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Authors	Ó Riain, Eoghan;McVeigh, Joseph G.;Fullen, Brona M.;Martin, Denis;Murphy, David
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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Design of a Physiologically Based Feedback Loop using Biosensors for Interactive XR and Spatial Computing Environments

Eoghan Ó Riain
School of Computer Science & Information Technology, School of Clinical Therapies
University College Cork
Cork, Ireland
eoghanoriain@ucc.ie

Joseph G. McVeigh
Discipline of Physiotherapy, School of Clinical Therapies
University College Cork
Cork, Ireland
joseph.mcveigh@ucc.ie

Brona M. Fullen
UCD School of Public Health, Physiotherapy and Sports Science
UCD Centre for Translational Pain Research
University College Dublin
Dublin, Ireland
brona.fullen@ucd.ie

Denis Martin
Centre for Rehabilitation
Teesside University
Middlesbrough, United Kingdom
d.martin@tees.ac.uk

David Murphy
School of Computer Science & Information Technology
University College Cork
Cork, Ireland
d.murphy@ucc.ie

***Abstract*—This work investigates the signal characteristics of a physiological response (acute stress) and determines the viability of developing a Virtual Reality (VR) integrated physiologically based real-time feedback loop.**

This work has possible applications in physiotherapy and patient rehabilitation for long-term conditions including long COVID, persistent pain, and chronic fatigue. Using real-time physiological data, this approach can offer an individualised and immersive therapeutic experience. By synchronizing VR experiences with physiological responses, clinicians can optimise treatment efficacy and facilitate targeted rehabilitation efforts.

A design and early prototype were developed to include a feedback loop driven by an ensemble of biosignal signatures, correlating with stress responses, that adjusts dynamic components in the environment. The prototype shows the feasibility of developing a physiologically based XR environment suitable for virtual physiotherapy interventions.

***Index Terms*—Virtual Reality, Measurement, Feedback, Adaptive, Dynamic, Biosensors, Sensor Fusion**

I. Introduction

Virtual Reality (VR) has become an established technology with potential applications in various fields, including education and training. As VR advances, the opportunities for immersion increase greatly, leading to a stronger sense of Presence. Spatial audio and haptic devices are just some of the multimodal tools used to create a more immersive experience to draw users further into the virtual environment. However, in order to achieve a symbiotic relationship between the user and the system, a tight coupling is required. The integration of a feedback loop is one way of achieving the required coupling.

The majority of existing systems do not incorporate a feedback loop to create an adaptive experience which is a lost opportunity to achieve a stronger sense of Presence. [14]'s systematic review of immersive virtual reality applications identified immediate feedback as a common feature in VR for higher education. Immediate feedback refers to alert systems, audio cues, correct or incorrect actions, and other mechanisms for delivering information to the user based on their actions. Immediate feedback, as stated by [14], is a common feature in VR. However, an interaction feedback mechanism expands on this feature to create a more immersive, dynamic experience and is less common.

Insights from the field of Embodied Cognition can help develop a deeper integration between the user and the system. Embodied cognition refers to the idea that cognitive processes are deeply intertwined with the body and its interactions with the environment. It suggests that our thoughts, perceptions, and understanding of the world are not solely products of the brain, but are also influenced by sensory and motor experiences. Embodied cognition suggests that physical experiences contribute to the formation of memories and understanding. Gallese and Cuccio explored the implications for an embodied approach to cognition and refered to embodied cognition as a research program that emphasizes the role of the body in cognitive processes, rejecting the idea that cognition is solely based on computational processes in the brain [19]. In VR, interactive learning experiences can be designed to align with this concept by creating a sense of proprioception whereby the user can experience an enhanced sense of presence, realism, and interaction by allowing the body to sense its own position, movement, and orientation in space through sensory feedback. Borrego et al. carried out a study that showed that the sense of presence provided by VR elicited a greater sense of body ownership and self-location in a patient, thus improving the

virtual therapeutic experience [2].

The purpose of the current work is to determine if it is possible to create an interaction feedback loop to identify, monitor, and respond to a user's physiological response to an environment. Thus, creating a deeper integration between the user and the system through latent interactions. Similar work was carried out by Mevlevioğlu et al. where a real-time anxiety classification system was developed for VR integration with physiological data being gathered by biosensors [8]. It is our hypothesis that an interaction feedback loop can be used to enhance the user's embodied cognition and create an individualized experience. This individualized experience could then increase the user's sense of presence. It is proposed that this heightened sense of presence will be achieved by integrating a feedback loop into a dynamic and adaptive VR environment.

