applied system innovation

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Investigating Stress During a Virtual Reality Game Through Fractal and Multifractal Analysis of Heart Rate Variability

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Abstract: This article presents the process of creating a virtual reality (VR) game designed to assess the impact of stress on heart rate variability (HRV). The game features dynamic and challenging scenarios to induce stress responses, incorporating advanced 3D modelling and 3D animation techniques. A study involving 20 volunteers was conducted, with electrocardiographic (ECG) data collected before and during game play. HRV analysis focused on fractal and multifractal characteristics, utilizing detrended fluctuation analysis (DFA) and multifractal detrended fluctuation analysis (MFDFA) methods. DFA results revealed decreased values of α_1, α_2, and α_{all}, indicating alterations in short-term and long-term correlations under stress. MFDFA further analyzed changes in fluctuation function Fq(s), generalized Hurst exponent Hq, multifractal scaling exponent $\tau(q)$, and multifractal spectrum $f(\alpha)$, showing significant differences in these parameters under stress. These findings validate the game's effectiveness in simulating stress and its impact on HRV. The present study not only demonstrates the relationship between stress and the fractal characteristics of HRV but also offers a new foundation for future applications in psychology, physiology, and the development of VR technologies for stress management.

Keywords: virtual reality (VR); virtual reality game; heart rate variability (HRV); stress; detrended fluctuation analysis (DFA); multifractal detrended fluctuation analysis (MFDFA)

Academic Editor: Christos Douligeris

Received: 25 November 2024
Revised: 13 January 2025
Accepted: 17 January 2025
Published: 21 January 2025

Citation: Lebamovski, P.; Gospodinova, E. Investigating Stress During a Virtual Reality Game Through Fractal and Multifractal Analysis of Heart Rate Variability. *Appl. Syst. Innov.* **2025**, *8*, 16. https://doi.org/10.3390/asi8010016

1. Introduction

Virtual reality (VR) and 3D games are technologies that can provide users with unique experiences, immersing them in three-dimensional worlds that can look almost like reality [1,2]. Although video games are often associated with negative effects on the psyche, there is research showing that 3D games can have positive effects on mental health, including reducing stress and increasing cognitive function. Some of these games offer opportunities for emotional release or provide soothing and relaxing experiences [3–5]. The authors of [6–8] show that immersive virtual environments can help with relaxation, meditation, and anxiety reduction. These applications are often used in stress management programmes, in the treatment of post-traumatic stress, and even in the rehabilitation of patients with chronic diseases [9,10]. Games developed in special VR environments can help players deal with anxiety by immersing them in relaxing or creative worlds. In addition, there are games that help control stress by practising breathing techniques or meditation [11,12]. Although VR and 3D games offer many benefits related to entertainment, learning, and therapy [13], there are also potential risks related to the impact of negative stress on the mental and physiological state of the human body [14,15]. Examining these risks is essential to understand the impact that these technologies have on human health.

One key aspect that deserves attention is how the VR environment, specifically in 3D games, can affect players' stress levels. Currently, there is no accepted standard for stress assessment [16–18] as it includes psychological, physiological, and emotional aspects. However, heart rate variability (HRV) is a biomarker that can be used as a method to assess the physiological response to stress. This approach is innovative in assessing autonomic nervous system responses, measuring fluctuations in the intervals between successive heartbeats, and reflecting the balance between the sympathetic and parasympathetic nervous systems [19,20]. The sympathetic system is associated with the "fight or flight" responses activated in stressful situations, while the parasympathetic system controls rest and recovery functions. During stressful situations, sympathetic activity increases, leading to an increase in heart rate and a decrease in HRV. Conversely, during relaxation and recovery, the parasympathetic system dominates, resulting in higher heart rate variability [21,22]. Therefore, valuable information about the body's psychophysiological responses, including levels of stress and mental strain, can be obtained through the analysis of HRV. Low HRV is often associated with chronic stress, fatigue, and risk of cardiovascular disease, while high HRV is a sign of good health and the body's adaptability to external stressors. This makes HRV a key tool for studying stress under various conditions, including intense situations such as those created by virtual realities and games [23,24]. Changes in HRV can reflect the impact of various external factors on the body, such as physical and mental exertion, stress and arousal. HRV analysis provides information on cardiac dynamics and nervous system regulation, making it a useful method for investigating stress during VR gaming. It allows researchers to observe in real time the physiological changes induced by these situations, providing valuable information about stress levels and the body's adaptability.

The research results in references [25–27] show that the heart rate increases significantly and HRV decreases when participants are subjected to gaming-induced stress. The study of HRV during VR gaming enables a better understanding of the interplay between emotions, the nervous system, and the gaming experience of gamers. This opens up new perspectives for the development of personalized training and relaxation programmes, as well as for the optimization of game environments. The research into the impact of VR and 3D gaming on stress is in its infancy, but initial results show that stress has an impact on the cardiovascular system.

One of the modern methods for the analysis of complex dynamic systems, such as the cardiovascular system, is fractal and multifractal analysis, which provides additional information about the nonlinear and chaotic characteristics of ECG signals [28]. Heart rate is not regulated linearly; instead, it has complex dynamics that change depending on the state of the organism and the influence of external factors (stress) that can cause physical or mental strain [29,30]. Fractal analysis is used to detect self-similar structures in the heart rate signal, allowing the recognition of specific patterns of behaviour at different time scales. It reveals how small changes over a single time interval in HRV can have a similar structure to larger intervals, which is an indicator of a healthy and well-functioning system [31,32]. Multifractal analysis extends the capabilities of fractal analysis by allowing the detection of more complex and diverse structural features of the signal. It measures multiple fractal dimensions that describe the different levels of variability in HRV [33]. This methodology is particularly useful in identifying more detailed and complex dynamics that would go unnoticed using traditional linear analysis. The use of fractal and multifractal analysis methods in the study of stress during virtual realities is a tool for detecting changes in the autonomic nervous system and, more precisely, measuring the body's response to stressful situations, such as are often created in virtual reality games [34–36].

This paper is an extension of the work originally presented in [37]. The aim of this paper is to study the influence of mental stress generated by a VR game on the HRV. To reach this aim, the following tasks have been defined:

- Presentation of the process of creating a VR game, which includes 3D modelling (polygon modelling, Bezier curves, texture, and material), 3D animation (spline and linear interpolators, translational and rotational motion, and morphing) and the mathematical apparatus (linear algebra, trigonometry, and geometry) used;
- Study of the stress reactions generated during the game by the participants by applying the following methods of fractal and multifractal analysis: detrended fluctuation analysis (DFA) and multifractal detrended fluctuation analysis (MFDFA);
- Statistical analysis of the studied parameters before and during the game by applying the *t*-test to assess the significance of the observed differences.

2. Materials and Methods

2.1. Process of Creating a Virtual Reality Game

The process of creating a virtual reality game involves modelling 3D objects, animation, and the mathematical apparatus used in the modelling and animation. Figure 1 shows a block diagram of the main components of the game.

