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Bachelor Thesis

Exploring the Visualization Effect of Asynchronous Player's Heartbeats in a Virtual Reality Escape Room on Social Connectedness

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Abstract

This bachelor thesis tackles the single-player problem very often found in VR games. It explores how to use physiological data to enhance player's social connectedness, social presence and gaming experience. After a design workshop with $N = 4$ experts, we agreed upon 4 types of visualizations using heart data, which contain data in an abstract or raw manner and from one or four prior players. Thus, we developed five escape room games, one for each visualization and one more for the base condition with no visualization, serving as a starting point and comparison base line. We tested the escape rooms with $N = 34$ participants in the context of a lab study. We gathered ECG data, eye tracking data, head tracking data, the required time to escape and the number of used hints. Results show that the visualizations had an impact on the social connectedness and were helpful in understanding the riddles and what other players did while playing. However, they were sometimes distracting, especially the multi-player ones, blocking the player's field of view. Furthermore, the players escaped the fastest and used the least amount of hints in the scenario with no visualization, suggesting that the gaming experience was altered in a negative way when the visualizations were involved.

Zusammenfassung

Diese Bachelorarbeit befasst sich mit dem Problem des Einzelspielers, das bei VR-Spielen häufig auftritt. Sie erforscht, wie physiologische Daten genutzt werden können, um die soziale Verbundenheit, die soziale Präsenz und das Spielerlebnis des Spielers zu verbessern. Nach einem Design-Workshop mit $N = 4$ Experten einigten wir uns auf 4 Arten von Visualisierungen mit Herzdaten, die Daten in abstrakter oder roher Form und von einem oder vier vorherigen Spielern enthalten. So entwickelten wir fünf Escape-Room-Spiele, eines für jede Visualisierung und ein weiteres für die Basisbedingung ohne Visualisierung, die als Ausgangspunkt und Vergleichsgrundlage diente. Wir testeten die Escape Rooms mit $N = 34$ Teilnehmern im Rahmen einer Laborstudie. Wir erfassten EKG-Daten, Eye-Tracking-Daten, Head-Tracking-Daten, die benötigte Zeit zur Flucht und die Anzahl der verwendeten Hinweise. Die Ergebnisse zeigen, dass die Visualisierungen einen Einfluss auf die soziale Verbundenheit hatten und hilfreich waren, um die Rätsel und das Verhalten der anderen Spieler während des Spiels zu verstehen. Allerdings waren sie manchmal ablenkend, insbesondere bei den Multiplayer-Visualisierungen, da sie das Sichtfeld des Spielers blockierten. Außerdem entkamen die Spieler am schnellsten und verbrauchten die wenigsten Hinweise in dem Szenario ohne Visualisierung, was darauf hindeutet, dass das Spielerlebnis durch die Visualisierung negativ verändert wurde.

Task

Asynchronous social VR

The loneliness from single-player VR games can be combated if other players could be present without actively playing the game. A gaming scenario will be developed, in which new approaches to improve social connectedness and social presence in single-player games will be explored. Physiological data of other players is a starting point and should be further analyzed to find new paths for its use.

Aufgabenstellung

Asynchrone soziale VR

Die Einsamkeit bei Einzelspieler-VR-Spielen kann bekämpft werden, wenn andere Spieler anwesend sein können, ohne das Spiel aktiv zu spielen. Es wird ein Spielszenario entwickelt, in dem neue Ansätze zur Verbesserung der sozialen Verbundenheit und der sozialen Präsenz in Einzelspieler-Spielen erforscht werden. Physiologische Daten von anderen Spielern sind ein Ausgangspunkt und sollten weiter analysiert werden, um neue Wege für ihre Nutzung zu finden.

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbstständig angefertigt, alle Zitate als solche kenntlich gemacht sowie alle benutzten Quellen und Hilfsmittel angegeben habe.

München, 25. September 2022

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I want to thank Linda Hirsch and Dr. Florian Müller for their guidance, which was essential in writing this bachelor thesis. Furthermore, I want to thank Francesco Chiossi for helping me with everything regarding the physiological data and analysis. I also want to thank my participants for their time and effort in making the lab study and this thesis possible. I want to thank Ana-Cristina Mănărcescu and Paul-Vasile Vezeteu for their valuable assessments. Moreover, I am thankful to Ludwig-Maximilians-Universität for providing a room, a computer and the VR Headset to facilitate the lab study and this thesis.

Remark

To facilitate the readability of this bachelor thesis, the generic masculine is used as a gender-neutral term. This selected masculine form refers equally to all genders.

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1 Introduction

Virtual Reality (VR) is spread and used in several domains, from education, medicine and real-life simulations to the entertaining industry containing activities like games in all their forms [14], but it was not always so prominent. The term "*virtual reality*" was first introduced in the 1980s by Jaron Lanier, the founder of VPL Research [13], which was one of the first companies to sell virtual reality products such as the DataGlove, the EyePhone, and the DataSuit [24]. VR games are slowly entering the gaming industry, yet most players still prefer the usual gaming environment (mouse, keyboard, and monitor), which is described by Parsons et al. [10] as a "*window on a world*", just replicating a virtual environment with narrow capabilities regarding the interaction with others. On the contrary, with realistic sound, three-dimensionality, and the ability to interact with the virtual world through physical interactions, the sensation of "*being there*" in VR is more pronounced than in usual gaming scenarios [8, 10][1]. Sheridan [11] first introduced the term presence, which was defined as "*the effect felt when controlling real-world objects remotely*". Parsons et al. [10] distinguish between the presence and social presence, the latter being interpreted as "*the degree of salience between two communicators using a communication medium*". In the context of VR, it refers to how users feel the presence of "*other social entities (living or synthetic)*". VR enables experiencing realistic scenarios, which are more impressive when paired with an instinct of human kind, the need to interact, creating the concept of social VR. It has received a lot of attention in the past years, as people felt the need to socially interact during isolation [9]. VR offers immersing experiences, which can be further cultivated in many ways, one of them being widely researched in this thesis: the asynchronous social connectedness between the players. Social VR games facilitate the meeting and communication with other players in virtual environments [1]. The social cues incorporated in those games augment the sensation of connectedness the players feel in VR scenarios. They integrate real people inside the virtual world. This type of social cues can be represented by the physiological data of asynchronous players. Heart rate, stress level, respiration rate, and electrocardiogram are a few examples of heart-derived data that can be useful in certain VR applications and use cases [12]. The social cues are also an indicator of others' presence, which is normally stored as leaderboards or friends lists. Involvement in social VR games positively affects one's well-being, but, as mentioned by Lee et al. [1], it has the effect of a "*double-edged sword*". Being too immersed or spending unlimited time in these virtual scenarios can yield emotional repercussions or negative side effects (e.g., depression, low self-esteem, game addiction) on the player [1].

One example of immersive social games are escape rooms. These are different from normal games because they are not just a simple game or service, but a set of riddles, puzzles, mysteries, or conundrums, summed up as memorable events that attract and captivate each player [3]. An escape room has the advantage that time pressure and level of difficulty can increase the immersion, making the user forget about the outside world. When paired with the possibilities of VR, a superior level of immersion is achieved, because VR not only makes the players concentrate on the riddles and obliviate the usual day-to-day thoughts, but also makes them forget about the real world and their whereabouts [10]. To our knowledge, there is little to no research on physiological data in such environments or on its impact on various factors that are going to be discussed in the next sections. This is the reason for choosing escape rooms together with physiological data in this thesis.

1.1 Problem Definition and Research Question

Exploring physiological data in escape rooms in VR is an under-explored topic. Yet, it can yield a new approach to experiencing this category of games and could be a more entertaining modality to accomplish the same goal: to escape. Because the human body and its movements cannot be

[1] This is the motivation for choosing VR instead of the normal gaming scenario for the user study of this thesis.

fully represented in VR yet, but the users still need the presence of other players, addressing the single-player problem (the loneliness, the need to interact and communicate with other players, etc.) is absolutely crucial. The goal is to make a single-player game feel multi-player, thus the materialization of some visualizations for the physiological data of other players is unquestionably needed. The interaction with other players elevates the gaming experience and immerses the player in the virtual world. Furthermore, because a real escape room should be played with at least 2 people, where they help and interact with each other, share the same emotions and frustrations, and the same achievements, the research question of this bachelor thesis is:

RQ: What impact do the visualizations, representing physiological data of prior users, have on the social connectedness, gaming experience, and presence of the single VR player?

1.2 Aim of the thesis

The thesis aims for a within-subject lab study, in order to determine the impact of the visualizations on social connectedness and the feeling of social presence of other players. We test if the user gains any help or advantage from the visualizations or if he is stressed/annoyed/frustrated/relieved when he sees the visualizations. Furthermore, we assess the objective and subjective opinions of the users, and how much the visualizations assist or help them achieve their goal, respectively solving the escape room.

1.3 Structure of the thesis

In the following sections, the current state of research will first be examined and gaps in present research regarding measuring physiological data in VR escape rooms, VR games, and social VR will be pointed out. Then, the creation of the virtual environment (VE), the visualization generation, and the study design will be described, as well as the type of collected data and data analysis. Afterwards, the study results are presented and finally interpreted. In the Discussion section, the results are reviewed in more detail. In the penultimate point, a summary of the work is presented and the most important findings of this bachelor thesis are encapsulated as a conclusion and some ideas for future work are proposed. Finally, the questionnaires, the used assets, the riddles of the escape rooms, the hints, and photos from the VE can be found in the Appendix.

2 Related Work

The focus of this section is to identify the current state of research on escape rooms in VR, that use physiological data as a connecting factor between the players. First, VR games that use social interaction are going to be presented. Afterwards, we will discuss the physiological data use in current VR games and applications. Lastly, current escape rooms in VR are going to be presented along with their difficulties and challenges.

Despite introducing VR into the escape room world [3] [4], physiological data of asynchronous players did not play an important role in the social connectedness observations. This field was not intensively researched in the past, making this thesis one of the first to tackle this area.

2.1 Social VR games

Seele et al. [15] have shown that different complexities for eye gaze visualizations have the same social impact on the user, taking into account the miss of subtle details caused by insufficient VR experience. Moreover, the connection between players can be improved by creating player avatars with face tracking, as shown in [16]. The facial expression is captured and reconstructed in VR, creating the illusion of other users being there and amplifying the social connectedness inside the game, because the facial expression is "*one of the most important social cues for expressing emotion*" [16]. Liszio et al. [18] have found that adding a co-player or an agent to the single-player game significantly decreases the sentiment of loneliness, although the perception of enjoyment is not necessarily enhanced. However, when the players were alone in the game, they experienced better presence and immersion.

2.2 Physiological data retrieval, interpretation and visualization

Measuring physiological data with the help of technology is currently a very common norm fulfilled by a lot of devices, for example, smartwatches. Understanding and interpreting this data is still in the hands of the experts, whose imagination is the only ambit for creating great visualizations, representing the heartbeat or the pulse, an electrocardiogram, or heart rate variability. Visualizations are the median between scientists and users, a number or an icon that everyone can understand. Quintero et al. [5] propose an "*Excit-O-Meter*", a software framework that can be integrated into every VR project. With a complex algorithm for the regular VR user, it represents data, which is easy to understand. However, it is up to the developer to integrate it into his project. Tsai et al. [6] also measured the physiological data in a study comparing VR and AR (augmented reality) scenarios. More exactly, the heart rate variability (HRV) was analyzed to test how claustrophobic the participants felt using the two different platforms. Although their participants wrote in the questionnaires that claustrophobia was more pronounced in VR than AR, the HRV analysis showed exactly the opposite. Bulagang et al. [7] used participants' physiological data acquired while they were viewing emotional videos in VR. Taking a complete other path in terms of physiological data, Bulgang et al. have used different machine learning classifiers to create a model for emotion prediction in four different emotion classes, which used the heart rate (HR) as a feature. Some of the potential applications that can benefit from this type of HR classification are VR health rehabilitation and interactive gaming. Wiederhold et al. [19] measured skin conductance and heart rate to measure presence in the VR environment. Findings show that the users exposed to the VR environment had higher skin conductance than the ones experiencing the same scenario on a screen projection.

2.3 Escape Rooms in VR and their challenges

Anatomic boundaries have to be taken into consideration while playing and creating VR escape rooms and they are described by David et al. [4] in three categories: motion sickness, cybersick-

ness, and simulator sickness. Yeasmin et al. [20] created an escape room game in VR, considering motion sickness. They tested the game using two different mechanics: teleportation and non-teleportation. The group using teleportation had significantly reduced motion sickness and also solved the escape rooms faster, whereas the non-teleportation group had difficulties regarding the time required to exit the escape rooms. Yeasmin et al. [21] also created another escape room game containing logic problems in different cultures and countries. Mystakidis et al. [22] used escape rooms in VR to evaluate the perceptions of Greek school teachers towards the games-based teaching for STEM education (Science, Technology, Engineering, Mathematics). Furthermore, Janonis et al. [23] also developed an escape room for educational purposes. They created a virtual environment where the player needed to perform certain chemical experiments to obtain digit codes, which, if put together, would help him escape.