A benefit of such a feedback loop is that it potentially leads to a higher level of user awareness in the environment. A further benefit of a physiological feedback loop is in its applications as a tool for monitoring a patient's condition and progress whilst enhancing their physiotherapy experiences. We have designed an experiment to investigate the feasibility of incorporating a feedback loop based on biosensors.

II. Background

To design and develop an effective interaction feedback loop, the various components involved in its design must first be reviewed and understood. This includes understanding what a feedback loop is. As well as this, the physiological response that the feedback loop will be tasked with identifying must be investigated to determine what biosignals correspond to the physiological response. The final step is the how. How can the biodata be fed into the feedback loop and how will that data be analysed.

A. The Applications of a Feedback Loop

Abrams and Gerber [18] define a feedback loop in game design as "a series of formative and summative on-screen assessments that work in concert to continually provide immediate and, thus, current information to help the student" in achieving a specified goal. The feedback loop develops as a user commences the experience and interacts with the environment. The application of a feedback loop within game design can be related to Vygotsky's study on the zone of proximal development as described by [15]. This study explores student engagement, determining that an individual will abandon a task should it be perceived as excessively difficult or exceedingly easy. Therefore, the feedback loop could be used to adapt the task to provide the appropriate difficulty for a specific user.

VR is a technology that is also increasingly being utilized in physiotherapy settings. Asadzadeh et al. explored the effectiveness of VR-based exercise therapy in rehabilitation. This study concluded that VR interventions had a positive impact on various rehabilitation objectives [1]. This conclusion was also reflected by Bateni et al, who demonstrated the benefits associated with the application of VR for those with conditions including gait and balance disorders as well as pain management [13]. One example where this technology would be effectively utilised is with patients living with long-term conditions, such as persistent pain, long COVID, and chronic fatigue, who often experience persistent physical symptoms affecting their health. By using a physiological feedback loop within a VR environment as part of their rehabilitation, patients can engage in immersive exercises tailored to their specific needs, while real-time physiological data such as heart rate (HR), respiratory rate, and oxygen saturation are monitored and analysed. This feedback would enable clinicians or the VR environment to adjust therapy sessions in real-time, ensuring that exercises remain within safe and effective parameters.

B. What is Stress?

Stress is a physiological response to endogenous and exogenous stressor stimuli. Stress can be biologically identified by measuring a subject's cortisol levels. Cortisol is the main glucocorticoid released from the adrenal cortex, and is commonly referred to as the body's stress hormone [20].

There are two different types of stress - acute and chronic stress. Acute stress is a short-term response to a stressor stimuli. It is characterised by physical and emotional changes that help the body cope. These changes include increased heart rate, breathing, and blood pressure; sweating; muscle tension; and a sense of alertness. Whereas chronic stress persists over a prolonged period. It can be caused by ongoing problems in daily life, or by major life events. Chronic stress can lead to a variety of health problems, including high blood pressure, heart disease, obesity, depression, and anxiety.

For the purposes of the current work, acute stress will be the focus. Understanding the physiological signature of stress and developing a feedback loop to identify acute stress and adapt the environment in response is the primary goal of the work.

C. The Biosignals, Biodata and Biosensors

The definition of a biosignal is any physiological signal emitted from a live subject which can be measured continually. Biosignals are commonly measured to determine various aspects of an individual's physiological response to internal and external stimuli. One common example of when biosignals are used is when a person's temperature is taken to identify if said person is unwell. Whereas electroencephalography (EEG), heart rate variation (HRV), and galvanic skin response (GSR) are often used to determine a person's emotional state [11].

A physiological stress response refers to bodily changes triggered by events or conditions, known as stressors. To achieve homeostasis in response to stress, the body regulates functions such as heart activity, temperature, respiration, blood pressure, and glucose levels, essential for survival through a range of environmental conditions [12].

Biosensors are used to record biosignals that emanate from the body, which carry biodata that represent physiological

changes. Physiological changes occur when alternating between different emotional states. Signal measures such as HRV, GSR, Blood Volume Pressure (BVP), Electrodermal Activity (EDA), EEG, and body temperature are primary indicators of human emotional state [7].

