PhysioHMD: A Conformable, Modular Toolkit for Collecting Physiological Data from Head-Mounted Displays

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ABSTRACT
Virtual and augmented reality headsets are unique as they have access to our facial area: an area that presents an excellent opportunity for always-available input and insight into the user's state. Their position on the face makes it possible to capture bio-signals as well as facial expressions. This paper introduces the PhysioHMD, a software and hardware modular interface built for collecting affect and physiological data from users wearing a head-mounted display. The PhysioHMD platform is a flexible architecture enables researchers and developers to aggregate and interprets signals in real-time, and use those to develop novel, personalized interactions and evaluate virtual experiences. Offering an interface that is not only easy to extend but also is complemented by a suite of tools for testing and analysis. We hope that PhysioHMD can become a universal, publicly available testbed for VR and AR researchers.

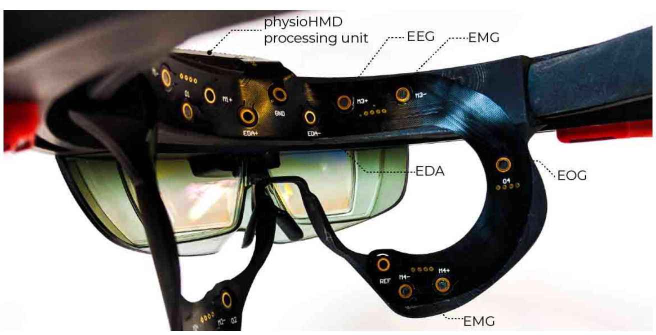

Figure 1: View of PhysioHMD hardware setup for AR experience. Gold plated electrodes and the flexible printed circuit board (PCB) record data through the contact with the skin.

ACM Classification Keywords
H.5.1. [Information interfaces and presentation]: Multimedia Information Systems - Artificial, augmented, and virtual realities. H.5.2. [User Interface]: Input devices and strategies

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Author Keywords
Affect recognition; virtual reality; augmented reality; physiological signals; BCI; behavioural measures

INTRODUCTION
Augmented Reality (AR) and Virtual Reality (VR) technologies, hereafter referred jointly in the context related to our system as extended reality (XR) technologies, have enjoyed increased popularity in the last few years thanks to the emergence of inexpensive and easy to deploy headsets. While XR technologies primarily support applications in the entertainment and gaming industry, they are also increasingly used in health care and human behaviors research to treat anxiety, phobias, psychosis, and post-traumatic stress disorder (PTSD). In both entertainment and health care applications, it is essential to understand the behavior, performance, and engagement of the user [22, 12, 3]. In clinical settings, XR technology has recently gained much interest because it enables novel, promising methods for treating anxiety and other mental disorders [15]. XR-based therapy is also opening up new and exciting opportunities for pain management and personalized physical and sports therapy [16, 5].

Typically XR based therapy requires that the user not just wear an HMD, but also an array of other sensors and devices that enable real-time monitoring of the user's physiological and cognitive state, for instance, electrocardiogram (ECG) and Electrodermal Activity (EDA) are used to understand emotional arousal and is used to identify the magnitude of the emotional response. Electrooculography (EOG) and Electroencephalography (EEG) provide data relevant to information about attention as well as valence, and Electromyography (EMG) provides data on facial expressions linked to positive or negative valence. This sensing technology is not just cumbersome to set up and wear, but it is also very costly, not standardized and often errors prone. To overcome these problems, we are developing a new platform, called PhysioHMD, that consists of both hardware and software, and that will make collecting and using information about the internal state of the user cheap and easy. Offering a standard for obtaining and comparing data across different users, sessions and study settings across multiple disciplines.

RELATED WORK
XR technologies offers the potential to develop human testing and training environments that allow for the precise control