3 Method

In this section, the study design and the game development are presented. We describe the implementation of the virtual environment, followed by the design decisions made to create the escape room scenarios for the user study. Furthermore, we present details about the creation and implementation of the visualizations using the physiological data and share information about the data collection.

3.1 Study Design

The escape room game was chosen for the user study of this thesis. Thus, we tested a multi-player type of game in single-player scenarios. We investigated it in this manner to gather data about the social connectedness and gaming experience while playing solo. Thus, asynchronous players' physiological data will be represented in the form of visualizations. A within-subject lab study approach with N = 34 participants was chosen. Every participant played all escape rooms and feedback was given through questionnaires and a verbal interview. We defined the independent variables in the Implementation of the physiological Visualizations section, as being 5 scenarios containing 4 visualizations (one of the scenarios is considered baseline and does not contain any visualization and it is referred to as "*no visualization*"). The dependent variables are the ECG data, head tracking data, number of hints used, the required time to solve the escape rooms, the presence, and social connectedness.

Therefore, the following hypothesis guided us throughout the study: Physiological data from asynchronous players taking the form of ECG or hearts visualizations can improve players' social connectedness and gaming experience.

3.1.1 Design Workshop

We conducted a design workshop to produce meaningful visualizations. Alongside four experts in VR design and physiological data for interaction design, we debated for over two hours over different visualization possibilities. The time and technical limitations were taken into consideration. The discussions brought interesting ideas, including the presence of ghost (previous) players or marking important emotional spots in the escape rooms, smoke trails based on players' positions, or ECG lines. The experts concluded with two main ideas. The first one was to take into consideration what the users could understand out of the visualization while playing a fast-paced game. They proposed to compare different types of visualizations, including ones containing raw or abstract data. The second idea was to analyze what impact the number of visualizations has on the player, thus using single and multi-player data. After investigating and interpreting the ideas and concepts from the workshop, we decided on the required scenarios. The visualizations are different in terms of raw versus abstract physiological data, and in terms of the number of players represented in the visualization, having data from either one (single) or four (multi) players (see Figures 3.11 and 3.12), resulting in a total of 4 visualizations. A 5th condition with no visualization was added as a base condition. It had the role to highlight the impact of the visualization on the player in the other conditions. Therefore, we created 5 escape rooms, which are going to be described in the following sections.

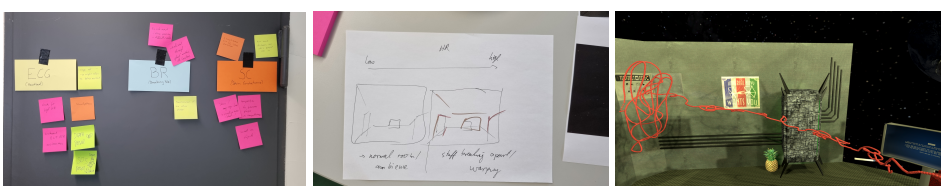


Figure 3.1: Pictures from the design workshop

3.2 Approach

3.2.1 Implementation of the virtual World

Before implementing the escape rooms, we wrote ideas on a digital whiteboard (see Figure 3.2). We compared and adjusted them until the level of difficulty and length were similar. The escape room environments and riddles were created in Unity version 2021.3.4f1 LTS [25].

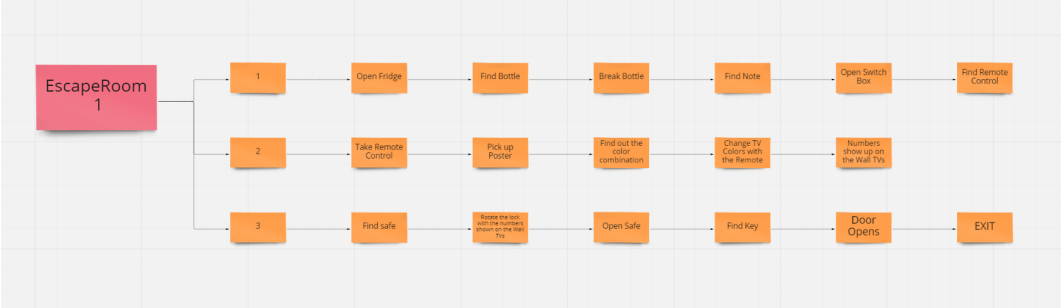


Figure 3.2: The whiteboard with the riddles for the first escape room

We found a space environment on GitHub [26] which represents the starting point of the entire project. It contained two escape rooms, both designed as video games. One of them was selected and redesigned to fit the needs of this thesis. Therefore the environment was totally changed, as it was never intended to be played in VR. The SteamVR API [29] was used inside Unity and it provided all the interaction mechanics: grabbing, throwing, touching, as well as the hand design and animations. The technical setup is completed with help of the Vive Pro Eye [30], which was responsible for the head and controller tracking.

Figure 3.3: The virtual environment

The walls and floor of the initial project were recreated, although some objects were reused, for example, the chair, the fridge, the safe, the poster, etc. (see Figure 3.3). Other objects were found on the internet, under a free license, and ready to be used inside the project, for example, the computer terminal, the pineapple, the food, the chess board, the revolver, etc. (see Figure 3.4).

Figure 3.4: The chess and the pineapple

We needed several iterations of the rooms to implement all game strategies and features. All five escape rooms have the same core components, the same walls, exit door, floor, and main objects (the chair, the televisions, the monitors, the computer terminal, the safe, the fire extinguisher, etc.). Although the majority of the objects were present in all of the escape rooms, most of them were used in riddles only a single time throughout the rooms. Some examples of such objects are the pineapples, the revolver, and the soda can, which were used in the third, respectively the fifth escape room. However, a few objects like the computer terminal, the safe, or the electricity box were used multiple times, each time in a unique way. Furthermore, an object could be grabbed only if it had a yellow highlight when the player's hand was close enough (see Figure 3.5). Thus it was very clear what objects the player could interact with. Some objects also got unlocked once the player completed certain tasks, meaning that they were interactable only after the completion of a prior riddle.

Figure 3.5: The interaction highlight

We applied storytelling to introduce the users to the gaming scenario. The introductory message (see Figure 3.6) applied some pressure at the beginning of each scenario and informed the player that he has 10 minutes to escape, which initiated the immersion process. The player could deactivate the message with help of a button on the controllers, but only after the message was fully written. Consequently, a message was shown at the end as well indicating that the player escaped. During the escape room, a timer counting down from 10:00 was also visible, helping the player to better asses the remaining time. Thus, the timer created a more rewarding finish, if it was still in the upper values.

Figure 3.6: The introductory message

We also developed a hint system (see Figure 3.7) using a papyrus object with text on it, which would fly from space towards the player and open in front of him, revealing the hint. Every hint could be individually activated by the moderator, depending on the needs of the player or the current state of the escape room. The hint can be activated by pressing a button inside the Unity editor (see Figure 3.8). Every escape room had 6 available hints which can be found in the Appendix. Hints 1, 3, and 5 had the purpose to guide the player in the right direction, whereas hints 2, 4, and 6 revealed the whole riddle, helping the player solve it and move to the next one. Hint 2 was the solution to 1, hint 4 was the solution to 3, etc. We created a head tracking system for this project and used it to better understand what caught participants' attention the most. It tracks the objects placed in the center of the screen and it creates a {object : time} dictionary that contains how long a participant looked at a specific object [17].

Moreover, we also added sound effects to the scenarios, specifically to the riddles that were not self-explanatory regarding their state, if they are solved or not. To prevent possible misunderstandings, the sound effects in form of some beep effects were triggered when a riddle was solved.

Figure 3.7: One of the hints being used

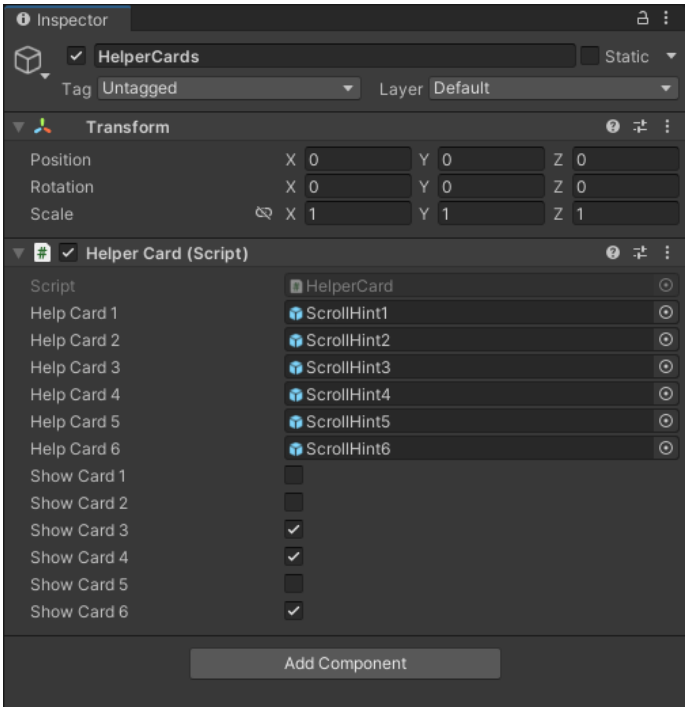


Figure 3.8: The hint system

Furthermore, we developed a training room, which contained objects that could be found while playing in the escape rooms (see Figure 3.9). It represented the learning environment for, but is not limited to inexperienced VR users, for whom the lack of VR knowledge could have impeded solving the riddles. The training environment helped the users to get familiar with the interaction and locomotion system. Not letting the users adapt to the virtual world could have possibly resulted in them losing time exploring all these systems in the first escape room, which would have led to an inaccurate comparison between the scenarios.

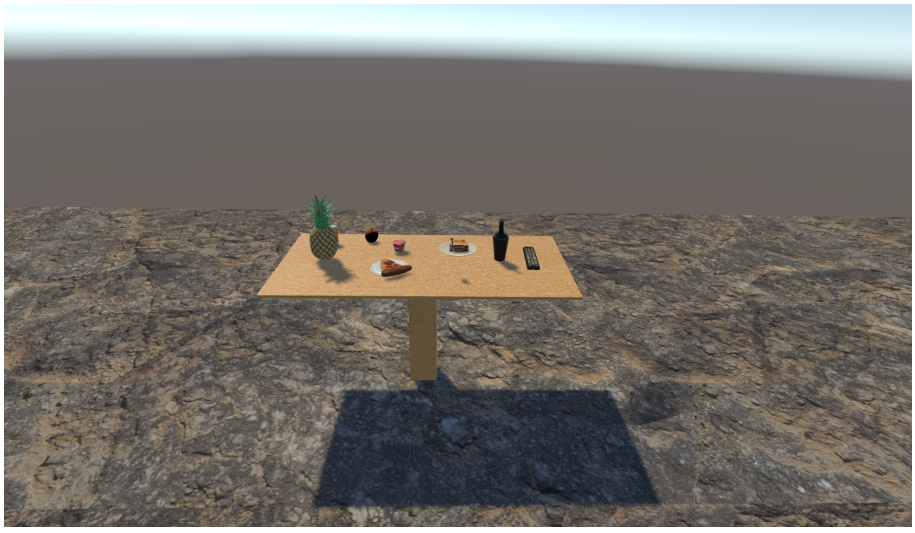


Figure 3.9: The training environment

Before starting the actual lab study, the virtual escape rooms were tested by users only to give feedback and fix bugs or mistakes in the implemented logic of the game. Given the fact that the environment represented a space station, one of our initial ideas was to not have gravity or friction force. This would have created a realistic space environment, which could have been even more

immersive for the player. We observed that it was so enjoyable for the players to throw objects into space and watch them disappear, that they did not concentrate on the given task or the riddles. Furthermore, mandatory objects for the riddles could have been lost, for example, the card, the pineapples, the notes, etc., which would have required restarting the entire escape room or even worse, the signal from the moderator, that a specific object should not be lost. This could have been an important indicator of the priority of that specific object. After some adjustments and further testing, the no-gravity functionality was not removed, but friction force was added to the objects. This was an essential change for the integrity of the acquired data and the user study. Thus, the objects could still float in the air, without the problem of being lost. As mentioned before, some objects still needed gravity to properly work as intended (e.g., the black bottle, the darts).

3.2.2 The escape rooms and their riddles

This section contains the explanation for the first escape room. The other 4 escape rooms are going to be described in the Appendix.

The first escape room has three riddles. To begin with, the player needs to open the fridge and find the black bottle, which should be broken. It is one of the few objects that have gravity enabled and the reasoning for it is that some players would not smash it into the floor to break it. Some of them would leave the bottle floating in the air (the player assumes that it has no gravity as well), so it would fall on the floor and break, revealing a note. The message on the note is ‘‘*Find the electricity box*”, which guides the user to the electricity box in the corner of the room. Now the door of the electricity box is interactable and can be opened (it was not interactable before, being unlocked by finding the first clue - the note. If it would not have been blocked before, the player could have opened it without needing to find the note, which is not intended). By opening the electricity box’s door, the player can find four non-interactable switches and a remote control, which can and should be used to control the blue monitors towards the exterior of the space station. While the remote control is pointing towards one monitor and is held in the hand, the monitor screen changes its color if the player presses button 2 (see Figure 3.10), button 7 being normally used for grab interactions. The right color combination on the 3 monitors needs to be obtained and it is available on the back of the poster that is hanging on the wall. This unlocks the next riddle, which consists of four random numbers appearing on the four side televisions. The numbers are indicators for the safe combination, which is sitting right below the televisions. After introducing the right number in the lock, a beep sound is indicating that it is correct. When the four numbers are correctly introduced, the safe door opens and reveals three objects, including the key to exit the escape room. To open the door, the player should hold the key in his hand and be within a certain range of the door. Afterwards, the player is greeted with a congratulatory message.