Galvanic Skin Response (GSR) is a biosignal that identifies the electrical conductivity of the skin. The conductivity of the skin varies over time due to the activation of the eccrine sweat glands. In the context of electrical conductivity, the sweat glands act as variable resistors. The addition of fluid to the glands decreases the skin's resistance and increases its conductivity. Sweat is a common indication that an individual is exercising. However, [5] found that emotions, including frustration, stress, or excitement, can induce a physiological response resulting in the activation of the sweat glands. For this reason, GSR is considered a reliable indicator of stress. The peaks of GSR usually appear between 1.5 and 6.5 seconds after the onset of stressor stimuli.

In the area of brain activity, [22] determined that EEGs have been shown to be effective in assessing human experience. [22] employed EEG, GSR, and Photoplethysmography (PPG) biosensors to record user data as they were non-invasive, easy to deploy, and could work with a virtual environment in a lab setting. From these findings, the use of an EEG as a non-invasive method of measuring the subject electrical brain activity and streaming the biodata is appropriate in the context of assessing the subject physiological response via a feedback loop.

Different biosignals are used to represent different physiological responses, each with their own characteristics and features. For instance, BVP measures pressure, whereas EDA measures conductance. These features need to be processed in order to interpret and compare the data, for example, the power spectrum for the EEG sensor and the number of peaks for the GSR sensor [22].

Muscle activity is another range of biosignals that could be monitored to evaluate a subject's latent physiological response to endogenous and exogenous stimuli. An electromyography (EMG) biosensor measures the electrical activity produced by skeletal muscles. Electrodes placed on the skin detect and record muscle activity, providing real-time feedback on muscle contraction intensity and timing. Therefore, an EMG could be used to monitor and assess a user's muscle function. The integration of EMG biosignals into a real-time feedback loop as part of a VR experience could be used in the context of physiotherapy and rehabilitation to monitor progress and tailor treatment plans for patients with long-term conditions.

D. Data Fusion

The term 'Data Fusion' refers to the integration of data and knowledge from multiple sources. [4] described two categories of fusion, early and late fusion. Early fusion is implemented in the first stages of an application and refers to the combination of the raw data (data fusion) or the extracted features (feature fusion). Late fusion refers to the combination of the results of different algorithms and is implemented as the last step of the analysis' pipeline. When dealing with multiple biosignals, we need to address the issue of bringing the signals together so they can be used collectively to ascertain the state of the user in that moment.

III. Design

In this research, feedback loops are considered to evaluate the user's biosignals in real-time and adapt the VR environment. Within this environment, the subject will be required to carry out a task that has been designed to induce a particular physiological response. It will be the role of the feedback loop to assess the subject's biodata and adapt the environment to maintain the appropriate physiological response. Therefore, the characteristics of the desired physiological response must first be identified and understood to optimize the feedback loop.

Acute stress is the physiological response of interest in this research, and therefore the first stage of the design process is to identify its biodata signature. Once identified, the feedback loop will analyse the biodata in real-time to identify signs of acute stress in the user. When a stress response has been registered by the feedback loop, the VR environment will adapt in response to this.

A. What are the characteristics/features of stress?

To identify if a user is in a state of stress using an interactive feedback loop, the biological characteristics of stress must first be understood. [21] investigated the effect of different physiological modalities in stress detection. They identified a combination of the subject's heart rate and the electrodermal activity provided a reasonably accurate stress identifier. In instances of stress, they found that the subject's body sweat and skin conductance increased. Regarding the subject's HR, the body's coping mechanism to stress is that the blood circulates faster through the body which subsequently delivers more oxygen to the skeletal muscles and organs to counter the stressor [12]. This can be seen as a decrease in the subject's Inter-Beat Interval (IBI) or an increase in their heart rate. To measure the subject's heart activity, the IBI was identified as an appropriate measure of the subject's heart rate. The IBI signal refers to the distance between detectable heartbeats in seconds. Thus, providing a more accurate unit of measure than the standard heart unit of beats per minutes (BPM).

EEG signals are another suitable indicator of a subject's response to stress. [16] found that the EEG alpha signals increased in intensity when the subject was calming down from stress, which is also interpreted as decreasing alpha levels indicating an increase in the stress levels. [10] noted that theta signals are detected in moments of anxiety, behavioral activation, and inhibition, hence, increasing theta waves imply anxiety or stress. The standard bandwidth of the clinical EEG signal analysis extends from 0.5 Hz to 70 Hz [10]. The bandwidth is then divided into five waves. The wave types, their associated frequency in Hertz (Hz), and the mannerisms they represent in the subject are summarised in Table I.