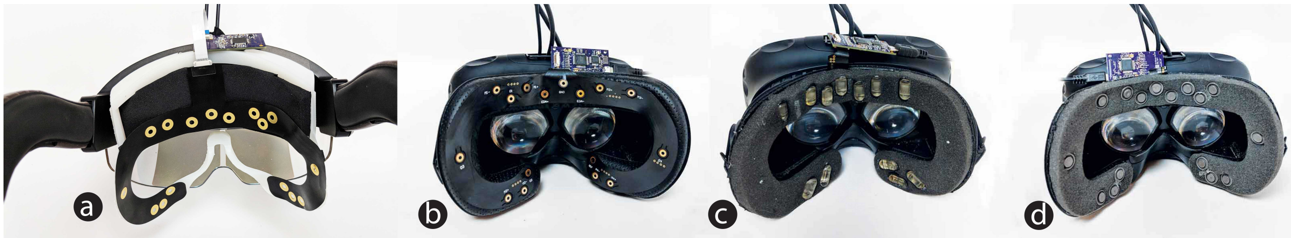

Figure 2: The image depicts every headset variation explored during this research. a) AR headset with flexible pcb & gold plated electrodes. b) VR headset with flexible PCB & gold plated electrodes. c) VR headset with hydrogel electrodes. d) VR headset with Ag/AgCI electrodes.

of elaborate stimulus presentations in which human cognitive and functional performance can carefully be evaluated and rehabilitated. In the case of AR, measuring focus and attention in learning/training scenarios is an essential component of the evaluation of this novel application which is gaining traction in industry.

Emotions are multifaceted events with corresponding physiological signs as well as human expressions [25]. Even though the majority of existing methods for automatic emotion recognition are based on audio-visual analysis [7], there is an increasing body of research on emotion recognition from peripheral and central nervous system physiological responses [23, 20]. There are advantages to using physiological signals for emotion recognition as opposed to using audio-visual signals. They cannot easily be faked, they do not require a front-facing camera, and they can be used in any degree of illumination/noise. Moreover, they can be combined with audio-visual modalities to construct a more robust and accurate multi-modal emotion recognizer [7]. A system like BIOPAC [24] is now being employed in a variety of applications [6, 28] for measuring facial movements using standardized tools such as Ekman and Friesen's Facial Action Coding System (FACS) and facial electromyography (sEMG). There are some startup companies like emteq [8] and mindmaze [19] that are working on toolkits focusing on bringing affective data to VR. However these setups focus only on EMG, and not much it is known about their setup and high price tag.

Filmmakers, entertainers and other storytellers are trying to figure out what XR as a medium might mean for their respective fields. Some interesting experiments that make use of physiological or affect data include PsychicVR [2], a VR system that integrates a brain-computer interface device with a VR headset to improve mindfulness while enjoying a playful, immersive experience. The interactive storytelling platform PINTER [10] uses physiological data to drive the unfolding of a plot. PINTER features an underlying narrative that consists of a medical drama which combines aspects of medical practice with the evolution of personal relationships between lead characters. Entertainment work like those mentioned above can leverage from a system like PhysioHMD to drive the immersive experience with the audience, and to explore new ways of telling a story.

PHYSIOHMD

PhysioHMD is a sensor and computing platform developed to support the analysis of multi-modal data related to the behavior and responses of a user, with the goal of enabling evaluation and customization of virtual experiences. This platform is consist of hardware and software.

Although hardware costs have come down for XR devices, researchers still do not have access to simple interfaces for deploying Virtual Environments (VEs), interfaces that require little knowledge of game engine content creation, sensor data, data logging and data visualization. Given these constraints, we compiled a list of requirements for the PhysioHMD platform:

1. A plug and play pipeline that can be deployed with minimal development effort.
2. Physical form factor must be comfortable to the user and easy to use.
3. System supports standard implementations of existing algorithms, feature extraction, and classification.
4. Offers a publicly available open-source code base for use and further improvement by the community interested in this body of work.
5. Includes a game engine interface with sample scenes and relevant tools.

Hardware

There are two main components to the PhysioHMD hardware. First there is the main PCB, an analog front end that collects bio-potential signals from muscle movements, eye movements, skin response and brain signals. Second, there is an ergo-electronics face-pad, a flexible PCB with gold-plated pickup electrodes that can connect to electrodes like Ag/AgCl (silver/silver chloride), hydro-gels or can be used by themselves as depicted in Figure 2. The PhysioHMD system collects sEMG, EEG, EDA, ECG and eye-tracking data.