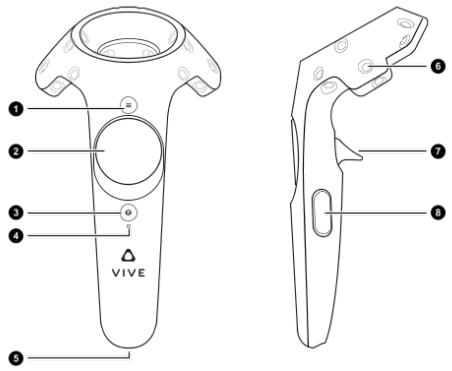


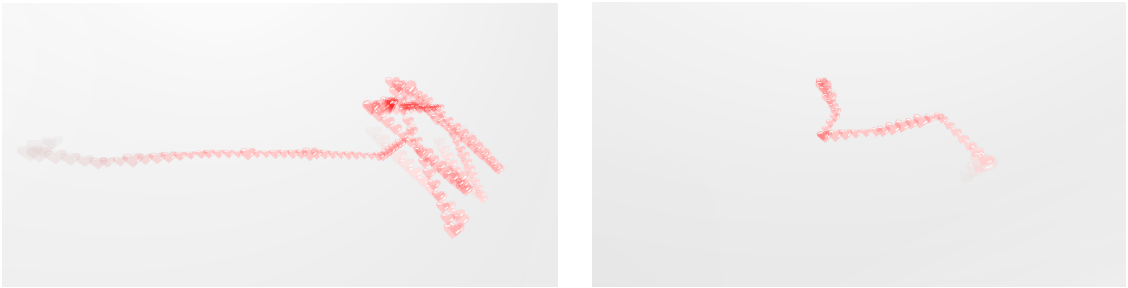
Figure 3.10: The Vive Pro Eye Controllers [33]

3.2.3 Implementation of the physiological Visualizations

In this section, the development and implementation of the visualizations will be described. We agreed to 5 scenarios: single hearts, multi hearts, single ECG, multi ECG, and a base scenario with no visualization. The multi visualizations contain data from 4 players, whereas the single visualizations contain data from a single player, namely the best of the 4. We designated the title of the best player to the one who escaped the fastest in each escape room. For example, three different escape rooms can have three different best players, so the data from the single visualizations is dependent on them.

After the ECG data was collected, it was analyzed using multiple python libraries and for each participant and room were generated 2 files containing heart data. One contained the heart rate data and the other one contained the clean ECG data. The first one was used for the heart visualization, whereas the latter was used to create the ECG visualization. Both of them are linked to in-game timestamps, so they are synchronized and represent the same data every time. Moreover, the tracked head position is now used, because both visualizations take the exact positions of the user in the room. Therefore, the visualization behaves exactly the same as the respective user on all the 3 axes. Both the heart and ECG visualizations were created in such a way to always face the player, indicating that he could move freely throughout the escape room and would always be able to look at the visualizations to gather information.

The heart visualization is a sequence of little heart objects which pulsate. The pulsation is based on the heart rate data (see Figure 3.11), so the heart object becomes bigger when the pulse of the prior user was higher and it stays normal when the user's pulse was normal or lower. Furthermore, at every timestamp new heart objects are being spawned and faded in into the visualization, following the path of the prior player. Every heart object has a lifespan of around 6 seconds, after which it is slowly faded out, creating a gentle floating and easing effect, being in continuous movement. In Figure 3.11a, 4 different heart visualizations can be depicted on the right of the image. One of them is heading towards the left side, while the others are moving in the same area (the right part of the room). Figure 3.11b contains the single hearts visualization, where the trace of one single player is visible.



(a) Multi hearts (b) Single hearts

Figure 3.11: The heart visualizations

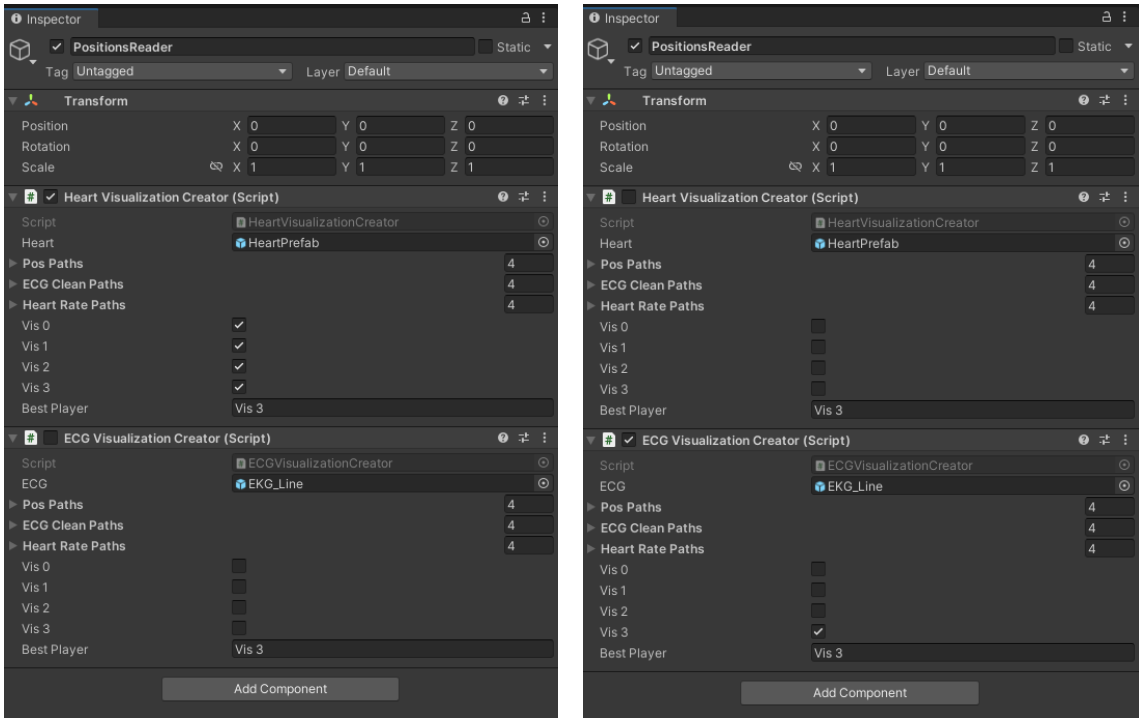
On the other hand, the ECG visualization was constructed like a plot (see Figure 3.12) using the line renderer component in Unity. It contains 100 points on the x axis, and the y point of each coordinate was imported from the clean ECG data. When the ECG plot needed to be updated, all the points of the plot were moved one position to the left, leaving the last position of the plot free, which was overwritten with new data from the clean ECG file. This gave the impression of a cursive moving plot. Compared to the hearts, the positions of the ECG visualization needed to be interpolated, otherwise the visualizations would not have looked smooth. The heart visualization did not need this feature, because it was not rendered with a continuous movement, but as a sequence of spawned objects. Figure 3.12a contains 4 ECG plots moving around the room. They are

all different and unique, given the fact that the provided data comes from different players. Figure 3.12b contains only one ECG plot given the fact that it represents the single ECG visualization.

(a) Multi ECG (b) Single ECG

Figure 3.12: The ECG visualizations

Before the escape room is started, the moderator has the possibility to choose if the heart or the ECG visualization is displayed and for each one of them if it should be the single or the multi-player one. For the scenario with no visualization, both visualization types can be disabled. Figure 3.13a contains the settings for the multi-player heart visualization, whereas Figure 3.13b has the single-player ECG visualization active and ready to be run.



(a) Multi hearts scenario (b) Single ECG scenario

Figure 3.13: The ECG visualizations

3.3 User Study

3.3.1 Pre-Study

The pre-study had the role of data collection for the visualizations and also of fixing minor bugs if any. It did not include any visualization, so it had the base condition with no visualization. A total of N = 4 participants enrolled for the pre-study and their physiological data was used to create

4 individual data sets. Their data was used to create and design the visualizations. Figure 3.14 illustrates exactly that, 4 different ECG plots, each one of them is distinct and unique, exactly like the players the data was recorded from.

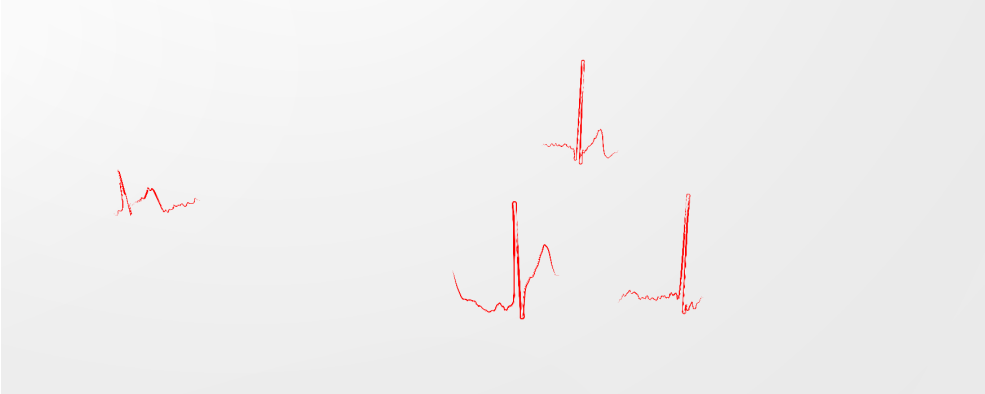


Figure 3.14: ECG Visualizations from 4 different players

3.3.2 Main Study

The main study began shortly after the pre-study and had the four visualizations already integrated and tested before starting. For each participant, the moderator began with a short overview of what the tasks and the goals are. Afterwards, the participant was asked to put on the Polar H10 [28] breast band. This was connected to Unity via a batch file that referenced a python script together with its MAC Address. To ensure that the connection was successful, the moderator connected the BrainVision LSL Viewer [27] with the breast band via Bluetooth. It offered a quick overview of the sent data from the breast band to the PC, showing ECG data from the connected user. Furthermore, the SteamVR interaction systems were explained, for example how to grab objects or how to have further interactions with them. Further, the moderator thoroughly explained the hint system and the possible sounds in the game. This was followed by a small briefing on how to use the controllers, which buttons should be used, how to put on the headset and what starting position to be in. Then, the training environment was deployed, which contained a floor, a table, and a few objects placed on the table (see Figure 3.9). After getting used to the controls, the interaction, and locomotion systems, the training room was closed and the first escape room was loaded. The escape room order was based on a Greaco-Latin square generated in R2022.07.1, which completely randomized not only the order of the rooms, but also the order of the visualizations. After finishing each escape room, the moderator asked the participants to complete a questionnaire regarding their latest gaming experience in terms of social presence and connectedness, and excitement while playing. The complete questionnaires are presented in the Appendix of the thesis. At the end, the moderator asked the participants to complete a last questionnaire regarding demographic data. It also contained questions on ranking the visualizations based on usefulness, emotional attachment, and how distracting or annoying they were. The study ended with a short recorded interview about the gaming experience, the social connectedness, and in general about the visualizations and their impact. The study took approximately 90 minutes and the participants were reimbursed with either 15 euros (5 euro / 30 minutes) or 1.5 MMI points.

3.4 Data Collection

Before starting the study, the participant had to read the Information Obligation for Data Collection of Study Participants according to act. 13 GDPR and agreed for the data to be used for the purposes of the study. The data collection consisted of multiple types of data obtained as follows. First, the heart data needed for the establishment of the visualizations and later for the final data analysis was

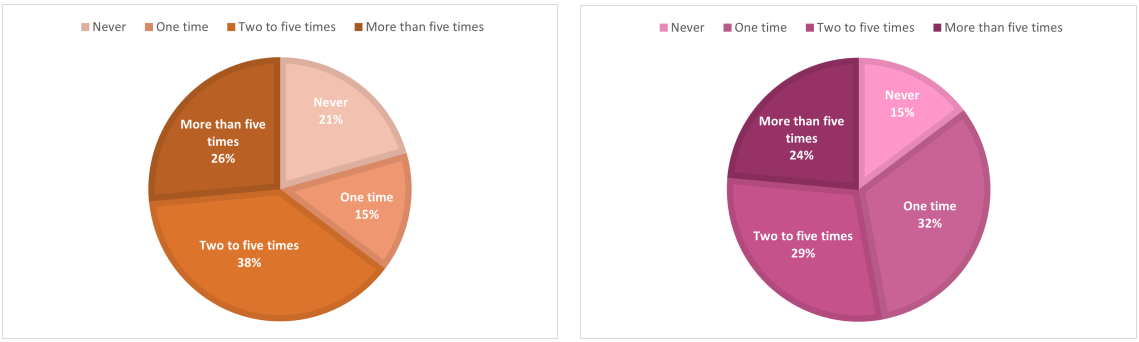
obtained using the Polar H10 breast band. The hint system also saved a file indicating which hints were used by the participant and how long the participant needed to escape. The head positions of the participant were saved in a separate file as well. An eye-tracking algorithm was developed specifically for this project, which saved the names of the objects and how long (in seconds) the participant looked at them in a file. Moreover, participants' performances were recorded with OBS version 72.2.4 [31]. Last, the results of the questionnaires were stored as data sheets and tables. All the gathered data is stored on a university PC and the study was approved by the ethics board of the Faculty of Mathematics, Informatics and Statistics.