TABLE I
THE VARIOUS BRAINWAVE TYPES AND THEIR ASSOCIATED FREQUENCY BANDS (HZ) AND STATES [9].

Wave Type	Frequency	Subject Status
Delta	0.1 - 4	Deep Sleep
Theta	4 - 8	Daydream, drowsiness
Alpha	8 - 13	Conscious relaxation
Beta	13 - 30	Focused, engaged
Gamma	30+	Cognition, memory

To identify a stress state in the subject the Alpha (8-13 Hz) and Theta (4-8 Hz) wave bands will be the primary focus.

The subject's body temperature and skin conductance can be identified from a wearable biosensor located on their wrist. Variations in skin temperature are a key signature of stress conditions and anxiety in a subject. A subject's stress response generally includes the release of stress hormones that boost the alertness of the body, resulting in an increase in HR, the blood supply to the muscles, respiratory rate, skin temperature due to higher blood circulation. Wearable sensors placed directly on the skin can be used to monitor temperature variations in a subject. There are many locations on the body where optimal temperature variation readings can be taken. However, under stress, temperature variations may differ at different locations on the body.

It has previously been reported that in test subjects completing the Trier Social Stress Test [3], the temperature of the fingertips, finger base, and hand palm decreased significantly. In contrast, the temperature of upper-arm shows significant increase under the test conditions [6]. Variations in temperature on different parts of the body as identified by [6] are summarised in Table II.

TABLE II
TEMPERATURE VARIATION COMPARISONS BETWEEN DIFFERENT BODY PARTS WHILST UNDER STRESS [6].

Feature	Increase	Decrease	No Change
Body	1	0	0
Finger	0	4	1
Whole Facial	4	1	0
Temperature	0	1	0
Forehead	3	0	2
Periorbital	1	0	1
Nose	0	3	0
Maxillary	0	2	0

B. Data Fusion

To analyze features of stress the associated signals must first be identified, processed and then interpreted. Once the individual signals have been analyzed the signals must then be combined to give a complete picture of the overall stress response. The combining of signal data is known as Data Fusion, which is a challenging undertaking as the different signals are measuring different features on different time windows. It is important that the streamed data is properly aligned and congruent.

C. Physiological Response Signature of Stress

Of the sensors and biosignals discussed earlier, EEG Theta, Low Alpha, High Alpha, and IBI, GSR and Temperature is proposed as a suitable ensemble of signals to represent a user's physiological state.

To determine their physiological response, the feedback loop must first establish a baseline set of signals for the current user. The baseline data can then be used as the reference point from which deviations would be measured. Table III contains the changes identified to reflect a stress response based on the main signal characteristics of stress.

TABLE III
BIOSIGNAL SIGNATURE FOR STRESS WHEN COMPARED WITH BASELINE BIOSIGNALS.

Biosignals Decreasing	Biosignals Increasing
Low Alpha	Theta
High Alpha	GSR
IBI	Body Temperature

The biosignals are measuring different aspects of physiology, using different measures with different values and ranges and scales. Each biosignal tells us something about a particular aspect of the user's physiological response to stress. They must then be brought together to establish a big picture overview of the physiological response. The individual values are not the area of focus here, but the directions and rates of change are. For instance if Theta rises and High Alpha decreases then together these would signal a change in stress. To bring the signals together we need to normalise the individual values and then standardize them on a unitless scale.

Once we have established the user's baseline, we can map the individual signals onto a scale where the baseline is given a nominal value of zero. Signals can move above (positively) or below (negatively) the baseline of 0.

To assist in data evaluation, stress levels will be calculated on a percentile scale. The values of the theta, GSR and body temperature biosignals would need to increase to represent a stress response, as listed in Table III. The baseline will represent a normalized value of 0, and the maximum value recorded will be represented as 1. Any values recorded below the baseline value will be set to a normalized value of 0. Signal values recorded between the baseline and the maximum value will also be normalized and indicate the extent that the signal is increasing.

Inversely, the low alpha, high alpha and IBI biosignals were identified as signals that would need a decreasing value to represent a stress response (Table III). In a similar process, the baseline values for these signals will be normalized to a value of 0. However, any value recorded above the baseline will also be set to 0. The lowest value recorded for each of these signals will be normalized to 1 and any values recorded between the baseline and the minimum value for that signal will indicate the extent that the signal is decreasing.

