StressVR: Visual Analysis Tool for ECG and HR Data in Virtual Reality

Raul-Alexandru Gorgan
Technical University of Cluj-Napoca
Str. G. Barițiu 28, 400027, Cluj-Napoca, România
gorganraul@yahoo.com

Adrian Sabou
Technical University of Cluj-Napoca
Str. G. Barițiu 28, 400027, Cluj-Napoca, România
adrian.sabou@cs.utcluj.ro

Teodor-Traian Ștefănuț
Technical University of Cluj-Napoca
Str. G. Barițiu 28, 400027, Cluj-Napoca, România
teodor.stefanut@cs.utcluj.ro

ABSTRACT
Analyzing large datasets from physiological sensors, such as ECG (Electrocardiogram) and HR (Heart Rate), presents significant challenges with traditional 2D visualization methods. These methods often fail to reveal detailed patterns and connections within the data, making it difficult for researchers to draw meaningful conclusions. StressVR addresses these challenges by offering a visual analysis tool that use Virtual Reality to create an immersive 3D environment for data exploration. With StressVR, users can interact with data in a more intuitive and engaging manner, enabling the selection and examination of individual data points, intervals, and multiple datasets simultaneously. This tool also offers advanced features such as data filtering, removal and annotation, improving the ability of the user to detect patterns and anomalies. Navigation between data points is possible, offering a clear advantage over the 2D approach. The evaluation of StressVR demonstrates that the immersive 3D approach improves the accuracy of data analysis compared to traditional 2D methods. The results indicate that StressVR not only improves the understanding of physiological responses to stress but also provides a more efficient and user-friendly platform for analyzing large-scale sensor data. This paper details the development, experiments and evaluation of StressVR, highlighting its importance in the field of physiological data analysis.

Author Keywords
HCI; Virtual Reality; Visual Analytics; Stress recognition; Heart rate variability; ECG; Unity;

ACM Classification Keywords
H.5.m. Information interfaces and presentation: HCI
I.3.7. Three-Dimensional Graphics and Realism
DOI: 10.37789/ icusi.2024.9

INTRODUCTION
In recent years, advancements of sensor technology in healthcare and research have generated large amounts of data from devices equipped with ECG (Electrocardiogram) and HR (Heart Rate) sensors. This data is important for understanding how individuals react to various conditions, including stress. The use of sensors data helps to obtain objective and reliable information on user conditions as described in [4]. Traditional methods, such as questionnaires and self- reported answers, can provide insights but are often subjective, as individuals may not always accurately identify or describe their own emotions. In contrast, sensor data offer an objective source of information, capturing physiological responses directly linked to the emotional and physical state of the user. This objectivity is important for meaningful and valid assessment of user conditions, ensuring that the data reflect true physiological and behavioral responses rather than subjective perceptions.

However, traditional 2D charts and tables are often not enough to fully understand these complex datasets. They can miss important patterns and connections, making it harder for researchers to draw useful and accurate conclusions. Traditional 2D visualizations have problems to effectively show the details and dynamics in physiological data. This can make it easy to miss fine patterns and relationships, slowing down the work of researchers. As a result, there is sign of a clear need for more advanced tools that can improve the visualization and analysis of large amounts of sensor data.

Virtual Reality (VR) has become a powerful solution to these challenges. By creating immersive 3D environments, VR allows users to interact with data in such ways that are not possible with traditional 2D methods. This approach helps users to gain a more intuitive and complete understanding of complex datasets. StressVR is a platform developed to meet these needs, focusing on the visual analysis of ECG and HR data. Using the capabilities of the Meta Quest 3 VR headset, StressVR lets users see and interact with sensor data in a 3D space. This immersive environment allows for navigation, close examination of data points and intervals from any perspective (not present in 2D approaches) and comparison of multiple datasets at once. Key features include the ability to select and highlight specific data points, filter and annotate data, remove noise or interpolate the data. These functionalities assist users in finding insights into physiological responses to stress.