4 Results of the Work

This section contains the analysis of the gathered data from the study. First, the demographic data is interpreted, providing an overview of the participants who helped with the study. Then, the impact of the visualizations on the solution findings and on social presence and connectedness is going to be presented and elaborated with statistical tests, analysis and commentaries. Last, the physiological data used for the study, the heart data derived from the ECG data will be interpreted. The questionnaires and the physiological data were analyzed using Python 3.9, Excel, R 4.2.1 and JASP 0.16.3.

4.1 Data Analysis

The study had a total of N = 34 participants, of which 18 females and 16 males, with the average age of 25. One participant had a Secondary School Certificate or equivalent (3%), 17 participants had a High School Diploma or equivalent (50%), 9 participants had a Bachelor's degree or equivalent (26%) and 7 of them had a Master's degree or equivalent (21%). Furthermore, 5 participants never had a 3D experience (15%), 5 participants had one 3D experience (15%), 7 participants had a 3D experience between two and five times (20%) and 17 participants had a 3D experience more than five times (50%). Additionally, 7 participants never had a VR experience (21%), 5 participants had only one VR experience (15%), 13 participants had a VR experience between two to five times (38%) and 9 participants had more than five VR experiences (26%). Likewise, 5 participants never had an escape room experience (15%), 11 participants had one escape room experience (32%), 10 participants had between two to five escape room experiences (29%) and 8 participants had more than five escape room experiences (24%) (see Figure 4.1).



(a) VR Experience

(b) Escape Room Experience

Figure 4.1: Participants' experience

4.2 Impact of the visualizations on the solution finding

We recorded the necessary time to solve each escape room (see Figure 4.2). We needed to exclude the first 6 participants due to technical issues that led to missing data, resulting in N = 28 data files to be analyzed. The time limit for every escape room was 600 seconds and only very few participants needed more time to escape. In the following analysis, μ refers to the mean amount of seconds the users needed to escape and σ to the standard deviation. They needed $\mu = 412$ seconds, $\sigma = 136$ seconds to solve escape rooms that had single ECG visualizations. Furthermore, they needed $\mu = 410$ seconds, $\sigma = 123$ seconds to solve escape rooms which had multi ECG visualizations. $\mu = 413$, $\sigma = 129$ seconds were needed to solve escape rooms that had the single hearts visualization. The participants needed $\mu = 441$ seconds, $\sigma = 133$ seconds to solve the escape rooms that had the multi hearts visualization. Lastly, $\mu = 389$ seconds, $\sigma = 128$ seconds were needed to solve the escape rooms with no visualizations. We did not observe any significant

difference between the scenarios ($p > .05$), although the participants escaped the fastest if no visualization was played.

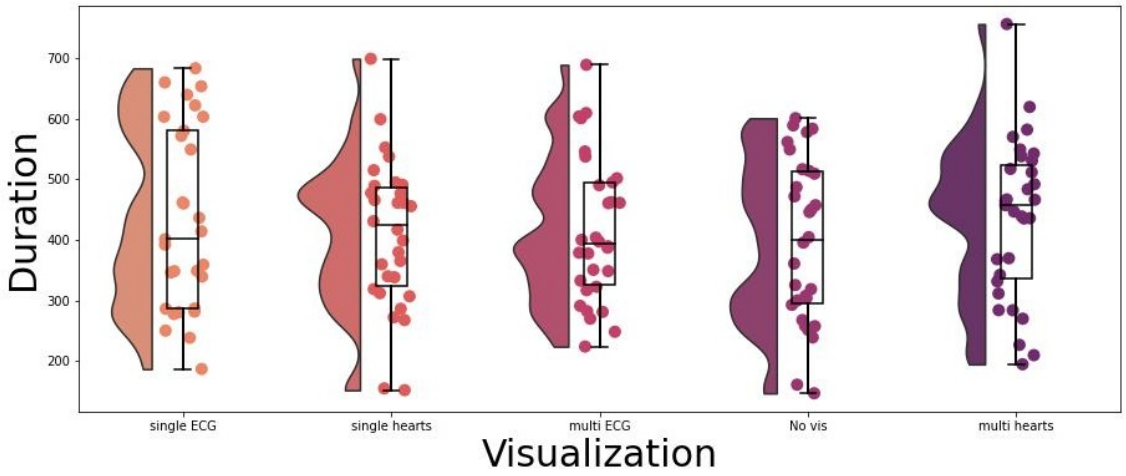


Figure 4.2: The time needed to solve the escape rooms based on the visualization. The points represent individual data points, and the left entity indicates the data distribution. The extremities of the boxplot indicate the 25th and 75th percentiles, while the center mark illustrates the median.

The players had to rank the visualizations based on different criteria, after which an explanation was written. The first ranking regards the usefulness of the visualizations in the escape rooms and they are ranked as follows from the most useful to the most useless: No visualization (19 votes as rank 1), single ECG (14 votes as rank 2), single hearts (14 votes as rank 3), multiple ECG (11 votes as rank 4), multiple hearts (11 votes as rank 5). The participants wrote that the visualizations were "*distracting*" and that they took too much of the screen, obstructing the view: "*They just prevented me from seeing the game, so less is better*" and "*The less visualization was within field of view, the more I could focus on the game itself*". Regarding the usefulness of the visualizations, 16 answers were negative, 7 were neutral and 10 were positive. "*ECG line preferable to hearts because more realistic, multiple preferable because it shows more players*" and "*Because I felt like that the heart lines were helpful*" are some of the positive answers from the questionnaire.

The next available ranking is regarding how distracting the visualizations were when solving the riddles: Multiple ECG (17 votes as rank 1), multiple hearts (11 votes as rank 2), single ECG (16 votes as rank 3), single hearts (18 votes as rank 4) and no visualization (30 votes as rank 5). The participants characterized the visualizations as distracting and confusing: "*I found the hearts very distracting*", "*ECG takes too much space*" and "*Hearts were most distracting, then ECG*". No participant had a neutral or positive response, but 30 had negative responses regarding the ranking of the visualizations. It is clear that the visualizations obstructed the gaming experience and the players felt distracted while playing.

The following hierarchy ranks the scenarios concerning how annoying they were: Multiple hearts (14 votes as rank 1), multiple ECG (9 votes as rank 2), single ECG (11 votes as rank 3), single hearts (16 votes as rank 4) and no visualization (31 votes as rank 5). From the 24 negative responses, we extracted that the visualizations were annoying, because they took too much space and the field of view was blocked, especially in the multi hearts scenario: "*They were all in the way, but the heart lines took up more space*". The other 3 neutral and 3 positive answers expressed either no annoyance or confusion: "*ECG lines were confusing but heart lines helped the more I saw of them*".

4.2.1 Eye tracking and hints

The five eye tracking lists contain a {object : time} structure and are sorted in descending order. There is an eye-tracking list for every scenario and one for all of them. Thus, we could verify the importance of certain objects through their place in the list. An important object is placed at the beginning of the list because it was watched very often and an unimportant one is placed at the bottom of the list with only a few seconds watched. The eye tracking lists offer a perspective on what the players watched the most and the objects that caught their attention. The multi visualizations drew players' attention more than the single visualizations, being watched 4 times (ECG) and 12 times (hearts) longer. In all single ECG scenarios, the visualization is ranked in the eye tracking list the 22^{nd} with 196 watched seconds. The visualization from the multi ECG scenarios is ranked the 2^{nd} with 887 watched seconds. In the single hearts scenarios, the visualization is ranked the 59^{th} with 12 watched seconds. The visualization from the multi hearts scenarios is ranked the 23^{rd} with 152 watched seconds. On the one hand, we observe that the scenarios containing the multi visualizations had a more pronounced impact on the time the player looked at the visualization. On the other hand, the multi scenarios had 4 times more visualizations, making it more natural to look more towards them.

In the following analysis, μ refers to the mean amount of hints used and σ to the standard deviation. The analysis of the used hints throughout the different scenarios indicates that the players needed the least amount of hints for the scenario with no visualization ($\mu = 1.6$, $\sigma = 1.2$). The most amount of used hints occurred in the multi hearts scenario ($\mu = 2.1$, $\sigma = 1.7$). Furthermore, the players needed $\mu = 1.7$, $\sigma = 1.1$ hints for the single hearts scenario, $\mu = 1.8$, $\sigma = 1.4$ hints for the multi ECG and $\mu = 2$, $\sigma = 1.3$ hints for the single ECG scenario.

4.3 Impact of the visualizations on the social connectedness

The first ranking in this category refers to the greatest emotional attachment. Multiple hearts (11 votes as rank 1), multiple ECG (6 votes as rank 2), single hearts (6 votes as rank 3), single ECG (8 votes as rank 4), and no visualization (28 votes for rank 5) is the overall order the users chose to best rank their emotional attachment. "*The symbol of a heart triggers more emotions than an ECG line*" or "*If there were more, there was some sense of multiple other players trying something*" are some of the 21 positive answers. The other 7 neutral and 5 negative answers have as reasoning for the ranking that the ECG visualization was highly scientific or that it did not impress them: "*Honestly I didn't feel any emotional attachment to any of them.*" Moreover, "*more hearts, more attachment*" are four defining words for the ranking, given the fact that the first two visualizations are the multi ones.

The next ranking refers to the greatest social connectedness: Multiple hearts (18 votes as rank 1), single hearts (11 votes as rank 2), multiple ECG (8 votes as rank 3), single ECG (15 votes as rank 4) and no visualization (30 votes as rank 5). As last time, the scenario with no visualization is ranked the last, which is a good indicator that the scenarios containing visualizations raised the perceived social connectedness. Apart from 1 neutral and 3 negative responses, 30 answers were positive. "*The visuals made it feel like others were there before*" and "*More people = more social connectedness*" express the main idea of all the answers, more precisely that the multi visualizations made the users feel more socially connected, because more people are involved.

4.4 Likert Scales

We analyzed the Likert questions only using the scenarios containing visualizations. Thus, Figures 4.4, 4.5, 4.6, 4.7 and 4.8 represent some of the questions and their responses. In Figure 4.3, the legend of the 7-point Likert scale is presented. The Wilcoxon signed-rank test was applied to every data frame to find significant differences between the visualizations. In this analysis, η refers to the median of the answers, 1 being "*strongly disagree*", 2 being "*disagree*", 3 being "*somewhat disagree*", 4 being "*neutral*", 5 being "*somewhat agree*", 6 being "*agree*" and 7 being "*strongly agree*".

Figure 4.3: Legend

I felt connected to the other(s) is depicted the first and has $\eta = 2$ for the multi ECG visualization, whereas for all the other three visualizations it is $\eta = 1$. Although the multi ECG visualization has a bigger median value, the analysis did not report any significant difference between the scenarios $(p > .05)$ on how connected the users felt.

I was immersed in the game is the next scale which has $\eta = 6$ across all visualizations. The analysis reported a significant difference between the multi ECG and multi hearts scenarios $(p < .05)$, revealing no other significant difference for the other scenarios $(p > .05)$.

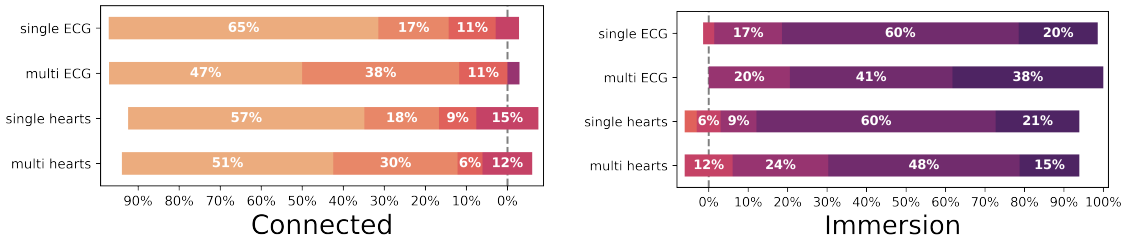


Figure 4.4

I understood what others had done in the VR through the heartbeat visualization has shown different results between the raw and abstract visualizations. The ECG visualizations have each $\eta = 1$, while the single hearts $\eta = 3$ and multi hearts $\eta = 2$ visualizations produced a more pragmatic understanding of what others had done in the escape rooms. Thanks to the lines produced by the heart visualizations, they created paths the player could follow. The analysis reported a significant difference between the single ECG and the single hearts scenarios $(p < .05)$, with no significant difference between the others $(p > .05)$.

I understood how others had felt the VR through the heartbeat visualization. In this case, it is not about the type of used data, but about the amount of data displayed. Both single visualizations have $\eta = 1$, the multi ECG visualization $\eta = 1.5$ and multi hearts $\eta = 2$ being also very close to another. Thus, we can understand that the multiple visualizations were more intelligible than the single ones, although the analysis did not report any significant difference between the scenarios $(p > .05)$.