Once the system identifies this signal trend from the combination of signals that make up the signature of stress in the

subject's real-time streamed biodata, the system will register that the subject is becoming stressed (Table III). Fig. 1 provides a graphical representation of how the signal data is evaluated to determine the user's level of stress.

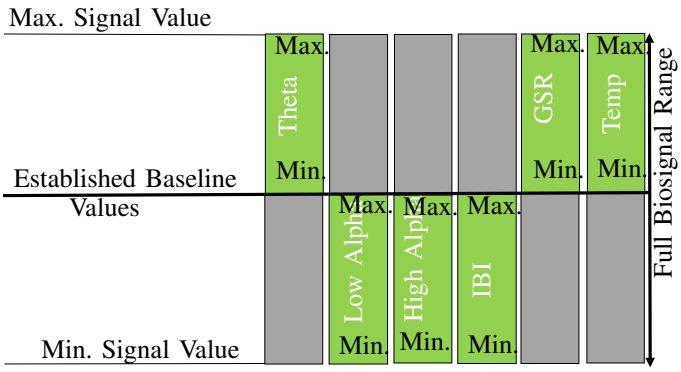


Fig. 1. Stress Calculation Representation.

D. Design of the Feedback Loop

A feedback loop in VR development refers to a systematic process wherein information, insights, or evaluations are continuously collected, analyzed, and utilized to iteratively refine and enhance various aspects of an experience throughout its development lifecycle. This cyclical mechanism is essential for improving the overall quality and functionality of the experience. The feedback loop typically involves the key components outline in Fig. 2

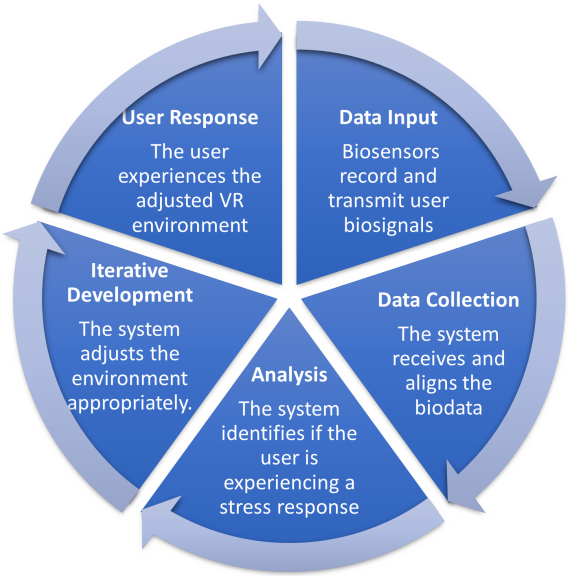


Fig. 2. Feedback Loop Design Cycle.

The design concepts previously discussed were integrated into a prototype feedback loop in order to determine its viability. The main goal of the prototype is to determine if the biosignal data could be streamed into the system as well as linking assets within the VR environment to adjust dependent on the streamed data. Therefore, a biosensor was selected and a VR asset was created and assigned as an adaptable component.

E. Prototype Biosensor Selection

The Empatica E4 was selected as the biosensor to be integrated into the prototype (https://www.empatica.com/). The Empatica E4 is a wearable wristband containing a PPG and an EDA sensor. The device is a consumer and research-grade unit used to measure blood volume pulse (BVP) from which the heart rate variability can be derived. The device also utilises the GSR sensor to measure the constantly fluctuating changes in certain electrical properties of the skin and an infrared thermopile to read the peripheral skin's temperature. It is for these reasons that the Empatica E4 was selected as the appropriate biosensor to be integrated into the prototype.



Fig. 3. Empatica E4.

Each biodata stream from the Empatica E4 delivers its sample data with an associated timestamp. The timestamps included within the streamed data are calculated in reference to the first packet of data received by the E4 streaming server. When the system receives the first packet, the timestamp is recorded, and any subsequent packets calculate their timestamp based on their predecessor. Each data stream has its own sampling rate. Therefore, the timestamp data can be used for data fusion.

F. Prototype Adaptable Asset

A heartbeat audio asset was selected as the adaptable component for prototyping. The aim of this asset was to mirror the user's heartrate as recorded by the Empatica E4. A 60 BPM heartbeat audio file was added to the user's virtual source. In order to adjust the rate at which the audio file is played, the pitch of the audio source component needs to be adjusted. This, in turn, will increase/decrease the BPM of the heartbeat. To do this, a script was generated to initialise the AudioSource.Pitch variable as a factor of 1 and locate the Empatica E4 game object which contains the ICATEmpaticaBLEClient script.