This paper details the development and experiments made on StressVR, highlighting its main features and functionalities. It will discuss the design principles and technologies behind the application, as well as the methods used to evaluate its usability. The results show that StressVR significantly improves the analysis of physiological data, offering an effective and user- friendly tool for researchers.

The following sections present related work in the field of visual data analysis, the methodology behind the development of StressVR, the implementation particularities, the experiments made, the evaluation of the platform and the conclusions. This paper emphasizes that visualization of big data can help people to find meanings that machines are not able to notice, to detect hidden patterns and correlations, and to make the numbers more understandable for both researchers and non-academic people.

RELATED WORK

This section provides an overview of existing tools and studies related to data visualization, emphasizing both 2D and 3D methods, and highlights the advantages of 3D visualization for managing large datasets. It also compares these tools with the proposed application developed using Unity and Meta Quest 3.

There is a variety of tools and applications that utilize 2D visualization techniques for data analysis. These tools are used due to their simplicity and ease of integration.

Tableau [12] is a leading data visualization tool widely used in business intelligence. It allows users to create interactive and shareable dashboards that effectively identify trends and patterns in large datasets. However, Tableau's 2D visualizations can be limiting when it comes to representing complex, multidimensional data. Similarly, Microsoft Power BI [6] offers robust 2D visualization features, enabling detailed report and dashboard creation. While effective in many scenarios, Power BI's utility can decrease as the complexity and volume of the dataset increases, potentially making it less intuitive for intricate data analysis.

As computing power and graphics technology have advanced, 3D visualization has become a better option for handling complex datasets. Paraview [10], for instance, is an open-source application designed for visualizing large datasets in a 3D environment. It is particularly useful in scientific research for analyzing complex simulations and models but may not be as focused on medical data analysis.

The development of StressVR is inspired by applications such as Virtualitics and Mindesk, which offers 3D data manipulation. These platforms demonstrate the potential of VR by intuitive data visualization and analysis. Virtualitics [13] is a platform that uses VR to offer immersive 3D data exploration, addressing the limitations of traditional 2D visualization. It allows users to navigate and manipulate complex datasets in a virtual space, applying advanced algorithms and machine learning to uncover hidden patterns. However, Virtualitics is aimed at a broad range of data types and may not provide specialized tools for medical data. Mindesk [7] integrates VR into computer-aided design (CAD), enabling real-time visualization and modification of 3D models with VR headsets like Meta Quest 2/3. While it excels in design and engineering tasks, Mindesk is less focused on data analysis, particularly in the medical field.

The VRAIn Visualization Tool [16] is a VR platform designed for analyzing extensive medical datasets. It provides users with an immersive environment to explore and interact with detailed 3D models derived from imaging data such as MRI and CT scans from patients or large datasets such as Harvard ADS or Niras. This tool excels in managing and visualizing large volumes of medical information, offering advanced features for data filtering, annotation, and real-time interaction. By enabling immersive navigation and manipulation of complex datasets, the VRAIn Visualization Tool significantly improves data interpretation and user engagement compared to traditional 2D visualization tools. However, it is more general, as the proposed application is more specific for ECG and HR data.

Recent studies have also explored visual analysis in specific domains. Tong et al. [15] introduced an interactive visualization tool for sensor-based physical activity data, featuring high-dimensional dataset exploration through data mapping, axis brushing and data group selection. Baltabayev et al. [1] developed smartphone applications using VR to visualize sensor data from a SensorTag device. By integrating VR into the process, the paper describes new possibilities for efficient and engaging sensor data analysis on mobile devices. Langer et al. [3] presented a visual analytics approach for industrial sensor data, focusing on interactive exploration and labeling for accurate data categorization and advanced classification models for predictions. The proposed application provides essential features for analyzing ECG and HR datasets in a straightforward, specialized and intuitive manner.

METHODOLOGY

This section describes the approach used to develop and implement StressVR, detailing the processes involved in data collection, data processing and the choice of visualization techniques. These steps are important to ensuring the accuracy, reliability and usability of the visual analytics tool.