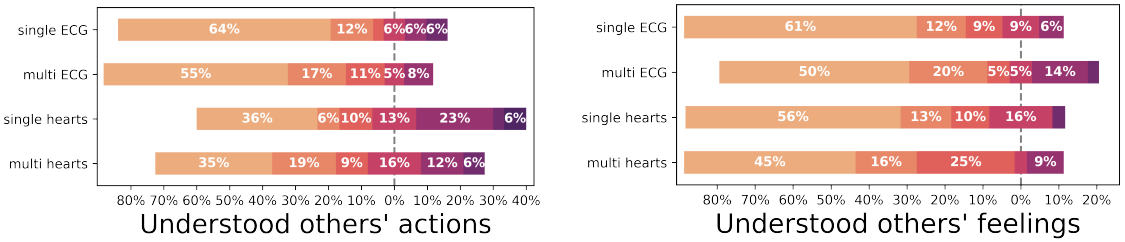


Figure 4.5

The challenges in the game were at the right level of difficulty for me. It is one of the most equal category that were compared, given the fact that all visualizations have $\eta = 6$. It indicates that the level of difficulty was equivalent for all the escape rooms, independent of the visualization. The analysis did not report any significant difference between the scenarios $(p > .05)$.

I liked the look and feel of the game. As seen before for the level of difficulty, the enjoyment level is again the same across all visualizations with $\eta = 6$. It shows that the designed escape rooms were appropriate for the study environment, creating data which is not reflecting the performances in a single escape room, but equally in all of them. The analysis reported a significant difference only between the single ECG and single hearts scenarios $(p < .05)$, with no significant difference between the others $(p > .05)$.

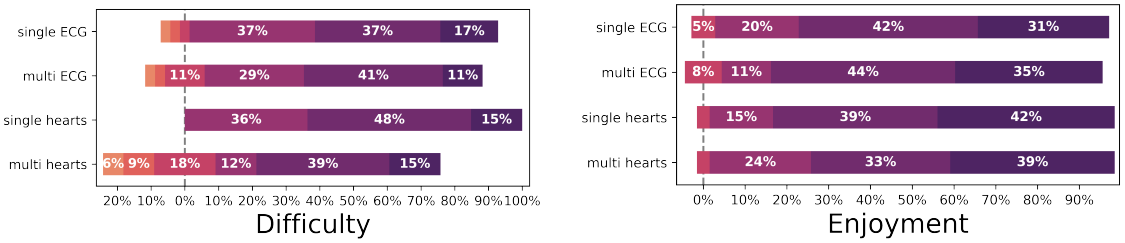


Figure 4.6

The visualization made me feel emotionally attached to other players. For this particular case, no particular rule applies, the multi ECG and single hearts scenarios have $\eta = 2$, whereas the single ECG and multi hearts have $\eta = 1$. Once again, the analysis reported a significant difference only between the single ECG and single hearts scenarios $(p < .05)$, with no significant difference between the others $(p > .05)$.

The visualization distracted me from playing the game. It is a clear difference between the heart and ECG visualizations. Both single and multi hearts visualizations have $\eta = 2$, which is considerably lower than $\eta = 3.5$ for multi ECG or $\eta = 5$ for multi hearts. As mentioned before, the multi visualizations obstructed the view of the player, making it harder to play the game and take decisions. The analysis reported a significant difference between the multi and single visualizations $(p < .05)$, although we did not find any significant difference between the hearts and the ECG visualizations $(p > .05)$.

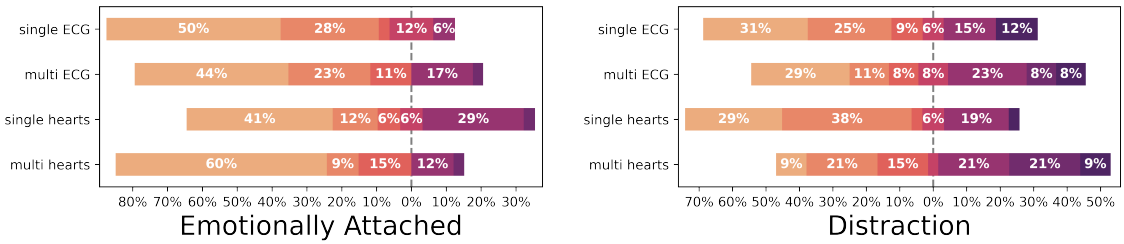


Figure 4.7

I felt like competing with others players. The multi visualizations have $\eta = 2$, whereas the single visualizations have both $\eta = 1$. It indicates that the player felt slightly more competitive, when multiple players played along with them, being replaced by the visualizations. However, the analysis reported no significant difference between the scenarios ($p > .05$).

I felt like collaborating with other players. All scenarios have in this case $\eta = 1$, no variation being observed by any of the visualizations. Furthermore, the analysis reported no significant difference between the scenarios as well ($p > .05$). This only confirms what the participants said in the interviews and is also connected to the sentiment of distraction or annoyance some of the players felt while playing the game.

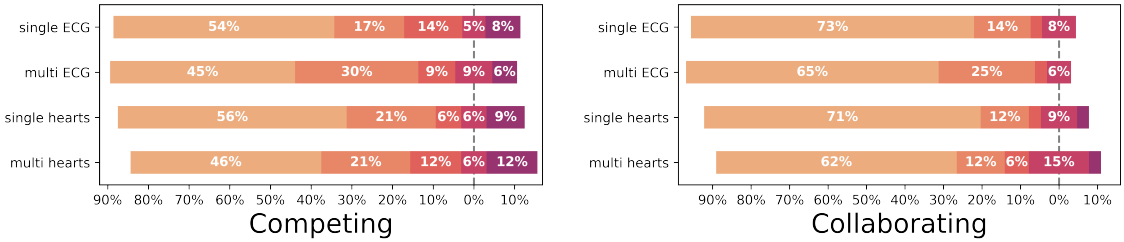


Figure 4.8

Please describe briefly what the size of the heartbeat visualizations meant to you; please also imagine how the effect would change if it had not been there. Regarding this question, the opinions are shared, with negative answers like "*they almost did not influence the way I played*" or with positive answers like "*How active or excited one is at a place*". For some of the participants, the size of the visualization meant "*how fast the heart beats*". A part of the participants complained about the visualization being too big or annoying, although other players thought that the bigger the visualization was, the more important the spot was or the more excited the prior player was.

Please describe briefly what the positioning of the heartbeat visualizations in the VR space meant to you; please also imagine how the effect would change if it had not been there. The answers to this question were very clear for the majority of the participants: "*The position helped me to see if I'm on the right track*". However, some of the participants explained that the positioning had no meaning or that the visualization obstructed the view.

Please describe briefly what the heartbeat pulsation of each visualization meant to you; please also imagine how the effect would change if it didn't pulsate. As some of the players did not notice the pulsation, the majority of them thought that it indicated the excitement or stress level of the previous players: "*How fast the heartbeat is, meaning how excited one maybe was.*"

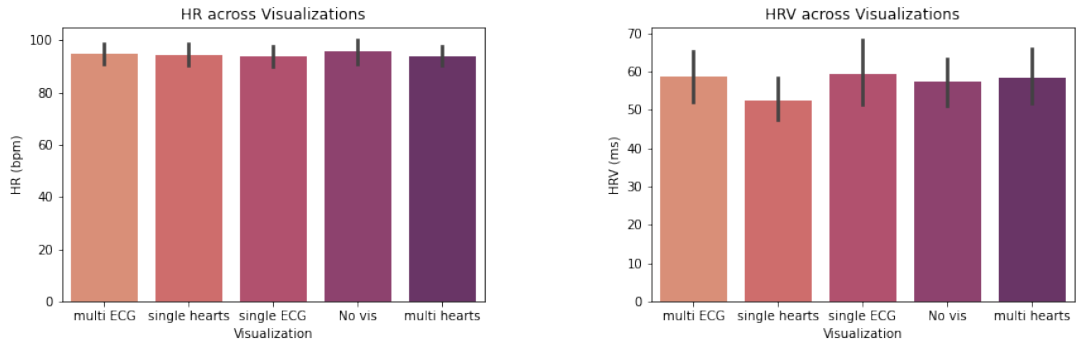
4.5 Heart Data Analysis

The ECG data were analyzed using Python 3.9 paired with Jupyter Notebooks and R version 4.2.1. First, with help of the pandas, numpy and neurokit libraries, all the ECG data were converted into a data frame, which consisted of the participant ID (pid), the room ID (rid), how long it took the

participant to escape (duration), the mean heart rate, the heart rate variability derived from the standard deviation of the normal to normal intervals (SDNN) and the heart rate variability derived from the root mean square of successive differences between normal heartbeats (RMSSD), the respective visualization, the z-score for the HRV SDNN and RMSSD, the excitement level [5] and finally the visualization coded as a number for easier data analysis (see Figure 4.9). Using the seaborn library [32], the plots regarding different aspects of the analysis were generated. Participant 22 was excluded from the analysis due to missing data.

pid	rid	duration	HR_Mean	HRV_SDNN	HRV_RMSSD	Visualization	Z_HRV_SDNN	Z_HRV_RMSSD	Excitement	Vis_Number
5	1	459.335813	82.104528	55.318066	51.995925	Multi ECG	0.077479	0.553133	0.315306	5
5	2	604.517827	84.365938	39.926484	31.193905	Single Hearts	0.621195	0.153613	0.387404	2
5	3	144.303438	79.142781	90.481194	26.800699	Single ECG	0.909201	0.307369	0.608285	4
5	4	252.824139	82.131353	45.315403	27.139527	No Vis	0.455493	0.295863	0.375678	1
5	5	709.969238	82.811168	39.993935	17.226992	Multi Hearts	0.619334	0.596013	0.607673	3
...	...	...	...	...	...	...	...	...	...	...
38	1	430.671171	96.151611	35.852000	32.242554	Single Hearts	0.723111	0.115778	0.419445	2
38	2	348.330625	93.536475	48.994470	20.305860	Multi ECG	0.324702	0.511857	0.418279	5
38	3	639.425117	93.750034	44.566710	26.037395	Single ECG	0.480483	0.333028	0.406756	4
38	4	449.830549	107.781899	41.359469	17.029606	No Vis	0.580458	0.601094	0.590776	1
38	5	367.927702	90.816608	35.627173	16.542933	Multi Hearts	0.728132	0.613458	0.670795	3

Figure 4.9: The pandas data frame table



(a) Heart Rate

(b) Heart Rate Variability

Figure 4.10: The HR and HRV across the visualizations

We ran the Shapiro-Wilk test for the HR ($W = .97, p < .001$) and HRV ($W = .94, p < .001$), both not being normally distributed. As a result, we conducted ART ANOVA which did not reveal any significant difference across the visualizations in HR ($F_{4,152} = 0.15, p = .96, \omega^2 = .02$) nor HRV ($F_{4,152} = 0.48, p = .75, \omega^2 = .012$). Results are depicted in Figure 4.10.

As proposed by Quintero et al. [5], we fitted a linear mixed model (estimated using REML and nloptwrap optimizer) to predict the "*Excite-O-meter*" level, as a measure of excitement level for each visualization. To account for the repeated-measures structure in our study, we added a random intercept for every participant to our model. We then applied an ANOVA to the outcomes of the model. Results showed no significant differences across the visualizations ($F_{1,126} = 0.48, p = .75, \omega^2 = 0.44$). Results are depicted in Figure 4.11.

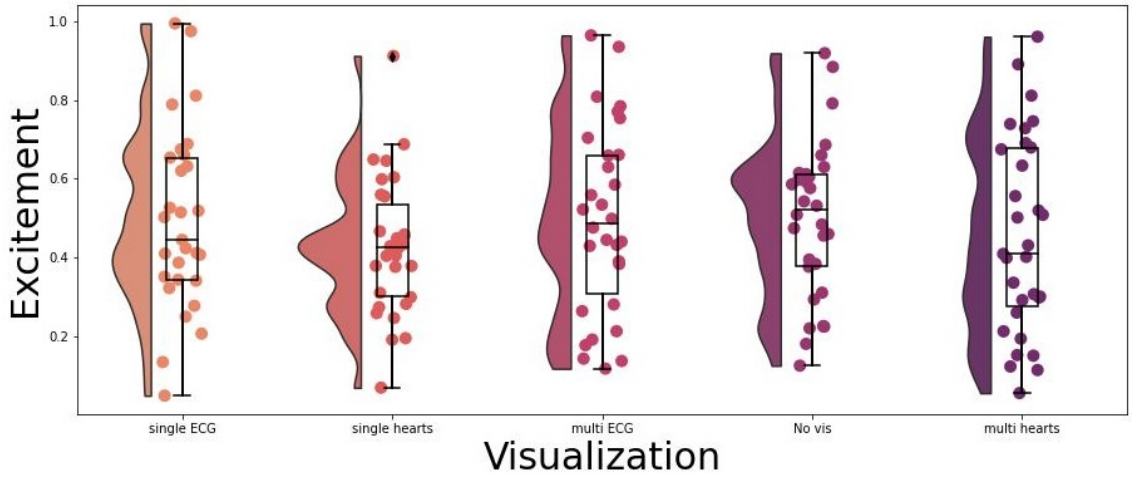


Figure 4.11: The excitement level across the visualizations. The points represent individual data points, and the left entity indicates the data distribution. The extremities of the boxplot indicate the 25^{th} and 75^{th} percentiles, while the center mark illustrates the median.