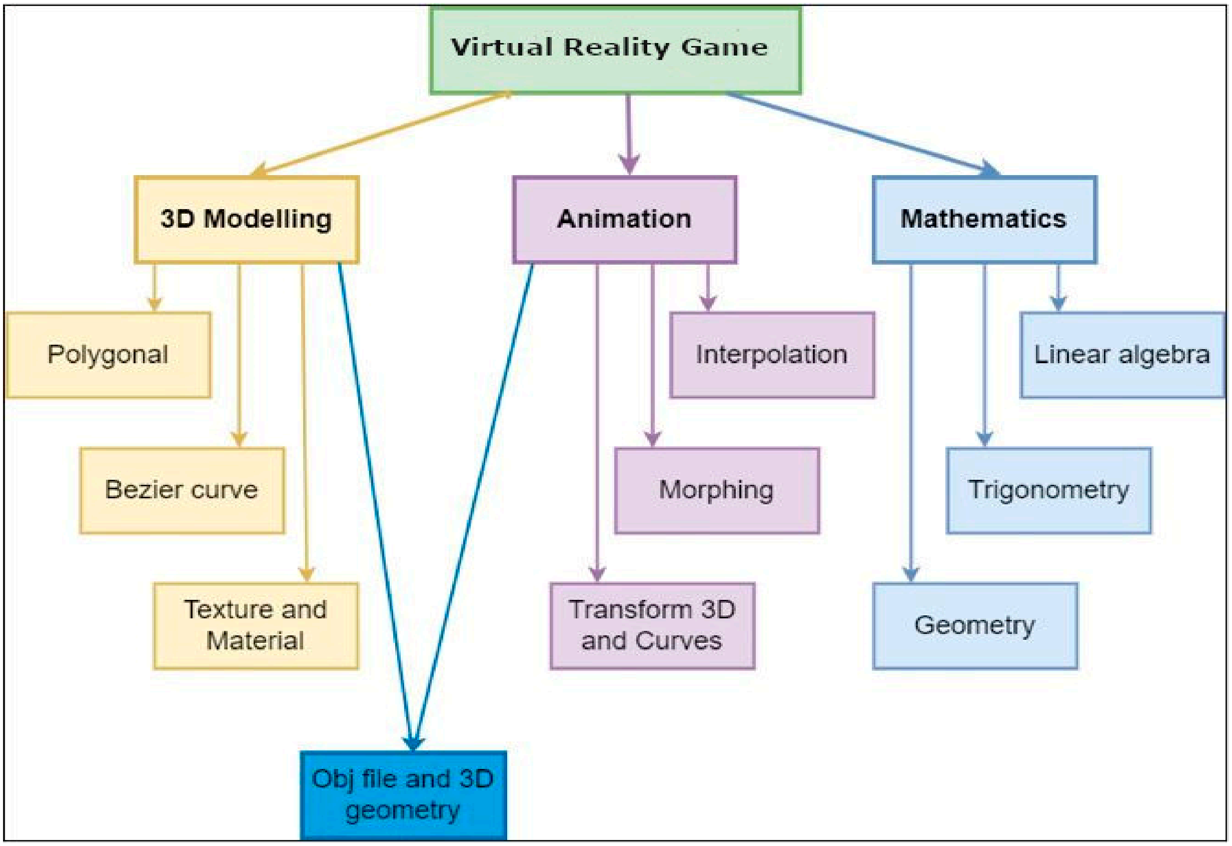

Figure 1. Block diagram of the main components of the VR game.

2.1.1. Three-Dimensional Modelling Techniques

Modelling 3D objects is a key stage in creating the game's visual content as it provides the basis for building realistic worlds that immerse players in a unique atmosphere. Some basic techniques include polygonal modelling, Bezier curves, texturing and material setting.

Polygonal modelling [38]—This technique is based on building objects by connecting vertices that form polygons, usually triangles or quadrilaterals. Polygons are formed by edges connecting the vertices that define the faces of the objects. A major advantage of this technique is the precise control over shape, making it suitable for complex patterns. A major disadvantage is that achieving high detail requires a large number of polygons, which can burden the system.

Modelling with Bezier curves (Java 3D, ver. 1.6.0) [39,40] can be used to create 2D and 3D objects. The main components of the curves are control points, degree of the curve, and weights. Control points define the shape of the curve or surface. These points usually do not belong to the curve itself, but their number affects its complexity. The degree of the curve determines the number of control points that affect the shape of the curve. The most commonly used degrees are 1 for a linear, 2 for a quadratic, and 3 for a cubic curve. Weights are applied to the control points to determine their influence on the shape of the curve. By changing the weights, the object can be adapted to achieve different visual effects, such as curves and bulges.

A Bezier curve of degree n defined by control points P_0, P_1, ..., P_n, as such, the following formula can represent:

$$C(t) = \sum_{i=0}^{n} B_{n,i}(t)P_i \tag{1}$$

where C(t) is Bezier equation and represents the position of a point on the curve for a given value of the parameter t, where $t \in [0, 1]$. This formula allows each point on the curve to be calculated as a linear combination of control points P_i, each weighted according to the Bernstein polynomial $B_{n,i}(t)$. The Bernstein polynomials Bn,i(t) are responsible for the influence of each control point P_i on the shape of the curve and are defined by the following formula:

$$Bn, i(t) = \frac{n!}{i!(n-i)!} t^i (1-t)^{n-i}. \tag{2}$$

This function includes:

- The binomial coefficient $\frac{n!}{i!(n-i)!}$ determines the intensity of influence of each control point;
- The terms t^i and $(1-t)^{n-i}$ set the weight for each point depending on the value of t.

An advantage of this technique is that it allows the construction of complex and precise shapes that would be difficult to model using the polygon technique. The downside is that objects can require more processing resources when rendering than polygon models, especially for complex geometries.

Modelling through texture and material [41] adds visual realism and detail to 3D objects. This technique involves applying two-dimensional images (textures) to the surface of a 3D object to simulate different materials and surfaces. Texturing is a key step in creating visually appealing and realistic 3D objects. By applying this technique, 3D models can be significantly enriched, adding depth and detail.

2.1.2. Creation of Obj File and 3D Geometry

An obj file is a format used to store model geometry information, including coordinates of vertices, normal, textures, and polygons [42].

Three-dimensional geometry describes the structure of the 3D object in space, and in OBJ files, it is represented by a mesh composed of vertices, edges, and polygons. The geometry of the 3D object must be manipulated over time to create motion. This is achieved through various methods, including mesh deformations and transformations that bring the object to life.

2.1.3. Animation in VR Games: Techniques and Applications

Animation in VR games is a key element contributing to the players' interactivity and visual experience. It covers various aspects, from the movement of characters and objects to the dynamic effects of the environment [37]. The main steps of animation are as follows:

- Creation of keyframe animation: Keyframe animation is a basic technique in 3D animation where keyframes are created, and the software automatically interpolates the movements between them;
- Animation curves: These animations control the speed and smoothness of movements between keyframes. They can be used to control the acceleration and deceleration of the movement. Reshaping of animation curves is applied to achieve smoother and more natural movements;
- Test and optimization: Once the animation is created, it must be tested in a game environment and optimized for performance.

Interpolation is a fundamental mechanism for generating the smooth and natural movements of objects and characters [42]. It is the process of calculating the intermediate values between two or more keyframes to make the motion smooth and natural. When key values are set for various parameters such as position, rotation, scale, or other attributes of a 3D model, the interpolator calculates how these values might change over time to make the transition between keyframes. In 3D games, the two types of interpolation most often used are as follows:

- Linear interpolation provides smooth and constant motion between two frames by changing values at a constant rate. This interpolation is suitable for simple and rectilinear movements;
- Spline interpolation uses a spline cubic curve to control the smoothness and naturalness of the movement. Control points are set between keyframes to determine the motion of the object. This interpolation allows smoother and more natural movements that simulate the real world. This drives the app's camera.

Applying Transform 3D and curves in animation helps to manipulate and manage objects in 3D space [42]. They play a key role in creating dynamic and realistic animations. The main components of Transform 3D are translation, which changes the location of the object in 3D space; rotation, in which the object rotates around a particular axis (x-horizontal, y-vertical, z-depth); and scale, which changes the size of the object about its original dimension.

Transform 3D finds applications in motion animation and camera control. Motion animation is all about changing the position, rotation, and scale of objects in keyframes and using interpolation to smoothly transition between them. Camera control consists of animating camera movements, including position, rotation, and scale, to create different viewpoints and dynamic scene transitions.