Data Collection

The data used in StressVR are collected from two primary devices, ensuring a comprehensive set of physiological data for analysis: the Samsung Galaxy Watch 5 Pro and the Neulog ECG sensor [9].

Heart rate data are collected using the Samsung Galaxy Watch 5 Pro, a smartwatch equipped with advanced biosensing capabilities and sufficient resources. This watch includes the BioSensor, which integrates photoplethysmography (PPG) and Heart rate (HR) sensors. Heart rate sensors are among the most common sensors in these devices. This sensor determines the heart rate in real-time using photoplethysmography technology. The technology measures blood flow and changes in light absorption, from which certain data can be extracted (e.g., inter- beat intervals). These data are used to calculate parameters such as Heart-Rate Variability (HRV) that is used to identify stress or heart conditions, as described by Moraes et al. [8].

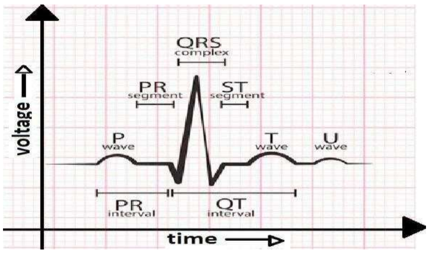

Figure 1 QRS Complex [5]

$$RMSSD = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(RR_{n+1} - RR_n)^2}$$

Equation 1 RMSSD formula

The second data source is the Neulog ECG sensor, specifically designed to capture detailed electrocardiogram readings. The ECG sensor can be set to work at a high sample rate of 100 values per second, providing sufficient data on the electrical activity of the heart. This level of detail is essential for identifying changes and patterns in the signal that might be missed with a less sampling rate. The ECG sensor collects raw data, which is then stored and prepared for processing and interpretation. This high-resolution data is important for assessing heart health and stress identification.

Data Processing

The data collected from the ECG sensor are directly stored in CSV (Comma-Separated Values) files (through an API), which allows for an easy method for importing and visualizing within the StressVR application. The data collected from the smartwatch are stored in a relational database and after that are exported in CSV format.

For heart rate data, the smartwatch provides HR (Heart Rate) values and IBI (Inter-Beat Interval) values. These IBIs are used to calculate HRV (Heart Rate Variability), a metric used to address cardiovascular health problems and identify stressful moments. Using the RMSSD (Root Mean Square of Successive Differences) formula, that is presented in Equation 1 (where RR is the inter-beat interval value and N is the total number of inter-beat intervals), HRV is computed to give a measure of variability in the time intervals between heartbeats. As described by Peabody et al. [11], HRV is one of the best metrics used to approximate and identify stress moments and health problems. Tiwari et al. [14] demonstrated that a high value for the HRV represents a healthy state and a low level of stress and a low level of HRV indicates problems and modification in cardiovascular system induced by stress or anxiety. The sampling rate for heart rate data is set at 1 value per second, ensuring detailed and continuous recording of heart activity. Each row in the CSV file includes the HR value, the computed HRV, and a timestamp to maintain the order of the recordings. This structured format allows for efficient storage, retrieval, and visualization of data in the application.

ECG data are captured at a high frequency of 100 samples per second, providing detailed information about the electrical activity of the heart. Each recorded data point includes a timestamp, the ECG value, and a user ID to ensure the owner of the data is known. The key feature of ECG data is the QRS complex, which represents, as described in Goldberger et al. [2], ventricular depolarization and is vital for heart function analysis. The QRS complex is illustrated in Figure 1. The R peaks within this complex are particularly important as they mark the peaks of individual heartbeats. By measuring the time intervals between these R peaks, known as Inter-Beat Intervals (IBIs), we can find essential information similar to that obtained from heart rate data. The improvement made by this dataset is that ECG is more accurate than the sensor provided by smartwatches.

The application can be useful in finding these R peaks in order to calculate IBIs. These IBI values are used to compute Heart Rate Variability (HRV) using the same RMSSD formula applied to heart rate data. This process offers valuable insights into the health of the user and stress level. The data is organized into a CSV file with timestamp, ECG value, and user ID. This format matches the heart rate data file format to be able to import, in the analysis tool, both sets of data.