5 Discussion

We revealed the results of the lab study and the questionnaires regarding the impact of the visualization on the player, the gaming experience, and the social connectedness. In the study, participants had to play 5 different escape rooms, each one paired with a type of visualization: single ECG, multi ECG, single hearts, multi hearts, and no visualization as a baseline to help us comprehend the differences. In this section, we discuss the results regarding social connectedness and the gaming experience, taking into account the weaknesses and limitations of the gaming scenarios. Furthermore, ideas for future work are presented and proposed as an extension to our work and project, but not limited to it.

5.1 Interpretation of the results

A high level of immersion was achieved and the players enjoyed the escape rooms and had overall an overwhelmingly pleasant experience. However, we did not find any significant difference between the rooms, which indicates that they were the proper environment for testing the visualizations. The escape room order was always randomized and we observed a learning curve the more the players experienced the game. Usually, the last escape rooms were solved faster than the first ones, but there were also exceptions. However, we did not find any significant difference in the order the escape rooms were played. Furthermore, we did not find any significant difference between the visualizations on the needed time to escape the game, but the scenario with no visualization had the best timings. Again, the hints did not play a significant role in solving the riddles based on the visualizations, but the players needed fewer hints in the scenario with no visualization as well. Thus, we conclude that most of the time, the visualization distracted the player from the game, thus interfering with the gaming experience. However, the visualizations developed an emotional attachment to the other players, especially the multi visualizations, which were ranked first in this category. Furthermore, the multi visualizations created the greatest social connectedness and awareness between the players, as one of the participants said: "*more hearts, more connectedness*". The scenario with no visualization was ranked the last in the questions regarding social connectedness and emotional attachment. Although no visualization was ranked the most useful, the hearts visualizations were more useful than the ECG ones in playing the game. They indicated better where others went or what they did, creating a heart trace that could be effortlessly followed. Furthermore, the single scenarios were better suited to the escape rooms, because the player's vision was not blocked like in the cases with the multi visualizations. The multi visualizations were also annoying and distracting from the riddles: "*Multiple things flying around were more distracting to me than single ones*". This could be the reason for the multi visualizations being better at social connecting players. Because the player is disturbed and distracted by the density of the visualization, he cannot concentrate on the game itself. Unable to fully experience the game, the player starts wanting to interact and connect with others. The second reason is also that the multi visualizations are denser, which creates the sensation of multiple players being inside the room. Despite that, when it comes to the size of the visualizations, the majority agreed that bigger visualizations distracted the players from playing the game. When the visualizations were smaller, they created a "*sense of connection*", which was "*lost for large icons*". Furthermore, the pulsation of the visualizations indicated an important spot or the "*emotional state*" of the player, how stressed he was at that moment. The positioning of the visualizations was helpful because it guided the players through the escape room and showed them what other players did or where they went. An important place in the escape room was highlighted when multiple visualizations gathered together.

Furthermore, we did not find any significant difference in the excitement level with different visualizations. The same rule applies to the HR and HRV, with no significant difference between the scenarios. Regarding the heart data of the visualizations, some of the players complained about

the ECG visualization being too methodical: "*[the] ECG symbol was too scientific and I didn't understand how to process it consciously*".

Our work partly confirms the hypothesis, that the visualizations had an impact on the perceived social connectedness and the gaming experience of the player. Opinions are divided between the usefulness and the distraction of the visualizations. On one hand, they guided the player, especially the hearts, towards important spots in the escape rooms. They also made the player not only feel more connected to the previous players, but also share experiences with them. On the other hand, the visualizations blocked the player's field of view and were annoying for interrupting the gaming experience. Thus, we recommend using single visualizations in combination with abstract heart data, in our case, the hearts, to create meaningful visualizations. The players had an overall better experience and felt more assistance when these there was only one visualization inside the game instead of four and if that visualization consisted of the heart object.

5.2 Weaknesses and Limitations

The gaming environments were very enjoyable, thus a lot of users tried to ignore the visualizations and focus on the game: "*I wanted to explore on my own so as least as possible distraction would be nice*" and "*I ignored them [the visualizations] and focused on the game*". This yielded a success for the gaming experience, but it was a disadvantage for the study. The players tried to solve the riddles faster instead of trying to connect with prior players or understand their actions or feelings in the room. Escape rooms demand fast paced gaming scenarios and the player does not have the time to waste on a "*possible*" help, the visualization.

The ECG plot is technical and only qualified people can understand it. Players need sentiments and feelings and those can be offered by an abstract heart object, like the hearts used in the visualizations, and not by an ECG plot. It resembles real heart data as well, like the heart visualizations do, but it is not very popular in our society.

The eye tracking is also a limitation of this thesis. It was not a real eye tracker, which could follow eye movements, but it rather deduced the data from the head tracking position and rotation. If we could have had an eye tracking solution, we could have compared other data as well.

5.3 Future Work

This thesis proposes the use of physiological data for enhancing social connectedness for asynchronous VR games. In the future, the following ideas might be taken into consideration and be of interest to further develop social VR:

- Try to create monotonous, more mundane environments for testing. Our work highlights that very entertaining gaming scenarios can have repercussions on social connectedness, as players are more focused on playing the game, than connecting with other players or being present. If the gaming environment would be boring and long, maybe the players would feel the need for social connectedness to escape the loneliness.

- Try to create a multiplayer gaming scenario, where the physiological data is being viewed in real-time. This means that 4 players could play at the same time, in one or multiple rooms, and their heart data is being displayed to others, contributing together to solving the game.

- Stress levels or other physiological data could be measured and compared based on different scenarios. Some of the scenarios could be stress amplifiers, whereas others could be relaxing environments. It could be tested if the visualization or the environment has the right impact on the player.

- Try to focus more on the abstract heart data visualizations, as the ECG was too scientific to be understood by normal players. The heart icon is a well-known symbol in our societies, even though it has no connection to anatomy or the physiology of the human body.

6 Conclusion

This thesis is one of the first to address the topic of using physiological data to increase social connectedness and social presence in a single-player VR game. After a lab study, we can affirm that the heart data of asynchronous players have a positive effect on the player regarding social connectedness and emotional attachment. We tested 5 types of scenarios, 4 of them containing data either from one (single) or four (multi) players and being represented either in an abstract (hearts) or raw (ECG) manner. The 5^{th} scenario did not contain any visualization and was used as a baseline for comparison with the scenarios containing visualizations. The multi visualization scenarios had an overall better impact on social presence and connectedness, although they blocked the player's vision and negatively altered the gaming experience. No significant rule applied to the time needed to solve the escape rooms or the hints used inside the game, but the escape room scenarios with no visualizations were escaped the fastest. Furthermore, the majority of the players solved the escape rooms faster than the proposed time limit of 10 minutes, and sometimes even without any hints at all. Again, the least amount of hints needed to solve the escape rooms are represented by the scenario with no visualization. Thus, we concluded that the visualizations interrupted the gaming experience, making the players need longer to escape, but encouraging them to socially connect. Additionally, the players felt the most socially connected in the multi visualization scenarios and then in the single scenarios, which endorses the earlier statements. We noticed that the heart rate or the heart rate variability did not significantly change depending on the scenario, nor did the excitement level of the players. The multi visualizations drew players' attention more than the single visualizations, being watched 4 times (ECG) and 12 times (hearts) longer. This thesis approached the use of physiological data in single-player VR games, although it can be used in a range of other VR scenarios. The outcomes could impact multiple fields of study. Further research regarding VR games and physiological data is encouraged, given the limitations of this thesis. Multiplayer gaming scenarios, measuring different heart data or creating uninteresting gaming environments are a few examples of future work which could have its foundation or starting point this thesis.

7 Appendix

7.1 Escape Room Riddles explained

7.1.1 Escape Room 1

The first escape room has three riddles. To begin with, the player needs to open the fridge and find the black bottle, which should be broken. It is one of the few objects that have gravity enabled and the reasoning for it is that some players would not smash it into the floor to break it. Some of them would leave the bottle floating in the air (the player assumes that it has no gravity as well), so it would fall on the floor and break, revealing a note. The message on the note is "*Find the electricity box*", which guides the user to the electricity box in the corner of the room. Now the door of the electricity box is interactable and can be opened (it was not interactable before, being unlocked by finding the first clue - the note. If it would not have been blocked before, the player could have opened it without needing to find the note, which is not intended). By opening the electricity box's door, the player can find four non-interactable switches and a remote control, which can and should be used to control the blue monitors towards the exterior of the space station. While the remote control is pointing towards one monitor and is held in the hand, the monitor screen changes its color if the player presses button 2 (see Figure 3.10), button 7 being normally used for grab interactions. The right color combination on the 3 monitors needs to be obtained and it is available on the back of the poster that is hanging on the wall. This unlocks the next riddle, which consists of four random numbers appearing on the four side televisions. The numbers are indicators for the safe combination, which is sitting right below the televisions. After introducing the right number in the lock, a beep sound is indicating that it is correct. When the four numbers are correctly introduced, the safe door opens and reveals three objects, including the key to exit the escape room. To open the door, the player should hold the key in his hand and be within a certain range of the door. Afterwards, the player is greeted with a congratulatory message.

7.1.2 Escape Room 2

The second escape room has three riddles as well. At the beginning, the player needs to find a note under the chair. The message on the note is "*Remember to turn on the electricity*" and it has 2 icons referring to the electricity box, indicating to turn on the first and the last switch. Thus, the computer terminal turns on and the first riddle is complete. A darts board appears on the computer screen. Two hints hidden behind the poster and the computer terminal indicate to look in the fridge, where 2 of the 3 darts points are. The 3rd darts point is placed behind the middle monitor. After they are thrown towards the darts board, a score indicates how many have been thrown correctly. After all of them are thrown, the metal box on the safe opens and reveals a revolver, ending the second riddle. After this, UFO space ships appear and rotate around the space station. They should be shot with the revolver. When all of them are eliminated, the key appears in the middle of the room and when the player approaches the exit door, it opens and a congratulatory message is revealed.

7.1.3 Escape Room 3

The third escape room has again three riddles. First, the player needs to find all the pineapples. They have the numbers 2, 3 and 5 written on their backs. The door of the safe also has a pineapple decal on it, indicating that it is related to the pineapples. A rule is written on the door of the safe, explaining what to do with the numbers on the pineapples. The first number introduced should be the number of pineapples, 3, and the second number is the sum on the backs of the pineapples, 10. After the correct numbers are introduced, the safe opens and reveals multiple objects including an USB stick. The computer screen contains the text "*Run the scripts*" and the USB stick should be plugged in the side of the computer. The screen updates with a new message: "The fires are put

out. We can clean up now." It indicates that the fire extinguisher should be put back in place. The right spot are the cables near the fridge, which have some little red spots on them. When the player approaches that part of the cables with the fire extinguisher in hand, the fire extinguisher snaps into place and starts rotating, changing its normal material to a pizza material. This indicates that the player should take a closer look at the pizza. Without the player knowing, a note was spawned between the pizza and the plate it was on. When the player moves the pizza slice, he finds the note with the message "- *1 0 1 1* -", indicating an encoded message. It refers to the switches of the electricity box. The first, third and fourth should be up, whereas the second should be down. When this happens, the exit door automatically opens and the player sees a congratulatory message.

7.1.4 Escape Room 4

The fourth escape room contains three riddles. At the beginning, half of the golden key is visible on the computer screen, indicating the computer has a role in this escape room. When the player finds the card sitting on the chair, he should introduce it in the computer. Afterwards, the player needs to play a reaction time game. When the computer screen turns green, he should press on a button of the controller as fast as he can. There are 3 turns and for each one, the player has to have a reaction time smaller than 0,5 seconds. After the game is solved, a small gray key is coming out of the computer screen. The player can take it and introduce it in the metal box. It opens and it reveals a note. It contains an image with the screens of the three monitors towards the margin of the escape room. Together with the note, a black button is spawned at the base of each monitor. After the player presses each one of the buttons, some words are revealed on the monitors, forming the message "*go to door*". At this moment, a big black button is spawned right next to the door and the player should press it to open the exit door. In that moment, a congratulatory message greets the player.

7.1.5 Escape Room 5

The fifth and last escape room has three riddles as well. This time, a chess board is placed on the safe and it misses 3 pieces. They are hidden in the room and the player has to find them and place them back on the board. When this happens, a note under the chess is revealed containing the Leo star sign. The player has to look towards the sky and recognize the stars forming the star sign. The star sign has a beaming light on the fridge, illustrating its importance in the riddle. The player needs to find an object that is/was in the fridge, because it contains valuable information in solving the escape room, namely the yellow soda can. The text on it is "*I open at the close...*" and has a lightning sign on it which can be found on the electricity box as well as near the the exit door. If the player approaches the soda can close enough to the lightning picture near the exit door, it snaps near the lightning and starts spinning and transforming into the exit golden key. When it stops spinning, the player can take the key and the door opens automatically and a congratulatory message is revealed.