Morphing [42,43] is a technique in animation that allows a smooth transformation of one form into another. It is used to create smooth transitions between different shapes of 3D objects, providing more realistic transformations. This technique is used in the current game with traditional 3D animation to control objects' movements better. Blend shapes is a specific technique in 3D animation that uses morphing to transition between pre-set shapes of the same object smoothly. Combining morphing and traditional animation techniques creates more complex and dynamic animations, which enriches the visual experience in 3D games. While animation provides the means to move objects, morphing adds smooth transformations between different object states.

2.1.4. A Mathematical Tool for 3D Modelling and Animation

Mathematics plays a major role in 3D modelling and animation in the creation of 3D games, and the mathematical apparatus used includes concepts and techniques from different areas of mathematics. Some key mathematical tools in 3D game modelling and animation are linear algebra, trigonometry, and geometry.

Linear Algebra: Basic mathematical objects of linear algebra include vectors, matrices, and transformations, which describe spatial relationships in 3D space [39,41].

- Vectors represent positions, velocities, directions of motion, or forces in 3D space. They describe distances, speed, and direction of movement of characters or objects;
- Matrices are used to describe transformations such as rotation, scaling, and translation. In 3D animation, they allow the transformation of the coordinates of points and objects in different coordinate systems, which is essential for a realistic representation of movements and perspectives;
- Homogeneous coordinates allow the different transformations (such as rotation, scaling, and translation) to be combined into a single matrix, making calculations easier.

Trigonometry is important for calculations related to angles and rotations, especially for motion and animation in 3D space. Basic trigonometric functions such as sine and cosine are used for the following [41]:

- Rotations of objects or characters around a given axis;
- The trigonometric calculations control the cameras, for example, when they rotate around an object;
- Trigonometry helps describe motion along arcs and curves, such as for animating objects that move in a circular path.

Geometry is essential in creating shapes, interactions, and collisions between objects in 3D games, such as the following [39,43]:

- Transformations: rotation, scaling, and translation are applied to geometric objects (models) through matrices;
- Curves and surfaces: splines and other curves (such as Bezier curves) are used to animate objects that move along a smooth path;
- Collision: the geometry is also key to detecting collisions between objects in space.

2.2. Fractal and Multifractal Analysis Methods

2.2.1. Fractal Analysis by DFA Method

DFA is a method used for analyzing time series with long-term correlations, which may be non-stationary, meaning they contain changing mean values or trends [44–46]. DFA is particularly effective for detecting hidden patterns and correlations in chaotic data or data containing trends. This method is often applied in the study of ECG signals to reveal fractal structures and long-term dependencies that standard time series analysis methods cannot detect. The main idea of DFA is to remove local trends in the time series and then examine the scalability of fluctuations around these trends. The main parameters that are calculated by DFA are:

- α_1 and α_2, which measure the short-term and long-term correlations in the time series, respectively;
- α_{all} summarizes the behaviour of the time series for all scales considered and is related to the Hurst parameter. The relationship between these two parameters is $H = \alpha_{all}$.

DFA provides important information about correlation structures in the data, allowing the analysis of long-term dependencies often associated with the fractal nature of ECG signals.

2.2.2. Multifractal Analysis Using the MFDFA Method

MFDFA [47–49] is a method that enables the analysis of the multifractal properties of time series, such as ECG signals and, specifically, the RR interval series. While the standard DFA method assesses the global scalability of fluctuations (fractality), MFDFA extends the analysis by examining how these properties vary across different scales and moments of the fluctuations, which is the main characteristic of multifractal signals. Multifractality is a property of time series that cannot be described by a single Hurst exponent or a single fractal dimension value, as is the case with monofractal signals. The MFDFA method examines several key parameters that characterize the complex dynamics of time series. These include the following:

- The fluctuation function Fq(s), which describes the degree of fluctuations depending on the scale s, providing information about the structural instability of the time series;
- The generalized Hurst exponent (Hq), which is a measure of self-similarity and long-term dependence, which varies with changes in the parameter q and reveals the heterogeneity of the fractal structure of the analyzed signals;
- The multifractal scaling exponent $\tau(q)$, which indicates scale dependencies and reveals the multifractal nature of the studied data at different values of parameter q;
- The multifractal spectrum $f(\alpha)$, which serves as a tool for the quantitative description of signals with a high degree of heterogeneity, providing information on the degree of non-uniformity and complexity of the signal, showing the distribution of different local dimensions in it.

2.3. Data and Statistical Analysis

To investigate the influence of stress on HRV, the following experiment was conducted. An extreme game, "asteroid shower", was loaded on a computer. To implement the game in VR, the participants were equipped with a VR helmet, Photontree Pro 3D (HMD), and a Dynamic ECG System TLC9803 Holter device (Contec Medical Systems Co., Ltd., Qinhuangdao, China) for recording ECG signals. Players use a joystick (Microsoft Xbox Series, Washington, USA or Microsoft Xbox 360 controller, Washington, USA) to control the game (shooting asteroids and movement). Figure 2 illustrates the configuration of the experimental system. The games lasted about 20 min and 20 volunteers participated in the experiment: 16 men aged 27 ± 8 years and 4 women aged 24 ± 6 years. The data required for HRV analysis were collected at rest and during play. The parameters studied by the fractal and multifractal analysis methods are based on the RR interval series determined by the ECG signals recorded at rest (Group 1) and during play (Group 2). Statistical analysis of the studied parameters for the two groups was performed with a *t*-test to determine whether the differences between them were statistically significant. The result of the *t*-test is a *p*-value that indicates the probability that the observed difference is due to chance. If the *p*-value is below 0.05, the difference between the two groups is considered statistically significant.

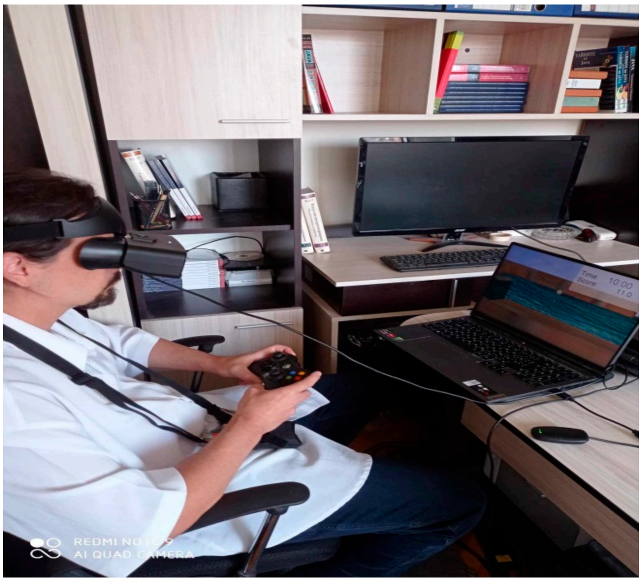

Figure 2. Configuration of the experimental system.

3. Results

3.1. Game "Asteroid Shower" with Virtual Reality

To investigate the impact of mental stress on HRV of the experiment participants, a high-intensity 3D action game was developed to test the player's fast reflexes [38]. In the game, the player has to destroy asteroids falling from space towards a city by shooting at them. When the asteroids hit, they disintegrate and explode with various visual and sound effects. As the game progresses, the speed and frequency of falling asteroids increase, requiring faster reactions and higher concentration. Several levels of difficulty are included to simulate different levels of stress and additional visual and sound effects. The game was created using Java (version 1.8, 2021), Java 3D (version 1.6.0, 2017), and Blender (version 3.1.2, 2022).