Visualization Techniques

StressVR uses multiple visualization techniques to convert raw sensor data into clear visual representations. This section describes the implemented features, focusing on 3D plotting of heart rate (HR) and ECG data, interactive data exploration, navigation into the environment, multi-dataset comparison, data cleaning and interpolation.

StressVR utilizes 3D plotting to represent HR and ECG data dynamically. Data points are plotted on three axes: x axis represents the time, the y axis represents the sensor value (HRV or ECG), and the z axis represents the user ID / dataset number.

This approach enables users to identify trends, anomalies, and correlations that might not be seen in normal 2D charts. The use of 3D plots eases the understanding of data and helps in the interpretation of complex patterns for the data that is disposed over time.

Interactive data exploration and navigation allows users to be engaged directly with the data. This is the main difference between the proposed application and the traditional 2D plots.

Users can navigate to the desired location within the scene and view the data from any angle. The user can select specific data points or intervals for detailed analysis, apply filters to focus on relevant parts of the data, and annotate (label) data segments. The annotation is made for a final interpretation, or for the use of dataset to train a ML model. The application uses intuitive VR controls for this interaction to provide an efficient analysis. Real- time manipulation of the data enhances user understanding about the data and the interpretation is made easier.

StressVR supports the visualization of multiple datasets simultaneously. This feature makes the identification of patterns and trends easier because the differences are observed across multiple datasets. By visualizing multiple datasets, users can draw conclusions and have a better overview of the data and the health condition that is analyzed. To ensure the accuracy of visualizations and the correct final interpretation, StressVR includes tools for noise reduction and data cleaning. Users can identify and remove irrelevant data points or intervals of data that does not represent a region of interest and refine the dataset for more precise analysis. This preprocessing step is essential for accurate visual interpretation of HRV or electrocardiogram data. By eliminating noise from the data, users can focus on meaningful variations in physiological signals and take important decisions.

An in-depth analysis was conducted regarding the different approaches that can be used in this application, from the types of data to be analyzed to the visualization techniques. Data visualization is used to visually analyze the behavior of the different variables in a dataset, such as a relationship between data points in a variable or the distribution of data. For this application, the appropriate analysis type is represented by the bivariate analysis because it helps to study the relationships between two variables, in this case the time and the sensor value. In other words, the need is to observe the evolution in time of the value of the sensor and to interpret the data accordingly.

There are a lot of visualization techniques in 2D that can be extended in 3D. Line plots are used to track the evolution of a variable over time but is inconvenient to use in 3D immersive environments. Bar plots are used to rank the data based on the category, a fact that does not help the objective of this application. Histograms are used to analyze the distribution of data. It can be used in this application to extract specific features. Scatter plots are similar to line plots, but it allows the use in 3D, as every data point is represented as separate object, based on the position. Heat maps graphically summarize the relationship between the two variables.

The objective of the application is to observe the evolution of a variable (sensor value) based on another variable (time) and to compare such plots (based on a third axis). In this case, the scatter plot is used because it can be included in 3D environments and represents a better option for interaction between user and data. This visualization technique, implemented in StressVR, transforms complex sensor data into interactive elements, improving the ability of the user or researcher to understand and analyze physiological data effectively.

IMPLEMENTATION

This section provides information about the setup of the environment in order to be able to run the application on the VR headset and information about the general implementation of the system.

VR Environment Setup

Unity is a cross-platform development tool for creating applications on Windows, macOS, Linux, mobile devices, consoles, and VR/AR headsets such as Meta Quest. Its IDE, visual scene editor and built-in tools support the entire development process, from design to deployment. The C# scripting language is used to control object actions within the scene, improving the interactivity and functionality of the application.

Meta Quest 3 offers a robust VR platform with powerful hardware components. The headset features 512 GB of memory, 8GB of DRAM, and advanced tracking technology. It simplifies the creation and deployment of immersive VR experiences. Thus, Meta Quest 3 provides the technical capabilities to create an impressive VR analysis tool.

