which lets us extract any clear conclusion.

Time domain analyses showed that heart rate increased in fear and decreased in contentment, as was supposed. Moreover, heart rate increased more when fear was experienced in VR than in videos, which makes it stronger. In the case of contentment, it decreased more in videos than in virtual reality, but due to the feedback of the patient it could be explained that the weight of the glasses played an important role in this result.

Deepening in the non-linear methods, which represent the variability in the periods between beats, Poincaré plots showed generally unchanged HRV during contentment and decreased HRV during fear. HRV did not show big differences between virtual reality and videos.

Some results were expected as they are similar to previous studies, but other needed to be analyzed to find possible improvements for future work. Weight of the glasses, arousal of the emotion and presence of the subject, immersion of the virtual reality and the difference between fear and suspense were pointed out as the main limiting factors of this project. However, emotions will be very difficult to quantify as the most important limiting factor is the status of the patient, which is a factor very unstable and can vary without the intervention of any other factor of the methodology.

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APPENDIX A

A.1 TABLES AND GRAPHS

As seven subjects were studied in four environments, and three types of analysis were made for two baselines recordings and the experience, 252 graphics were obtained. Here, there is only showed a simple example of each one. Moreover, results of the significance from Kruskal-Wallis test are presented.

SUBJECT	CONTENTMENT VIDEO	FEAR VIDEO	CONTENTMENT VR	FEAR VR
1	1,75e-06	2,19e-21	5,50e-112	7,07e-100
2	1,26e-21	9,51e-49	9,95e-20	6,75e-09
3	0,45	4,15e-20	0,08	1,18e-20
4	2,33e-39	1,26e-21	4,66e-72	1,80e-48
5	3,61e-32	5,82e-63	1,74e-87	5,62e-103
6	1,33e-24	1,03e-88	9,06e-43	1,54e-33
7	2,27e-109	7,64e-74	9,15e-55	5,29e-23

Table 1. Significance of all Kruskal-Wallis tests carried out for the baselines and experiments of all the subjects.

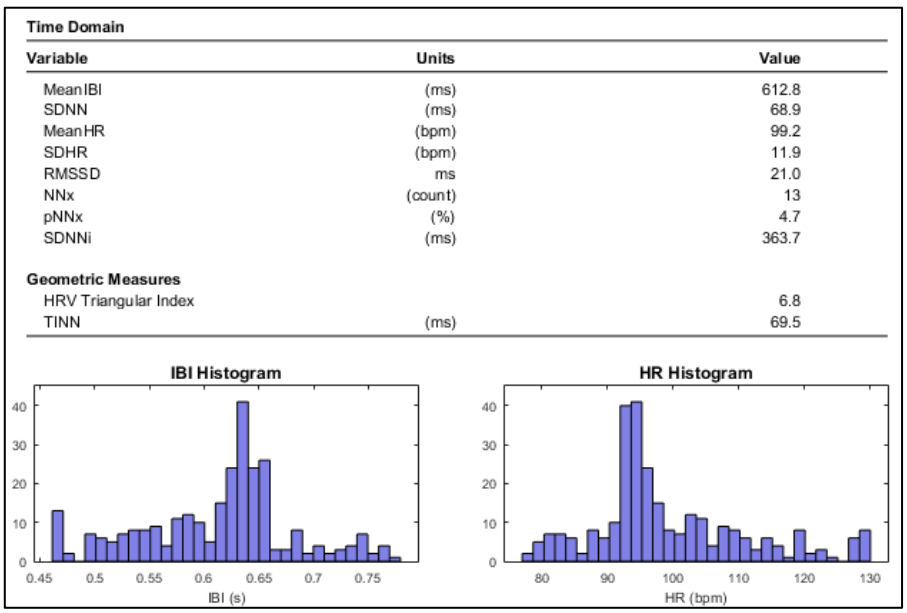
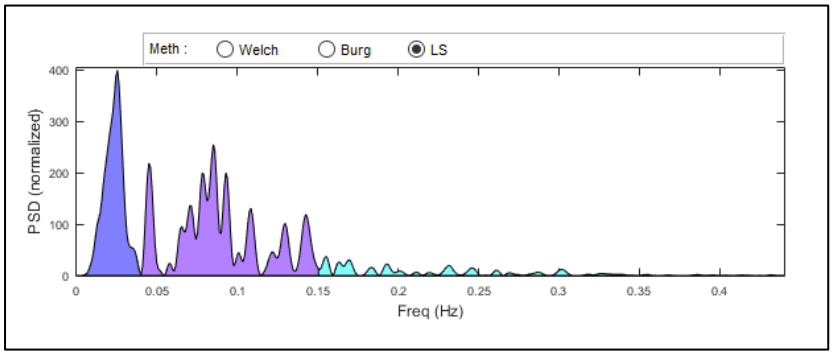