3.1.1. Modelling 3D Objects

Figure 3 shows the polygonal modelling process of a 3D object (bullet). The main steps of the process are as follows:

1. Selection of primitive shape (Figure 3A–C): Modelling begins with the selection and construction of a basic geometric shape, a regular polygon, by applying a new boundary method [50] that gives a better result than the traditional trigonometric method. This shape serves as the basis of the object to be created, which is subsequently modified and detailed. The information from this step is stored in an obj file;
2. Subdivision (Figure 3D): This technique divides the object into smaller parts, increasing the number of vertices and edges. The process produce enables higher detail and smoother surfaces;
3. Extrusion (Figure 3E–H): The extrusion technique involves extending a 2D/3D face or edge to create a new surface that continues the object's existing geometry. This process adds complexity to the object by creating new shapes while preserving its structure;
4. Merging and manipulating vertices and edges (Figure 3I): The vertices and the edges are used to create more complex object geometry. This step involves merging vertices and edges to achieve greater control over the object's shape and detail;
5. Smoothing (Figure 3J): This operation softens the object's edges to remove hard lines between polygons and create a smoother surface;

6. Mesh representation of the object (Figure 3K);
7. Adding texture (Figure 3L): After completing the object's geometry, the texture is added. This is important in adequately applying visual details such as colours, patterns, and other textures.

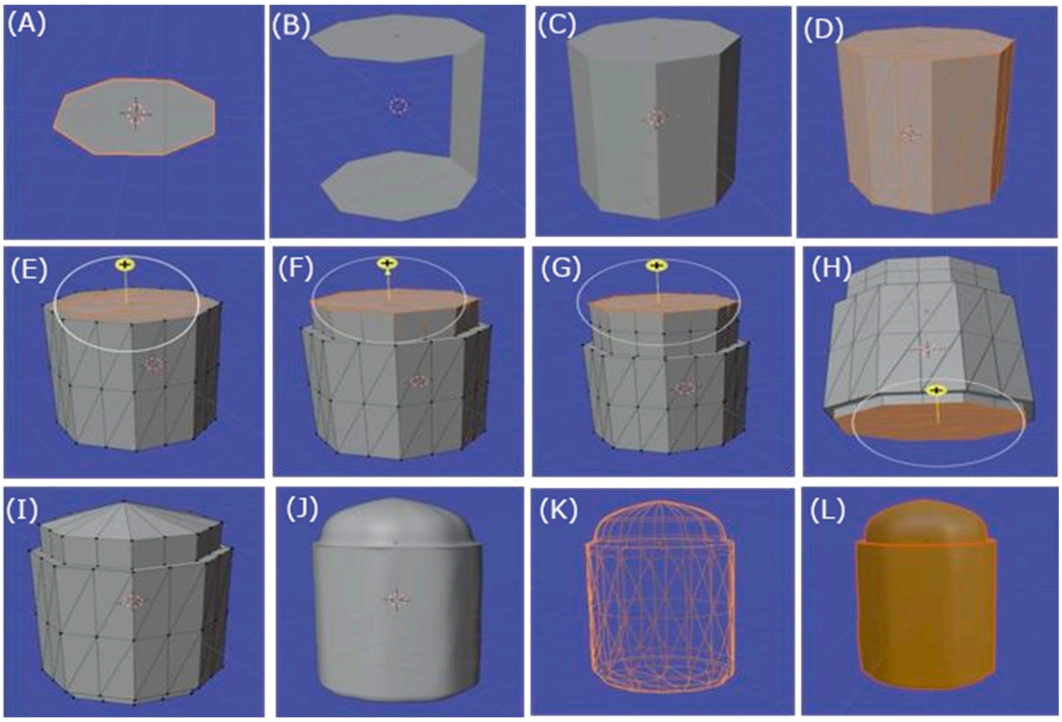

Figure 3. Polygonal modelling of a 3D object (bullet). (**A**) Primitive selection: regular polygon, by polygon technique; (**B**) detailing by adding walls and upper base; (**C**) prism creation; (**D**) subdivide the object; (**E**–**G**) extrusion of the upper base of the prism; (**H**) bottom base extrusion; (**I**) combining vertices; (**J**) object smoothing; (**K**) network representation of the object; (**L**) adding a texture to the generated object.

Figure 4 shows the process of modelling a 3D object (asteroid) using Bezier curves. The main steps of the process are as follows:

1. Selection of a linear Bezier curve primitive (Figure 4A): The process begins by selecting a basic primitive shape—a regular octagon—and calculating its vertices by applying the method presented in [50]. The process that continues the linear Bezier curve is applied to the polygon for the initial shaping of the object. Formulas (1)–(3) represent the Bezier curve with two control points (linear curve), and Formula (4) shows a parameterization of the linear curve for 2D Bezier coordinates, where x and y are the coordinates of the points. Table 1 presents the coordinate values for each segment along the abscissa and ordinate. The length of each side of the polygon is assumed to be equal to one;
2. Extrusion of the polygon into a prism (Figure 4B): The 2D polygon is extruded into a 3D prism-shaped object. This adds volume and creates the foundation upon which the shape will be further developed. The information is saved in an obj file;
3. Defining the basic geometry of the object (Figure 4C): The basic structure of the asteroid begins to take shape, adding details that are important for the next stages;
4. Subdivision of the prism (Figure 4D,E): The "subdivision" technique divides the surface of the prism into smaller polygons. This results in a smoother shape and creates more vertices and edges for fine-tuning the object;

5. Transformation of the prism into a sphere (Figure 4F): The prism transforms into a more rounded shape, approaching a sphere. This step is key to creating the asteroid's basic rounded structure;
6. Creation of a solid ellipsoid (Figure 4G): The shape is reshaped as an ellipsoid to add irregularity and a more exciting appearance. This gives the object a natural look and more variation;
7. Creating the final shape of the asteroid (Figure 4H): The final shape of the asteroid is achieved by deforming and adding surface irregularities using techniques such as noise modifications that create craters and depressions;
8. Mesh representation of the asteroid (Figure 4I): The mesh representation of the object is shown, helpful in checking surface uniformity and geometry detail. The grid structure also makes it easy to add textures;
9. Adding texture (Figure 4J): Finally, a texture is added to the object to give the asteroid a realistic appearance. Texture includes colours, relief, and visual depth, highlighting specific surface features such as craters and rock formations.

$$\begin{aligned} P_0 B_{1,0}(t) + P_1 B_{1,1}(t) &= P_0 \binom{1}{0} t^i (1-t)^{n-i} + P_1 \binom{1}{1} t^i (1-t)^{n-i} \\ &= P_0(1-t) + P_1 t \end{aligned} \tag{3}$$

$$C(t) = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} (1-t) + \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} t, \text{ where } t \in [0,1] \tag{4}$$