Developing this VR application requires specialized tools and plugins to manage virtual environments and interactions:

- XR Plugin Management is a Unity subsystem that simplifies the integration and management of XR platforms. Its use helps the setup process, ensuring compatibility with the VR device.
- XR Core Utilities provides the essential tools and components for XR development in Unity.
- XR Interaction Toolkit offers a high-level toolkit for interactions like grabbing and throwing, user interface integration, locomotion, and an event-driven system for managing user inputs and interactions.
- Input System is the input handling for VR controllers.
- OpenXR Plugin offers support for deploying the Unity application to the Meta Quest 3.

System Implementation

The implementation of the StressVR application involves creating the user interface designed for effective interaction and data analysis in the VR environment. This section describes the main interface components and the elements added to ensure the VR experience. The interface, as shown in Figure 2, includes:

- Left action panel with the buttons: select, select interval, delete, annotate, filter, interpolate (1).

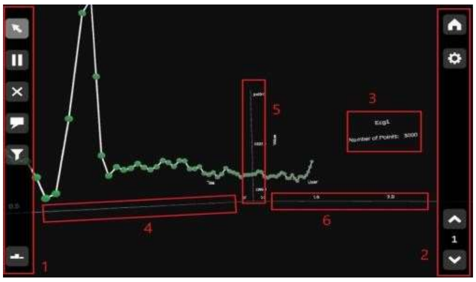

Figure 2 Interface components

- Right action panel with buttons: settings, home, save and change pages (2).
- Visualization area and 3D scatter plot with labeled axes for time, value and user ID (4, 5, 6).
- Datasets information panel showing metadata of loaded datasets (name, number of data points) (3).
- The data point info panel and data interval info panel containing information about selected data point and interval selected respectively.
- The delete data panel, label data panel, filter data panel, message panel (display feedback to user).

To ensure effective interaction in the VR environment, the next components were added to the objects:

- Tracked Device Graphic Raycaster to allow the users to interact with the UI elements within the VR environment using their VR controllers.
- Render Mode is set to World Space to provide a more natural immersive interaction.

These components and settings ensure the application is efficiently displayed in the 3D immersive environment, facilitating user interaction with the elements.

EXPERIMENTS

This section details the experimental scenarios designed to demonstrate the functionality of the StressVR application. These scenarios include dataset importing, data point selection, interval selection, data removal, data annotation, data filtering and saving modified datasets.

Importing Datasets

In this scenario, datasets containing heart rate data from a smartwatch and ECG data from a specialized sensor were imported into StressVR. The data, stored in CSV format, included parameters such as heart rate and heart rate variability (HRV) or raw ECG values.

The import process involves: selecting the type of data that will be imported (ECG or HRV), selecting the CSV files and visualizing the data (Figure 3 a.).

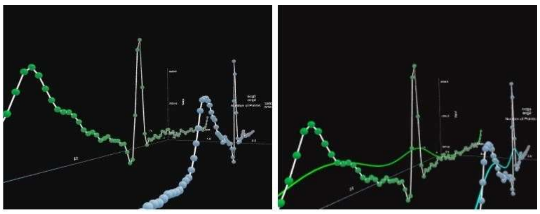

Figure 3 Two datasets imported a). no interpolation b). with interpolation

Data Point / Interval Selection

This scenario involved selecting individual data points and specific intervals from the datasets. Users can interact with the visualized data to highlight particular data points (Figure 4 a.) or select intervals (Figure 4 b.) for more detailed examination. This functionality allows users to focus on specific events or periods within the dataset. If simple selection is made (Figure 4 a.), a panel containing information about the point is displayed. The panel contains the id, the timestamp, value, user ID and the associated label. If interval selection is made (Figure 4 b.), a panel with information about the interval is displayed. The panel contains the differences on the three axes between the endpoints of the interval.