7.2 Hints

7.2.1 Escape Room 1

Hint 1: Look deep into the bottle.
Hint 2: Take the whiskey bottle in the fridge and smash it on the ground. You will find a note. Open the electricity box left to fridge on the wall. (Solution to Hint 1)
Hint 3: The TV... maybe the remote and the other thing can help...
Hint 4: Press on the touchpad button while aiming towards the TVs to change their color. The right color combination is on the back of the poster: Green Red Blue (Solution to Hint 3)
Hint 5: The numbers are safe.

Hint 6: Insert the numbers on the screens in the safe. There you find the key to exit! (Solution to Hint 5)

7.2.2 Escape Room 2

Hint 1: Pull me aside!
Hint 2: Pull away the chair and read the note positioned under it. Turn on the first and the last switch from the electricity box attached to the wall next to the fridge. (Solution to Hint 1)
Hint 3: You have to find 3 of me to aim!
Hint 4: You have to find 3 darts. Two are in the fridge, one is behind the middle blue TV. Throw them at the dartboard now! (Solution to Hint 3)
Hint 5: The aliens are coming. Shoot them!
Hint 6: There is a box on top of the safe, which just opened. It contains a revolver. Use it to shoot the aliens that fly around you. This will give you the key to exit! (Solution to Hint 5)

7.2.3 Escape Room 3

Hint 1: We always ate so much pineapple. Maybe we should count how many we have left.
Hint 2: Unlock the safe with the numbers: first, total number of pineapples = 3, the second number is the sum of the numbers on the back of the pineapples = 10. (Solution to Hint 1)
Hint 3: Where to plug in the USB?
Hint 4: Take the USB from the safe. You need to plug in the USB into the right part of the Computer, where the 3 ports are located. It is enough to hold the USB close to it. (Solution to Hint 3)
Hint 5: Is there a place for the fire extinguisher?
Hint 6: Put the fire extinguisher on the red part of the cables right of the fridge. Find the note under the pizza and change the state of the switches of the electricity box (left from the fridge attached to the wall) according to the note: Up Down Up Up (Solution to Hint 5)

7.2.4 Escape Room 4

Hint 1: That looks like I need to swipe my card.
Hint 2: You can find a card on the chair. Swipe it on the computer and play the reaction time game. You need to push the controller fast enough 3x. (Solution to Hint 1)
Hint 3: So much fake news on those TVs...
Hint 4: Take the key out of the computer, open the box on the safe, and look at the note. Push the black buttons placed on the bottom of the TV frames. (Solution to Hint 3)
Hint 5: Push the buttons
Hint 6: The buttons on the TV frames need to be pushed. After this, a button near the exit door will appear. Press this one as well. (Solution to Hint 5)

7.2.5 Escape Room 5

Hint 1: What's that!? There are 3 chess pieces missing!
Hint 2: You can find the 1st chess piece on the computer, the 2nd piece in the fridge and the 3rd piece in the electricity box. Place them back on the chess board. This opens a hidden compartment. (Solution to Hint 1)
Hint 3: It's written in the stars tonight.
Hint 4: Look towards the stars and find the sign indicated on the card. You can find the Leo star sign that points you towards the fridge, more exactly to an object that is/was in the fridge: the yellow vitamin juice can! (Solution to Hint 3)
Hint 5: I've seen that lightning before...

Hint 6: Did you see the lightning on the vitamin juice can? There is another one to the left of the door. Place the vitamin juice there to enable the exit! (Solution to Hint 5)

7.3 Sources of the Assets used in Unity

Walls, Floor, Monitors, TVs, Safe, Switch Box, Fridge, Cables, Exit Door, Fire Extinguisher, Chair, Poster: [26]

Chess board and pieces: https://sketchfab.com/3d-models/chess-board-pieces-829e0fc85ec244eaa3d86310f6ef0150

Pizza:https://open3dmodel.com/3d-models/pepperoni-pizza$_4$77512.*html*

Soda Can: https://free3d.com/3d-model/soda-can-v3–253775.html

Sandwich: https://free3d.com/3d-model/reuben-sandwich-on-plate-v2–546020.html

Darts Board: https://www.turbosquid.com/de/3d-models/free-obj-model-dart/393892

Darts Point: https://www.turbosquid.com/de/3d-models/free-obj-model-dart/393892

Pineapple: https://free3d.com/3d-model/pineapple-v1–245845.html

Remote Control: https://www.turbosquid.com/de/3d-models/free-samsung-tv-remote-control-3d-model/604040

Golden Key: https://www.turbosquid.com/de/3d-models/free-old-key-3d-model/716567

Grey Key: https://www.turbosquid.com/de/3d-models/key-keyholder-max-free/246564

USB: https://www.turbosquid.com/de/3d-models/free-obj-mode-usb-flash-drive/678221

Computer Terminal: https://free3d.com/3d-model/sci-fi-computer-terminal-starlink-s101–751079.html

Leo Star Sign: Removed from Internet

Heart Texture: https://gpway.itch.io/2d-hearts

Earth: https://www.turbosquid.com/de/3d-models/earth-max-free/1016431

Apple: https://www.cgtrader.com/free-3d-print-models/art/scans-replicas/red-apple–3

UFO: https://www.turbosquid.com/de/3d-models/free-3ds-model-flying-saucer/1081073

Revolver: https://free3d.com/3d-model/nagan-ww1-revolver-903287.html

Gray Box: https://www.turbosquid.com/de/3d-models/3d-old-metal-box-games-model-1508804

Lock: https://www.turbosquid.com/de/3d-models/golden-padlock-lock-3d-model-1350782

Papyrus: https://free3d.com/3d-model/pirate-treasure-map-scroll-v1–897332.html

Ramen bowl: https://www.turbosquid.com/de/3d-models/3d-ramen-model-1897804

Whiskey botte: https://devassets.com/assets/western-props-pack/

Transparent bottle: https://www.turbosquid.com/de/3d-models/free-water-bottle-3d-model/751609

Warning symbol: https://vectorportal.com/vector/danger-electricity-vector-sign.ai/9187

Futuristic Vehicle: Removed from Internet

7.4 Questionnaires

7.4.1 Questionnaire after each escape room

1. Please enter the participant ID:
2. Please enter the visualization type:
3. Please enter the scene number:

The following questions had answers on the Likert-scale from 1 to 7:

4. Please rate your sense of being in there at the virtual space station on the scale from 1: not at all to 7: very much, where 7 represents your normal experience of being in a place.
5. To what extent were there times during the experience when the virtual space station became the 'reality' for you, and you almost forgot about the "real world" of the laboratory in which the

whole experience was really taking place? (1: at no time ... 7: almost all the time.)
6. When you think back on your experience, do you think of the virtual space station more as images that you saw or more as somewhere that you visited? Please answer from 1: images that I saw to 7: somewhere that I visited.
7. Consider your memory of being at the virtual space station. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been to today? By 'structure of the memory' consider things like the extent to which you have a visual memory of the station, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements. (from 1: not at all to 7: very much so.)
8. During the time of the experience, which was strongest, on the whole, your sense of being in the virtual field, or of being in the real world of the laboratory? From 1: the real world of the laboratory to 7: the virtual reality of the space station.
9. During the time of the experience, did you often think to yourself that you were actually just standing in an office wearing a helmet or did the virtual space station overwhelm you? From 1: most of the time I realised I was in the lab to 7: never because the virtual space station overwhelmed me.
10. Please rate your connection to other players based on your latest gaming experience:

- I empathized with the other(s).
- My actions depended on the other(s) actions.
- The other's actions were dependent on my actions.
- I felt connected to the other(s).

11. Please rate the effect of other players' influences based on your latest gaming experience:

- I felt like competing with others players.
- I felt like collaborating with other players.
- I felt like being motivated through other players.
- I felt like being demotivated through other players.

12. Please select which of the pictures below best describes your relationship with other players considering your latest gaming experience.
13. Please rate the heartbeat visualization in your latest game experience according to the following statements:

- The visualization distracted me from playing the game.
- The visualization supported me in playing the game.
- The visualization made me feel emotionally detached to other players.
- The visualization made me feel emotionally attached to other players.

14. Please describe why you rated the visualization as you did above. (free text)
15. Please rate the heartbeat visualization in your latest game experience according to the following statements:

- I got confused about how others had felt in the VR through the heartbeat visualization.
- I understood how others had felt the VR through the heartbeat visualization.

- I got confused about what others had done in the VR through the heartbeat visualization.
- I understood what others had done in the VR through the heartbeat visualization.

16. Please describe why you rated the visualization's effect as you did above: (free text)
17. Please rate the meaning of your latest game experience:
    - Playing the game was meaningful to me.
    - The game felt relevant to me.
    - Playing this game was valuable to me.
18. Please rate your latest game experience according to:
    - I felt capable while playing the game.
    - I felt I was good at playing this game.
    - I felt a sense of mastery playing this game.
19. Please rate your latest game experience according to the level of immersion:
    - I was no longer aware of my surroundings while I was playing.
    - I was immersed in the game.
    - I was fully focused on the game.
20. Please rate the level of autonomy in your latest game experience:
    - I felt a sense of freedom about how I wanted to play this game.
    - I felt free to play the game in my own way.
    - I felt like I had choices regarding how I wanted to play this game.
21. Please rate your level of curiosity in the latest game experience:
    - I felt eager to discover how the game continued.
    - I wanted to explore how the game evolved.
    - I wanted to find out how the game progressed.
22. Please rate the ease of control in your latest game experience:
    - I thought the game was easy to control.
    - The actions to control the game were clear to me.
    - It was easy to know how to perform actions in the game.
23. Please rate the challenge level of your latest game experience:
    - The game was challenging but not too challenging.
    - The game was not too easy and not too hard to play.
    - The challenges in the game were at the right level of difficulty for me.
24. Please rate the level of feedback in your latest game experience:

- The game gave clear feedback on my progress towards the goals.
- I could easily assess how I was performing in the game.
- The game informed me of my progress in the game.

25. Please rate the appeal of your latest game experience:

- I enjoyed the way the game was styled.
- I liked the look and feel of the game.
- I appreciated the aesthetics of the game.

26. Please rate your latest game experience:

- The goals of the game were clear to me.
- I grasped the overall goal of the game.
- I understood the objectives of the game.

7.4.2 Demographic questionnaire

1. Please enter the participant ID:
2. What gender do you most identify with?
3. Please enter the year that you are born in:
4. What is your highest educational degree?
5. How many times have you had a virtual 3D experience before your participation today?
6. How many times have you had an experience with VR before your participation today?
7. How often have you played an escape room or a similar game before?

7.4.3 Questionnaire regarding the visualizations

The following questions the participants were asked to rank the visualizations (see Figure 7.1) and explain their choice in free text.

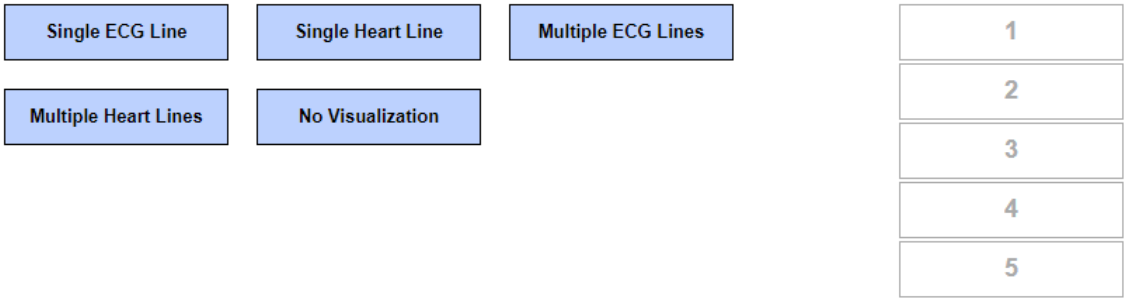


Figure 7.1: The ranking of the visualizations. 1 is the best, 5 is the worst

8. Please describe briefly what the size of the heartbeat visualizations meant to you; please also imagine how the effect would change if it had not been there.
9. Please describe briefly what the positioning of the heartbeat visualizations in the VR space meant to you; please also imagine how the effect would change if it had not been there.
10. Please describe briefly what the heartbeat pulsation of each visualization meant to you; please also imagine how the effect would change if it didn't pulsate.

11. Please rank the visualization regarding how *useful* you found them for solving the riddles.
12. Please explain briefly why you ranked the visualizations as you did.
13. Please rank the visualization regarding to which triggered the *greatest emotional attachment* to other players.
14. Please explain briefly why you ranked the visualizations as you did.
15. Please rank the visualization regarding to which triggered the *greatest social connectedness* to other players.
16. Please explain briefly why you ranked the visualizations as you did.
17. Please rank the visualization regarding which *distracted* you most of solving the riddles.
18. Please explain briefly why you ranked the visualizations as you did.
19. Please rank the visualization regarding which *annoyed* you most.
20. Please explain briefly why you ranked the visualizations as you did.