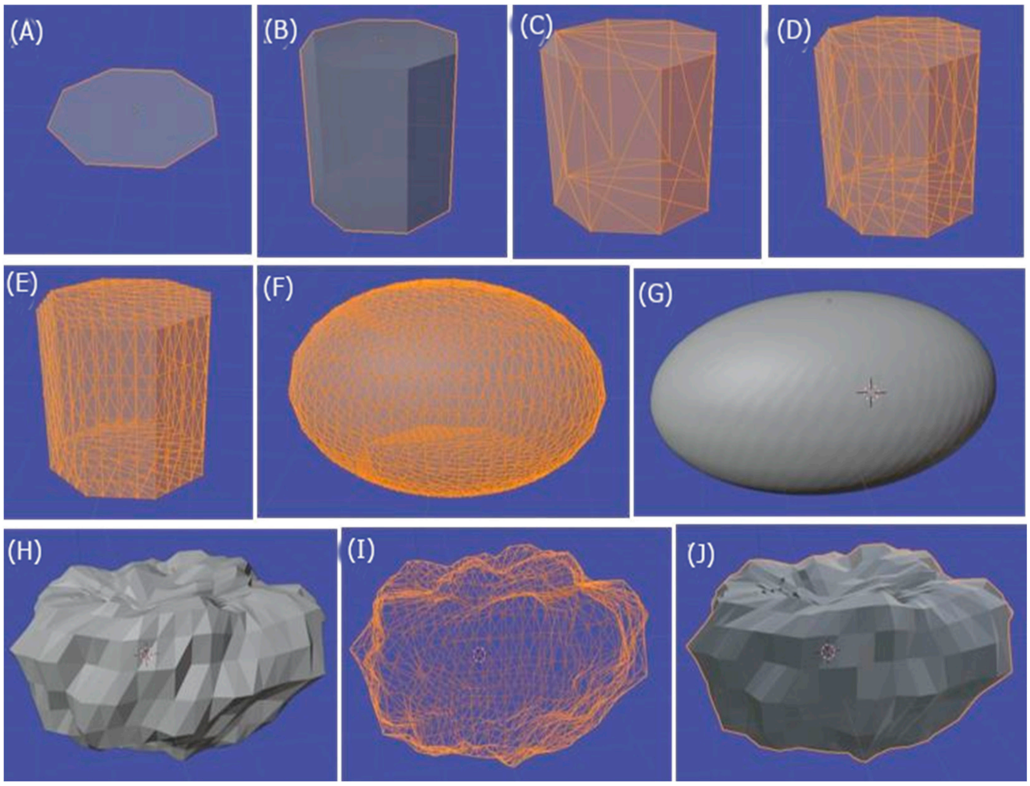

Figure 4. Modelling a 3D object (asteroid) using Bezier curves. (**A**) Primitive selection: a regular polygon with a linear Bezier curve; (**B**) extruded polygon in a prism; (**C**) basic object geometry; (**D**) and (**E**) subdivide the object (prism); (**F**) transformation of prism to ellipsoid; (**G**) creation of solid ellipsoid; (**H**) created asteroid; (**I**) wireframe representation of an asteroid; (**J**) add texture to the generated object.

Table 1. Coordinate values of the vertices of a regular octagon by applying the Bezier curve.

Step	Coordinate Values of the Vertices of a Regular Octagon							
	C_1 (x; y)	C_2 (x; y)	C_3 (x; y)	C_4 (x; y)	C_5(x; y)	C_6(x; y)	C_7 (x; y)	C_8(x; y)
0.1	−1.17; −0.4	−1.103; 0.574	−0.4; 1.242	0.567; 1.167	1.17; 0.4	1.103; −0.574	0.4; −1.242	−0.567; −1.167
0.2	−1.17; −0.3	−1.036; 0.648	−0.3; 1.242	0.634; 1.093	1.17; 0.3	1.036; −0.648	0.3; −1.242	−0.634; −1.093
0.3	−1.17; −0.2	−0.969; 0.722	−0.2; 1.242	0.701; 1.019	1.17; 0.2	0.969; −0.722	0.2; −1.242	−0.701; −1.019
0.4	−1.17; −0.1	−0.901; 0.796	−0.1; 1.242	0.768; 0.945	1.17; 0.1	0.901; −0.796	0.1; −1.242	−0.768; −0.945
0.5	−1.17; −0.0	−0.835; 0.871	0.0; 1.242	0.835; 0.871	1.17; 0.0	0.835; −0.871	0.0; −1.242	−0.835; −0.871
0.6	−1.17; 0.1	−0.768; 0.945	0.1; 1.242	0.901; 0.796	1.17; −0.1	0.768; −0.945	−0.1; −1.242	−0.901; −0.796
0.7	−1.17; 0.2	−0.701; 1.019	0.2; 1.242	0.968; 0.722	1.17; −0.2	0.701; −1.019	−0.2; −1.242	−0.968; −0.722
0.8	−1.17; 0.3	−0.634; 1.093	0.3; 1.242	1.036; 0.648	1.17; −0.3	0.634; −1.093	−0.3; −1.242	−1.036; −0.648
0.9	−1.17; 0.4	−0.567; 1.167	0.4; 1.242	1.103; 0.574	1.17; −0.4	0.567; −1.167	−0.4; −1.242	−1.103; −0.574

3.1.2. Three-Dimensional Animation

In the created VR game, the camera is driven in two ways: by a linear interpolator or by a spline curve. Linear interpolation moves the camera smoothly from one point to another by specifying a start and end position and the speed at which the camera moves through them. This interpolator is used for rectilinear movements and more straightforward camera transitions. Spline curves are applied when more complex motion is sought, while simultaneously applying a 3D transformation. The movement of the camera by applying Transform 3D with translational movement along the z-axis is shown in Figure 5 and by rotation along the y axis in Figure 6.

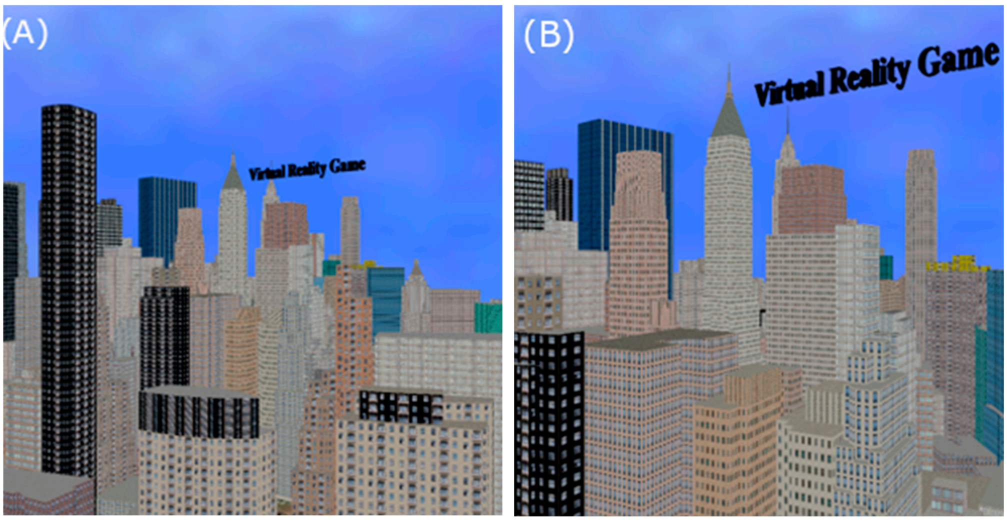

Figure 5. Translational movement of the camera along the z-axis. (**A**) Positive value for z axis; (**B**) negative value for z axis.

Figure 7 shows an asteroid's explosion. It combines several basic techniques: modelling and texturing the asteroid; shredding by exploding and morphing; and light and sound effects that create a spectacular and realistic explosion that looks impactful in virtual reality. The camera is above the city and has been moved using spline curve and Transform 3D.

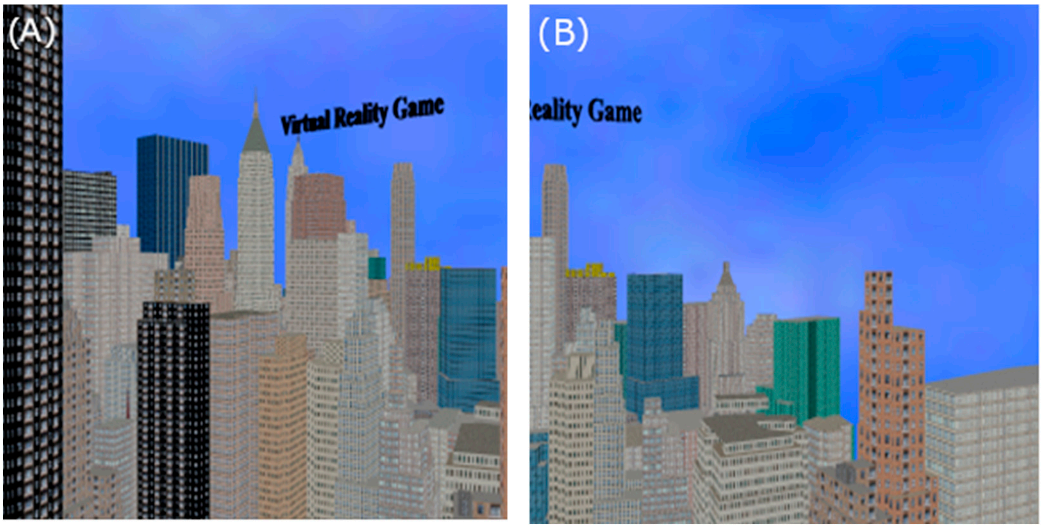

Figure 6. Rotational movement of the camera along the y-axis. (**A**) Positive value for y axis; (**B**) negative value for y axis.