Data Removal

The data removal scenario tested the ability of the application to delete unwanted or noisy data points. Users can select and remove unnecessary data, ensuring a cleaner dataset for analysis. When a successful removal takes place, a “Deleted successfully” message appears. If there is an error, the message “Error in deleting the data” is displayed.

Deletion is done by selecting a point or interval and pressing the “Delete” button on the left panel. The user is prompted by a message to confirm. The graph updates automatically and the “Save changes” button appears. The feedback is assured by using messages that are displayed to the user, a fact that helps the user to better understand the actions made. The interaction is presented in Figure 5.

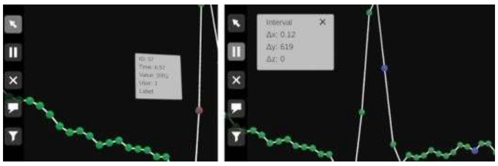

Figure 4 a). Simple selection. b). Interval selection

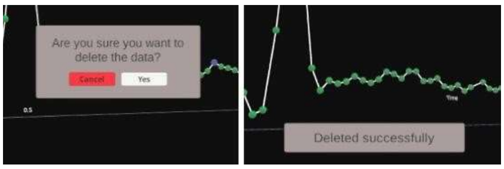

Figure 5 Removal of data

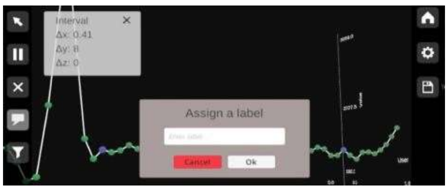

Figure 6 Annotation of data

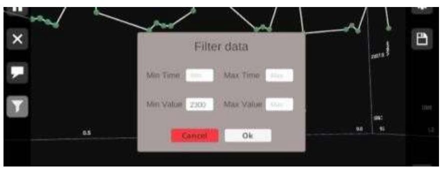

Figure 7 Filtering the data

Data Annotation

In this scenario, users annotate the data with custom labels such as “stress” or “no stress”. They can tag individual data points or intervals and receive a “Label added” message when successful annotation occurs. Errors in labeling are prompted with an “Error in annotating the data” message.

Annotation is done by selecting a point or interval and choosing the “Label” button from the left panel. The user types the new label in the input field and confirm. The graph is updated automatically with the new labels, and the Save button appears if changes are made. This interaction is presented in Figure 6.

This sequence of tasks represents the main purpose of the application. The idea of the system is to be able to view the data in an immersive environment for a better experience and to interpret the displayed data. The data is interpreted by being annotated by the user or researcher. In this way, at the end, the newly generated file will have the labels added by the user. The person that interprets the data can observe the patterns and annotate accordingly in order to obtain important conclusions.

Data Filtering

In Figure 7, data filtering is demonstrated by selecting the “Filter” button on the left panel. Users can input filtering criteria for time and value. When pressing “Ok”, the graph is updated. This functionality helps in extracting valuable insights of the data.

The scenario tested the ability of the application to filter datasets based on specific criteria. Users can view segments that meet the desired conditions such as: data points below a certain heart rate threshold, ECG data over a certain value or data from a period of time.

This supports focused analysis of relevant data subsets and a better understanding of segments from data.

Data Interpolation

Another feature of the application is the interpolation of data, presented in Figure 3 b. This feature is essential for allowing users to more effectively observe trends and, more importantly, to intuitively compare two datasets. The user can simultaneously view patterns and trends across multiple datasets, making it easier to extract key characteristics.

EVALUATION

The evaluation of the StressVR application is made by a cognitive walkthrough approach and by Nielsen's ten usability heuristic questions, for heuristic evaluation of usability. The purpose is to demonstrate the functional correctness, the overall usability of the application and the adherence to pre-established standards.

To perform the cognitive walkthrough evaluation, main scenarios were developed, and, for every scenario, five questions are addressed. The scenarios are: dataset importing, data point selection, data removal, data annotation, data filtering, data interpolation, modified dataset saving.
The questions addressed for every scenario are:

- Will the user understand what task they have to execute?
- Will the user be able to identify the correct interaction techniques (controls)?
- Will the user see the desired effect of their actions through appropriate feedback?
- Is there a risk that the user may select a different interaction technique (control) than the correct one (risk of error)?
- Will the user understand the system feedback in order to interact correctly?