7.5 Screenshots of the Escape Rooms

Figure 7.2: Screenshots of the escape rooms - single hearts visualization

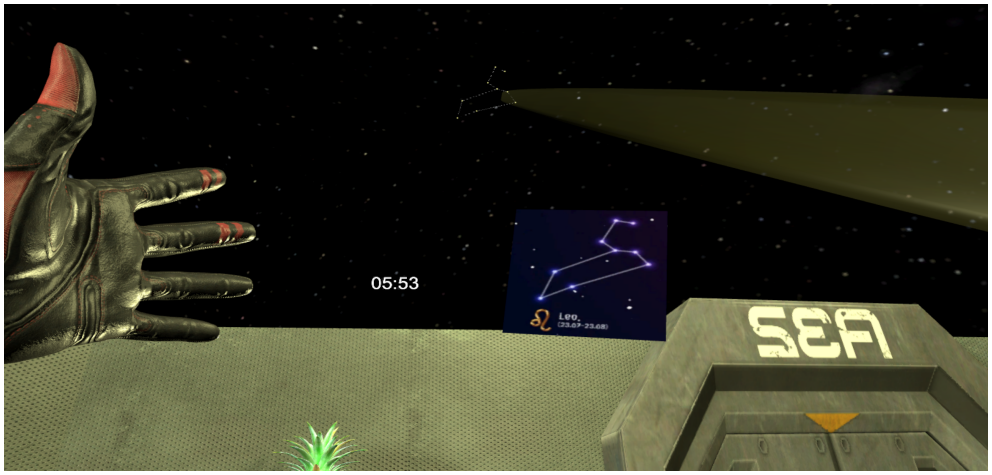


Figure 7.3: Screenshots of the escape rooms - solving the 2nd riddle of the 5th escape room

Figure 7.4: Screenshots of the escape rooms - single hearts visualization

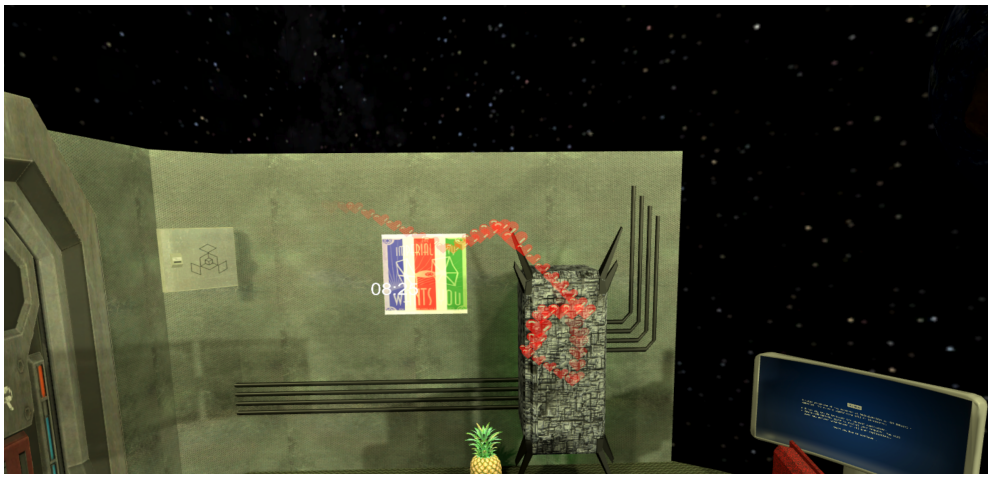


Figure 7.5: Screenshots of the escape rooms - single hearts visualization

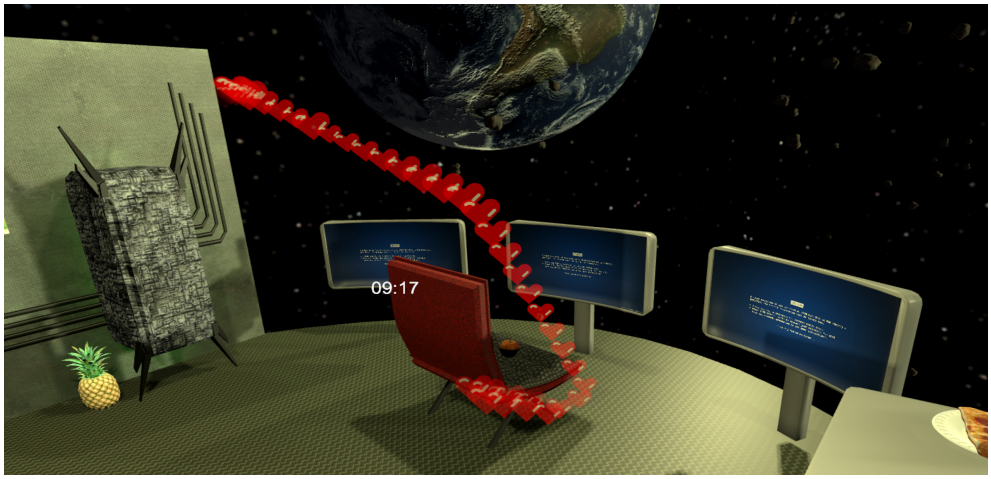


Figure 7.6: Screenshots of the escape rooms - single hearts visualization

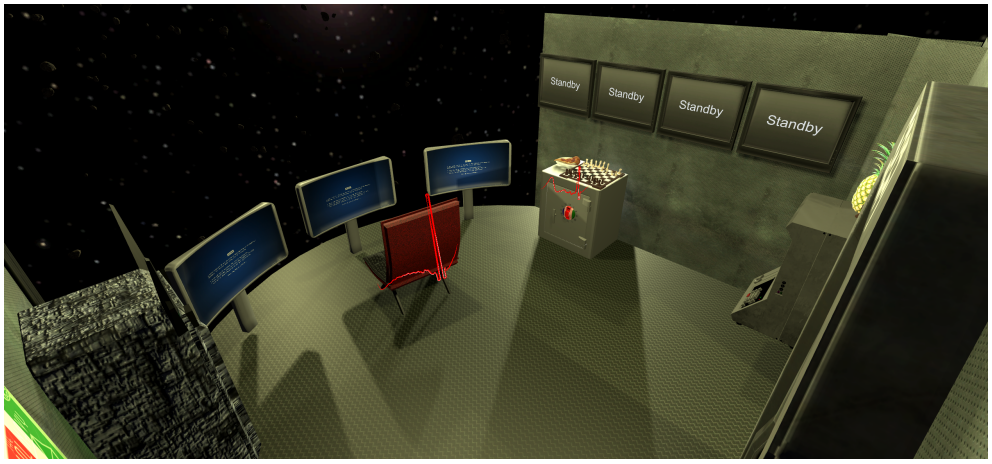


Figure 7.7: Screenshots of the escape rooms - multi ECG visualization

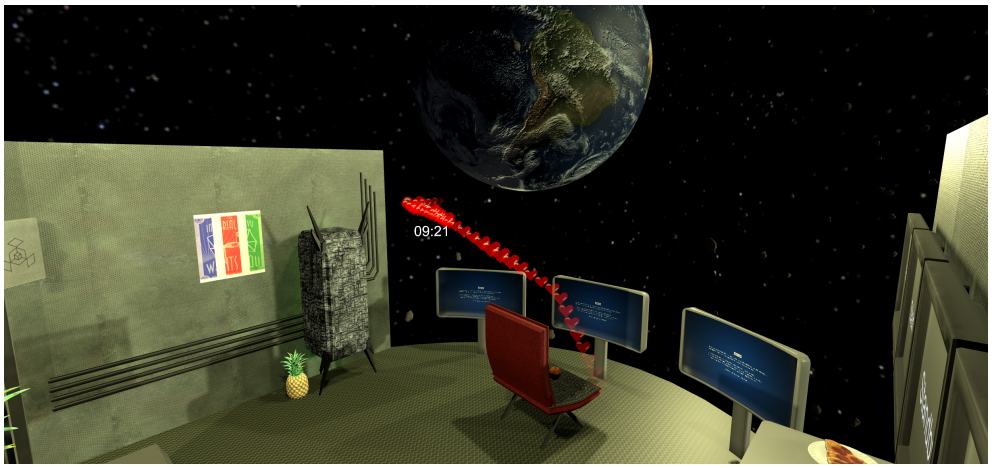


Figure 7.8: Screenshots of the escape rooms - single hearts visualization

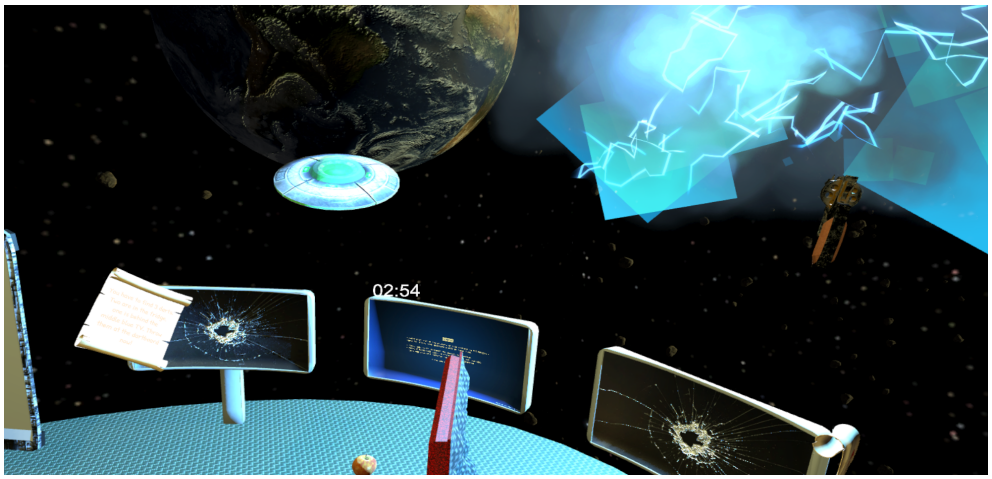


Figure 7.9: Screenshots of the escape rooms - shooting UFO space ships with the revolver

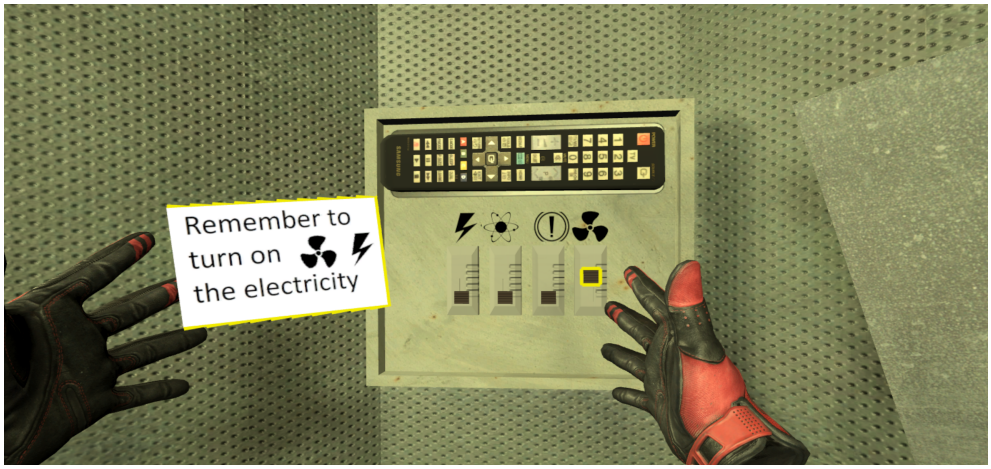


Figure 7.10: Screenshots of the escape rooms - solving the 1st riddle of the 2nd escape room

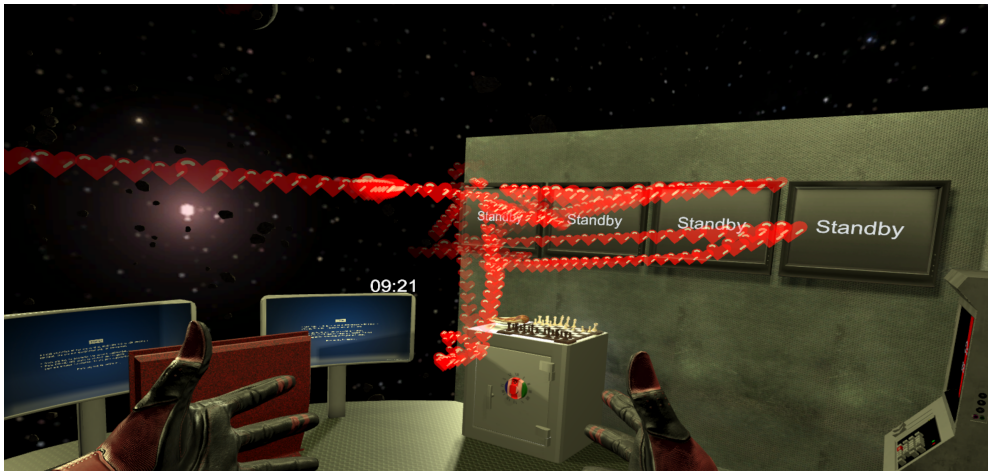


Figure 7.11: Screenshots of the escape rooms - multi hearts visualization

Figure 7.12: Screenshots of the escape rooms - multi ECG visualization

Figure 7.13: Screenshots of the escape rooms - multi ECG visualization

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