Table 2. Example of Time-Domain complete analysis. Subject 3 experiencing Fear in VR.



Frequency Band		Peak (Hz)	Power (%)	Power (n.u.)	LF/HF (ratio)
Lomb - Scargle PSD	LF	0.08	57.5	0.87	6.69
	HF	0.16	8.7	0.13	

Table 3. Example of Frequency Domain analysis. Subject 3 experiencing Fear in VR. Percentage missing corresponds to Very LF which was not interesting for our study.

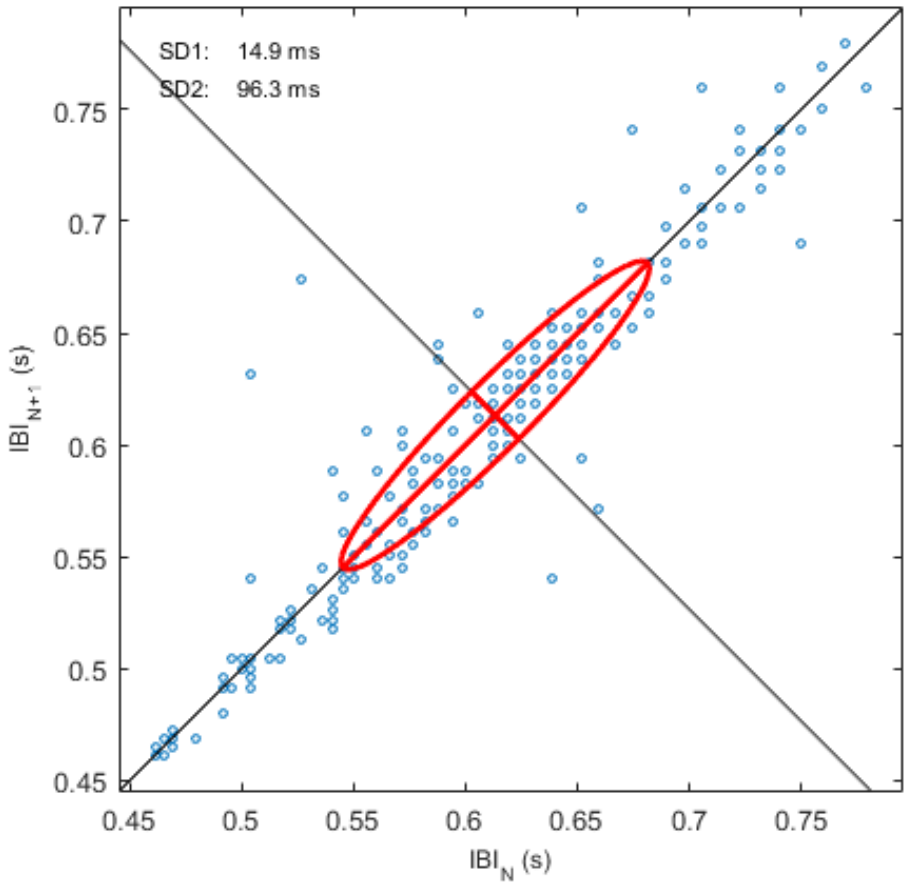


Table 4. Example of Poincaré plot. Subject 3 experiencing Fear in VR.

A