After this evaluation, it was demonstrated that the interaction technique with the system is clear for the users, thus, they navigate through the scene easily and perform the desired actions. The actions that the user can take are well described, thus, incorrect actions cannot be performed.

The ten usability heuristic questions proposed by Nielsen are a set of guidelines for evaluating the usability of user interfaces. Developed by Jakob Nielsen, these heuristics provide a framework for evaluating the quality of the user interface, ensuring it is well-designed and provides a satisfying user experience. The system was evaluated by two reviewers who observed and analyzed the entire development and implementation phases without directly making any implementation or change. Table 1 presents the results of the evaluation. The score is 76.5, which means that the application has good quality, usability and offers a satisfactory user experience.

Heuristic question	1	2
1. Is the system status visible?	85	75
2. Is the system (game) designed according to real-world processes?	80	80
3. Does the user have the freedom to control the execution?	70	65
4. Is there consistency and adherence to standards?	90	85
5. Are there techniques for preventing errors?	75	70
6. Is the interaction based on recognition rather than recall?	80	75
7. Is there flexibility and efficiency in use?	70	65
8. Is the design simple and aesthetic?	85	80
9. Is the user helped to recognize, understand, and resolve errors?	75	70

10. Is there help and documentation available?	80	75

Table 1. Usability Heuristic Evaluation

To validate the advantages of the 3D VR approach, a comparative evaluation was conducted using three setups: a simple 2D interface, a normal 3D model (Unity interface) and the full 3D VR system used by StressVR. The results showed that the 3D VR interface provided a more intuitive, immersive experience, improving data interaction and understanding. Users preferred the 3D VR setup for its ability to explore and manipulate data spatially. Further testing, limiting users to 2D interactions within the VR environment, confirmed that the full 3D VR experience significantly improved user engagement and accuracy in data analysis and understanding.

CONCLUSIONS

The development of this interactive application followed the steps of the game development methodology, ensuring a high-quality final product. The process includes several phases: planning, design, implementation, testing, evaluation and optimization. Planning involved setting objectives and the main functionalities, identifying technical requirements and finding necessary resources for development using Unity and Meta Quest 3 platform. The design phase involved creating a detailed plan for the application, focusing on the user interface, game mechanics and interaction elements and techniques. Prototyping was an essential part of this stage because helped the continuous improvement of the system. For implementation, Unity was used to build the UI and core features for running the application on the VR headset. By testing and evaluating the system, there were found and fixed the errors and performance issues. Optimization was done by improving the frame rate and assuring a seamless experience for the user.

Analyzing the heart rate and ECG data is very important for obtaining information about the health condition of the user. This data is important to derive the heart rate variability. This physiological metric can indicate stress levels, cardiovascular health and overall well-being. A 3D visualization approach offers significant benefits over traditional 2D methods. It allows for a more valuable and intuitive visualization and exploration of complex datasets, identifying patterns and correlations that might be missed in 2D. Moreover, using VR improves the benefits of 3D by providing an immersive environment where users can interact with data in a more natural and engaging manner and observe them from any angle. VR offers a better understanding of data by interactive manipulation, which is not possible with standard 3D displays. This immersive experience can lead to more informed decision-making and better insights into the health data.

In conclusion, this application combines advanced visualization techniques with the immersive capabilities of VR to create a more effective and engaging tool for data analysis. This approach highlights the value of using innovative technologies to better analyze and interpret complex health data, making it easier to obtain insights and improve understanding and the decisions taken.

ACKNOWLEDGEMENTS

The research leading to these results is in the frame of the "EMPOWER. Design and evaluation of technological support tools to empower stakeholders in digital education" project, which has received funding from the European Union's Horizon Europe programme under grant agreement No 101060918. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

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