Once found, the AudioSource.Pitch variable was set to the EmpaticaE4Controller IBI value by getting its inverse value. This script would now adjust the pitch of the heartbeat audio to match the BPM of the user's heart rate.

G. Prototype Viability

The Empatica E4 biosensor was successfully integrated into the VR environment and an adaptive asset was created that would respond to the user's biosignal. From initial testing of the prototype, it was determined that these features operated as required. Therefore, the prototype was deemed successful.

The prototype verified that the user's biosignals could be used to adjust a dynamic asset in a VR environment in real-time. By integrating an interaction feedback loop, the system can be optimally calibrated to respond to stress signatures.

Assets within the VR environment will be dynamic and adaptive. This will enable the system to adapt them depending on the subject's physiological response. These assets will be used to evoke a stressing or calming response within the user by manipulating visual and auditory cues.

Each dynamic asset will be driven by the system feedback loop. This allows the asset to adapt accordingly in order to bring the user within the desired stress range. This could be, for example playing calming music should the stress level exceed the desired stress band, or tense music should the stress level fall below said band.

The feedback loop requires a process of delicately balancing stressor and calming cue activations, including transitions in and out of various states.

IV. Proposed Experiment

To evaluate this feedback loop integration, we intend to run a pilot study. We plan to use a combination of qualitative questionnaires to determine perceived stress, and compare that with measured physiological stress signals from the biosensors.

V. Discussion

The development of an interaction feedback loop that responds to a subject's latent interactions is an important step toward creating dynamic and personalized experiences for VR users. The relevance of this work lies in its potential to create a stronger sense of presence for the user in a VR environment by achieving a symbiotic relationship between the user and the system.

Further development in this area will lead to a more accurate and sensitive analysis of a subject's physiological response to stimuli. This design focuses on identifying signs of acute stress and having the system respond accordingly. This work can be further developed to identify other physiological responses. Examples of these applications could include identifying concentration in the subject for educational applications or identifying relaxation in well-being applications.

In this work, the biosignals associated with a physiological stress response were identified and the feasibility of streaming that biodata from each of the corresponding biosensors was assessed. It was surmised that having data streamed from multiple biosensors may result in a misalignment of data, resulting in an inaccurate reading of the subject's physiological response. Therefore, the process of data fusion was identified as an appropriate solution to aligning data from multiple sources. The next stage of this work will be to develop the interaction feedback loop and integrate it into a dynamic and adaptable VR environment before carrying out user testing.

The advantage of using an interaction feedback loop that will analyse and respond to a subject's physiological responses is that it can enhance the user's embodied cognition and create an individualized experience. Consequently, this individualized experience can then increase the user's sense of presence.

The applications of such a feedback loop in a VR setting are far-reaching. By integrating an EMG biosensor stream into the feedback loop, the VR experience could be used to assess and evaluate a user's neuromuscular response, as well as their physiological responses. This functionality could be used in a physiotherapy setting to monitor a patient's engagement and progress as part of their rehabilitation. A real-time analysis of a combination of a patient's neuromuscular and physiological response would be beneficial in the treatment of patients with long-term conditions, such as persistent pain, long COVID, and chronic fatigue. It would allow the clinician to monitor a patient's condition and progress, whilst providing them with an individualised VR environment for their rehabilitation.

We acknowledge that there are limitations in the proposed design. The use of a single biosensor and adaptive element constrains the system's ability to capture a broad spectrum of biological signals. These limitations, however, are recognised as part of an incremental development process. Future iterations will address these constraints by incorporating additional biosensors and adaptive elements.

The next stage of this work will be to develop a physiologically based feedback loop that will adjust dynamic components in the environment depending on the users' stress levels. It is proposed that this will integrate multiple biosensors and process their data streams to measure the users' stress levels in response to stimuli in real-time based on the learning outcomes of this paper.

Once this feedback loop is shown to work, it opens up the possibility to use AI and Machine Learning as an adaptive layer to drive the simulation, creating a fully dynamic and responsive system. With AI integration, the simulation will be allowed to continuously learn from new data, adapt to changing conditions, and refine its predictions over time. By leveraging AI and Machine Learning, the system can identify patterns and anomalies that might be missed by traditional methods, enhancing its accuracy and efficiency. Additionally, the adaptive nature of this approach means that the simulation can evolve in real-time, providing more relevant and actionable insights as it responds to new inputs.

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