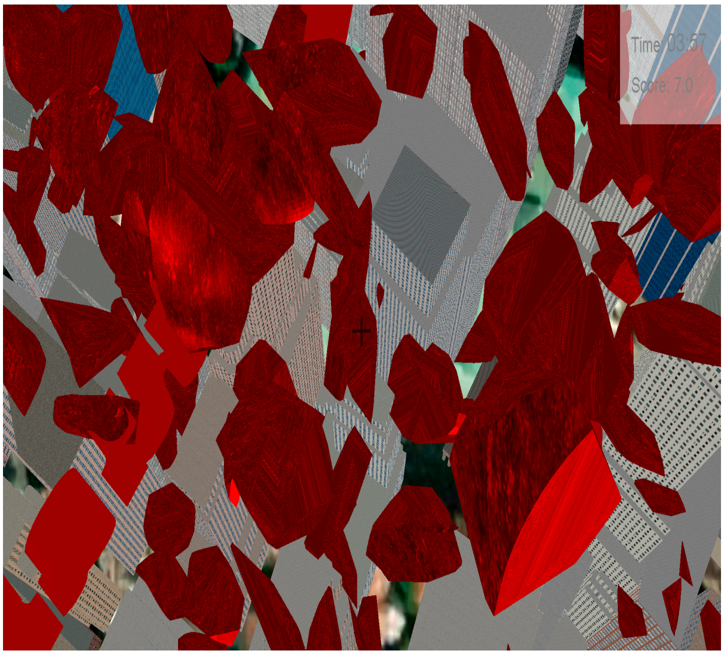

Figure 7. Asteroid smashing and exploding.

3.2. Fractal and Multifractal Analysis

The following two groups were studied with the DFA and MFDFA methods:

- The RR interval series of 20 volunteers at rest, before they started playing;
- The RR interval series of 20 volunteers in a stress state, recorded during a game.

The analyzed data contains approximately 2000 RR time intervals corresponding to 20 min ECG recordings. Figures 8 and 9 show the plots obtained using the DFA method, both at rest and under stress conditions. The first section of the graph's slope (Figures 8A and 9A, in green) corresponds to the short-term fractal exponent α_1 for segments of size $4 \leq s \leq 16$, and the second part (red) corresponds to the long-term fractal exponent α_2 for segments of size $16 < s \leq 64$. The slope of the graphs in Figures 8B and 9B (magenta) corresponds to the parameter α_{all}.

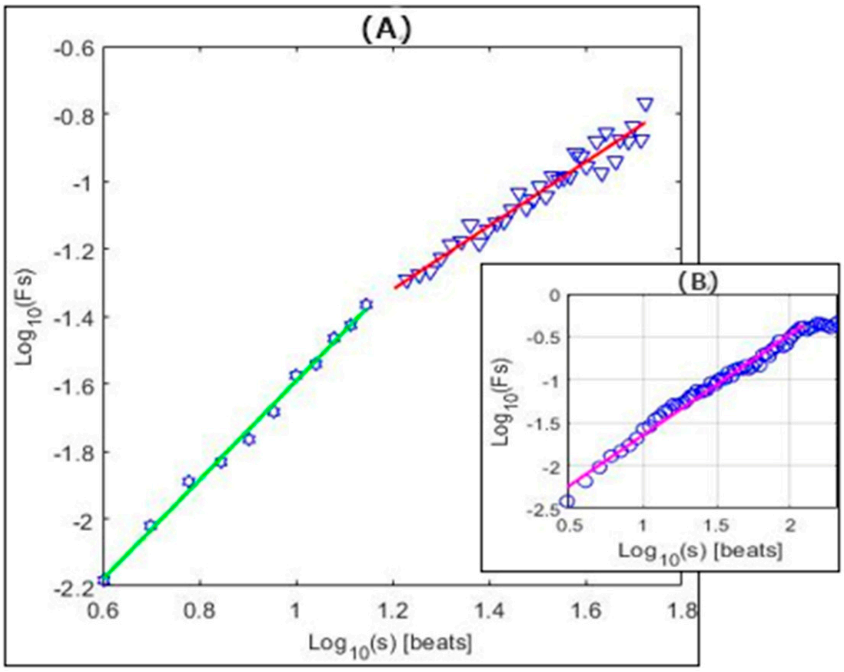

Figure 8. DFA of RR interval series under resting conditions: (**A**) for α_1 and α_2 (**B**) for α_{all}.

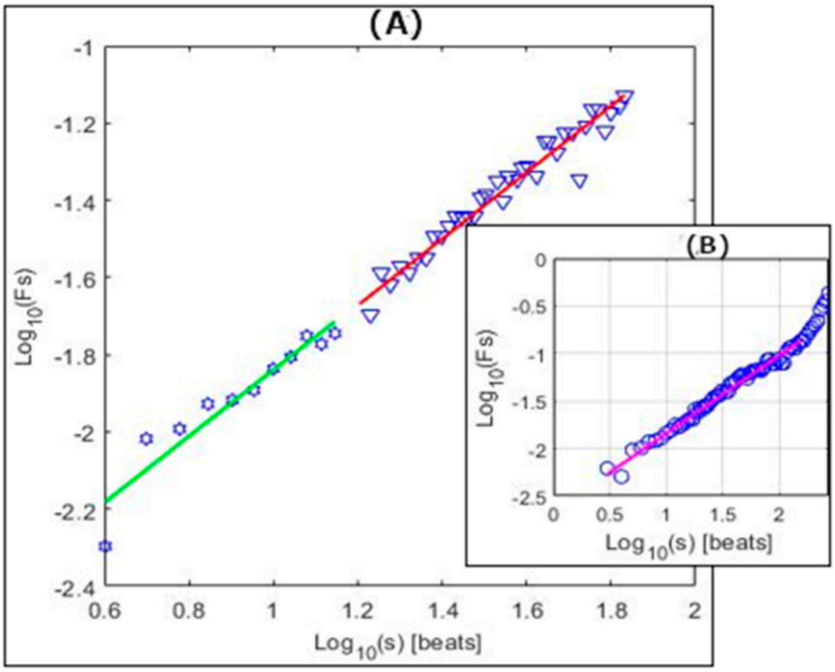

Figure 9. DFA of RR interval series while playing: (**A**) for α_1 and α_2; (**B**) for α_{all}.

Figures 10 and 11 show the graphs obtained by the MFDFA method at rest and during the game. Through the resulting graphs, the following functions and parameters can be examined: the fluctuation function Fq(s) (Figures 10A and 11A); the generalized Hurst exponent (Figures 10B and 11B); the multifractal scalable exponent (Figures 10C and 11C); and the multifractal spectrum (Figures 10D and 11D).

Table 2 presents the values of the studied parameters, determined by DFA and MFDFA, for the two study groups: Group 1—rest and Group 2—stress, as well as the *p*-value determined by the *t*-test.

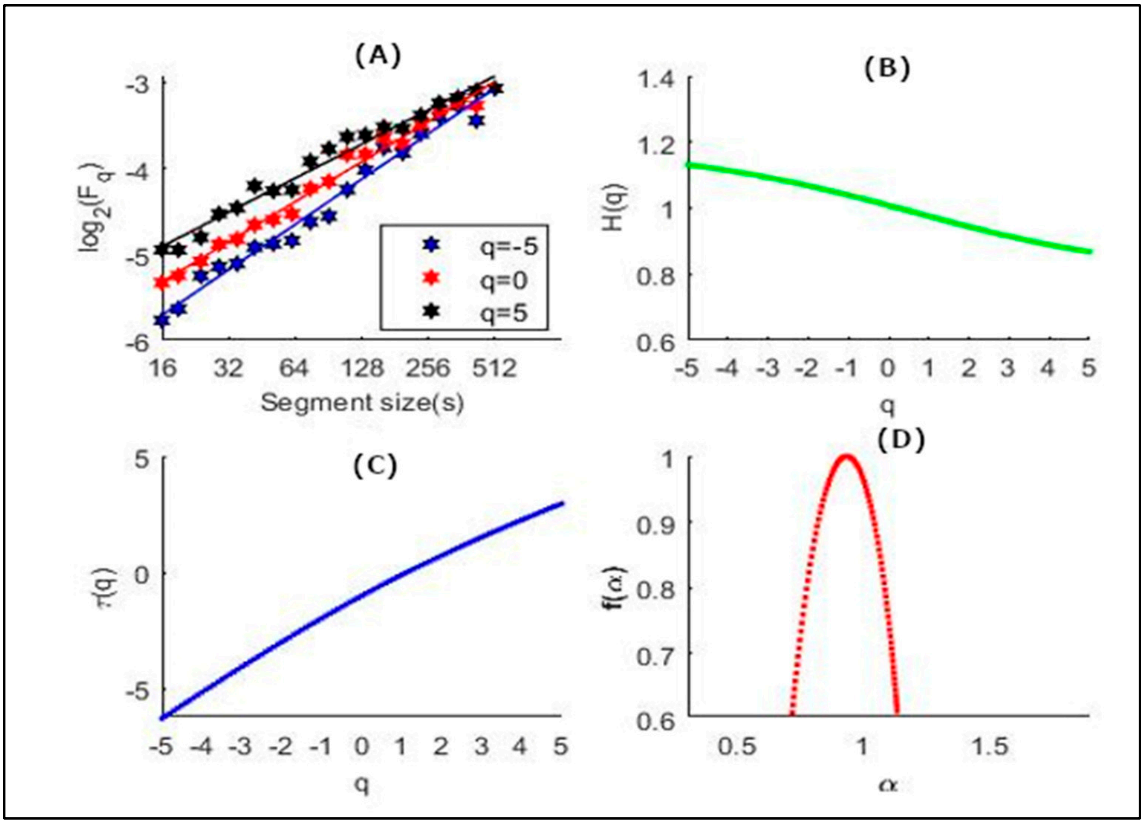

Figure 10. MFDFA of RR interval series at rest: (**A**) for Fq(s) (**B**) for Hq; (**C**) for τ(q); (**D**) for f(α).

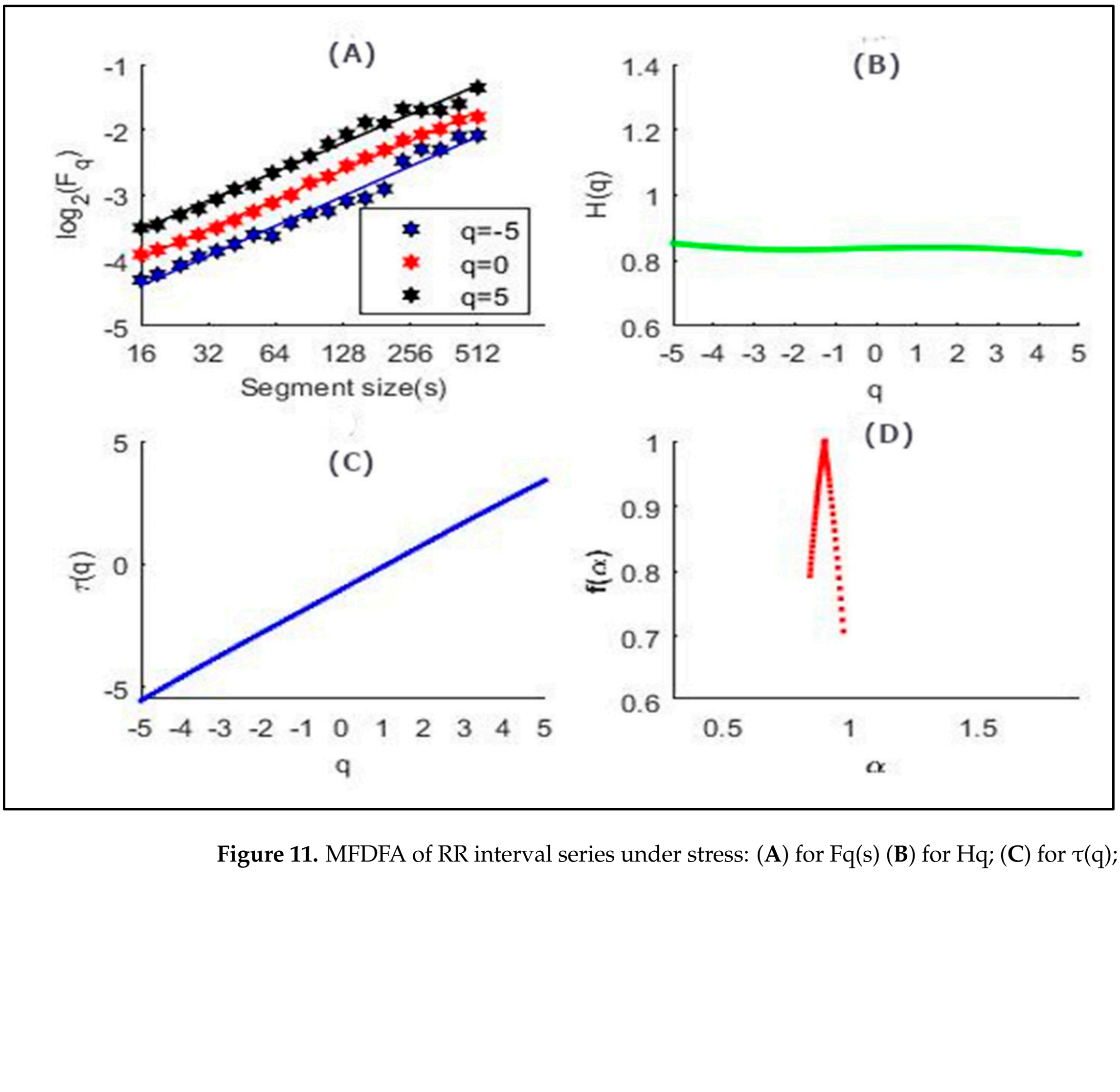

Figure 11. MFDFA of RR interval series under stress: (**A**) for Fq(s) (**B**) for Hq; (**C**) for τ(q); (**D**) for f(α).

Table 2. Comparative analysis of DFA and MFDFA-derived parameters at rest and under stress.

Parameter	Group 1-Rest [Mean ± SD]	Group 2-Stress [Mean ± SD]	*p*-Value
α_1 (DFA)	1.167 ± 0.09	0.753 ± 0.14	<0.0001
α_2 (DFA)	0.945 ± 0.18	0.861 ± 0.10	0.0760
α_{all} (DFA)	0.981 ± 0.08	0.847 ± 0.02	<0.0001
$H_{q=2}$ (MFDFA)	0.979 ± 0.02	0.851 ± 0.09	<0.0001
α_{min} (MFDFA)	1.45 ± 0.16	1.08 ± 0.11	<0.0001
α_{max} (MFDFA	0.63 ± 0.06	0.79 ± 0.04	<0.0001
$\Delta\alpha = \alpha_{max} - \alpha_{min}$ (MFDFA)	0.82 ± 0.11	0.28 ± 0.18	<0.0001

4. Discussion

The study of stress generated through a VR game is an innovative approach that not only creates realistic and immersive conditions for simulating stressful situations but also provides an opportunity for in-depth fractal and multifractal analysis of HRV. The use of VR as a means of inducing stress allows the creation of a controlled and realistic environment that can reproduce stress without endangering the safety of research participants. The connection between the extreme game and virtual reality is realized through the use of a VR helmet, which provides an immersive experience, creating a sense of presence in a dynamic and intense environment. The helmet allows the player to fully engage with the virtual environment by providing visual and audio stimulation that enhances the game's impact on the senses and psychophysiological response.

To validate the presented stress simulation game, fractal and multifractal analyses were performed on the generated ECG signals before and after the game.

4.1. Fractal Analysis

The DFA method enables the assessment of the fractal structure in the time series of the RR intervals, providing information on short-term and long-term correlations in cardiac dynamics, as well as information on the adaptability and regulation of the autonomic nervous system. Based on the results obtained from the analysis using the DFA method, the following findings can be made:

- Under mental stress, the value of α_1 ($p < 0.0001$), determining short-term dependencies, decreases, which means that the short-term dynamics of the RR interval series become more chaotic and less correlated, which is an indicator of a stress response. This dynamic is due to a disturbed balance between sympathetic and parasympathetic activity, i.e., stress causes activation of the sympathetic nervous system, which leads to a more chaotic rhythm and reduced HRV. This information can be helpful in developing stress management strategies that include relaxation techniques and increasing parasympathetic activity;
- The value of the parameter α_2 ($p = 0.076$), which reflects the long-term correlations in the heart rate, shows weaker changes under the influence of stress compared to $\alpha 1$. This can be explained by the fact that long-term correlations are more resistant to short-term stressful stimuli. This result is consistent with studies [45,46] that also show that α_2 is primarily affected by long-term changes in cardiac function associated with stress or disease;
- The summary value of the α_{all} parameter ($p < 0.0001$) also decreased under stress. The value of this parameter reflects the overall decrease in autocorrelation and increase in irregularity in the RR interval series. This parameter is related to the Hurst exponent by the following equation: $\alpha_{all} = H$. This relationship reflects the key concept that the two quantities measure the fractal properties of time series. The Hurst parameter is a measure of the long-term correlation in data and is widely used in time series analysis, particularly in the context of the statistical properties of cardiac variability. Higher

values of H (or α_{all}) indicate better adaptability of the organism to stressful situations and higher resistance to stress. The relationship between α and H is particularly useful in the context of DFA, as the method is designed to assess the fractality of time series, allowing us to identify and analyze complex dependencies that cannot be revealed by the application of standard statistical methods. Similar results were reported in publication [46].

4.2. Multifractal Analysis

While DFA only estimates the monofractal structure of the time series, which can be determined from only one value of the Hurst exponent for the entire series, MFDFA allows the analysis of the multifractal structure of the time series by determining multiple Hurst exponents. Based on the results obtained from the analysis using the MFDFA method, the following conclusions can be drawn:

- The fluctuation function Fq(s) shows the degree of variability in the data at different scales s (segment size) and instantaneous values of q. The graphs of the fluctuation function at different values of q for the two studied interval series (rest and stress) show linear dependencies, which is evidence of fractal behaviour. The graphs in Figure 10A are of different slope, indicating that the interval series at rest have a multifractal behaviour, while at stress the graphs (Figure 11A) are parallel, i.e., the slope of the fluctuation functions is constant and the signal is monofractal;
- The generalized Hurst exponent (Hq) is a measure of correlations in signals. Under stress, Hq values are lower, suggesting a more pronounced anticorrelation. At rest, Hq values are higher, which is evidence of greater stability in cardiac activity. From the graphs of Figures 10B and 11B, it can be seen that, at rest, the value of the exponent H changes for different values of the parameter q, which is indicative of a multifractal behaviour. Under stress, the dependence of H on q is nearly constant, suggesting that the signal is monofractal. Similar results were reported in publication [47,48];
- The multifractal scaling exponent $\tau(q)$ exhibits more nonlinearity (Figure 10C) at rest than at stress (Figure 11C) where the dependence of this exponent on the parameter q is linear;
- The multifractal spectrum $f(\alpha)$ is broader at rest, which may be an indication of greater heart rate variability. Conversely, in a stress state, the spectrum is narrower, reflecting lower multifractal complexity and heart rate variability. Similar results were reported in publication [51].

Based on the obtained results, it can be summarized that the DFA and MFDFA methods can successfully evaluate and analyze the impact of stress on cardiac dynamics, revealing key changes in the short-term and long-term structure of HRV.

4.3. Limitations

Fractal and multifractal analysis of HRV is conducted to validate the proposed stress simulation game and evaluate its effectiveness. The primary objective in this context is to identify statistically significant changes in HRV that reflect the physiological response to the induced stress, without requiring maximum precision in the analysis.

However, the limitations of the present study related to the analysis of ECG signals recorded before and after the game are as follows:

- Small sample size: Only 20 volunteers were analyzed, which limits the accuracy of the results. A larger sample size could have increased the statistical accuracy of the study.
- Limited length of ECG signals: The length of the signals is about 2000 RR intervals recorded over a period of 20 min. This duration is limited due to the nature of the experiment to simulate a temporary acute stress. Although this is appropriate for the

chosen methods (fractal and multifractal analysis), longer recordings could provide additional information on the long-term dynamics of heart rate.
- High variability of some parameters: Some parameters show higher standard deviation values compared to the mean. This can be explained by the influence of various factors, such as the activity of the autonomic nervous system, metabolic processes, and external stress stimuli. Although this variability can be considered natural for biological systems such as the cardiovascular system, it limits the precision of some analyses.

Despite the aforementioned limitations, the results of the statistical analysis performed using the *t*-test show that a large part of the studied parameters demonstrate statistically significant differences ($p < 0.05$) between the two groups before and after the game.

4.4. Future Work

The future studies on the effects of stress on HRV will include a larger sample of volunteers to increase the statistical accuracy and reliability of the results. In addition, other methods of analyzing ECG signals will be considered, which could contribute to a deeper understanding of the effect of stress on cardiac dynamics.

5. Conclusions

The results of the study indicate that the developed extreme VR game is an innovative tool for inducing stress, which impacts the fractal and multifractal characteristics of the RR time interval series. Changes in HRV parameters, determined by DFA and MFDFA analyses, demonstrate a decrease in fractal complexity and loss of adaptability in cardiovascular activity under stress. This decrease in the fractal structure of HRV signals reflects the enhanced response of the sympathetic nervous system under stress conditions. These findings support the hypothesis that VR technology can successfully simulate a specific stress response, measurable by HRV parameters. The present study opens new perspectives for studying the psychophysiological response to stress in controlled and safe virtual settings and can serve as a basis for the development of VR tools for stress assessment and management in future studies.

Author Contributions: Conceptualization, P.L.; methodology, P.L. and E.G.; software, P.L.; validation, P.L.; formal analysis, P.L. and E.G.; investigation, P.L.; data curation, P.L.; writing—original draft preparation, P.L. and E.G.; writing—review and editing, P.L. and E.G.; visualization, P.L.; supervision, P.L.; project administration, P.L.; funding acquisition, P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Fund of Bulgaria (scientific project "Research, mathematical analysis and assessment of the impact of stress on cardiac data"), grant number KP-06-M72/1, 5 December 2023.

Institutional Review Board Statement: The study was approved by the Ethics Committee of Institute of Robotics at Bulgarian Academy of Sciences (protocol code 6 and date: 2 November 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: This work was conducted with the financial assistance of the National Science Fund of Bulgaria project number KP-06-M72/1, 5 December 2023, which is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.

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