Electronics

We chose to build our hardware to capture the bio-signals coherently and to avoid the inconvenience caused during the setup of multiple signal acquisition devices as shown in Figure 4 a. We used a pair of TI ADS1299 (ADS) as the front-end for the Analog-to-digital converter (ADC) operations: one ADS is used for sEMG and the possibility for EOG data acquisition

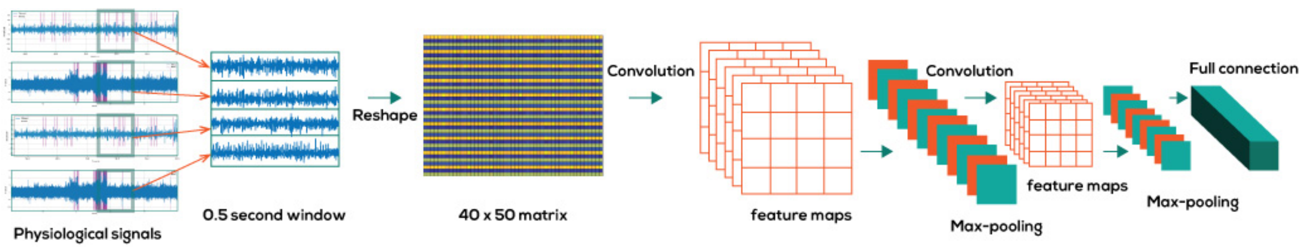

Figure 3: The process of our classification systerm and the CNN architecture used.

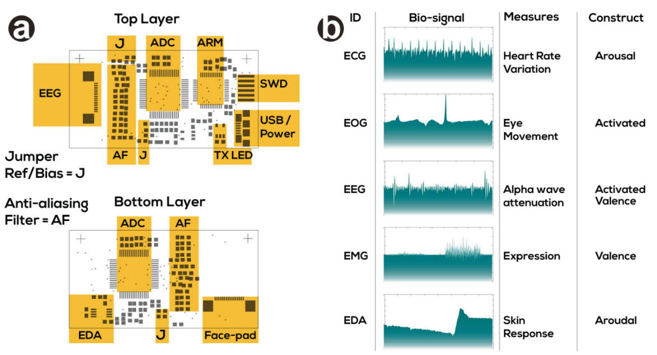

Figure 4: a) PCB configuration is depicting locations of main components on top and bottom planes. b) A Sample of signals gathered from PhysioHMD and their relevance in gathering affective state data.

while the other ADS acquires the frontal EEG data. Both the ADS are controlled by an ARM Cortex M0+ processor using SPI communication standard. Our PCB design provides flexibility on the board configuration by exposing multiple jumpers of both ADC's Reference and Bias. Communication with the PC is done by using the inbuilt USB interface. We use anti-aliasing filters before both ADC's and sample at 500Hz. We also integrated EDA measurement by using a voltage divider and a bandpass filter of 1.5 Hz to 15 Hz to remove artifacts. Then, we buffer the signal with an amplifier of gain 2 V/V and use ARM's ADC to sample the data.

Electrodes

We built and tested the sensing face pads that integrate the bio-signal sensors for detecting affect (Figure 3b) of users into two HMD platforms: one into the face cushion of an HTC VIVE VR headset and the other on the Meta 2 AR headset. To fit into an HMD face-pad, we determined it best to develop a flexible PCB that connects directly into the PhysioHMD's face-pad. The flexible PCB has gold plated pads which can either be used as standalone electrodes or as a connector compatible with external electrodes.

We chose to place the EDA electrodes on the forehead region because it is one of the regions most dense with sweat glands which provides arousal information. We placed sEMG electrodes above the eyebrows on the *frontalis* muscle and on cheeks on the *zygomaticus* muscle, providing insight into facial muscle activation. Eye movement is measured by setting EOG Vertical (EOGV) and EOG Horizontal (EOGH) electrodes in a standard placement. Further, we set EEG electrodes according to the 10-20 international electrode system on the user's frontal lobe.

Software

The software side is similarly composed of two main components. First, a signal processing component with normative data for signal pre-processing, feature extraction and a multivariate visualization method for data interpretation by end-users and second, a game engine package that can be dropped in any virtual scene.

Machine Learning for Pattern Recognition

We use a LeNet-5 [11] five-layers CNN architecture to classify the collected data as shown in Figure 3. There are two convolution layers and two pooling layers, with one full-connection layer. Convolution layers are used to extract the main feature while pooling layers will subsample the feature maps. We reshape the multichannel data into a matrix and use a 3*3 size convolution kernel in the first layer and third layer. In the second and fourth layers, the subsample window size is 2*2, and max-pooling is used. In the full-connection layer, rectified linear units [21] are used to improve the nonlinear performance of the network.

To train the network, we collected data from 6 users (three females and three males ages 19-30) for 12 different expressions. As part of the data collection procedure, we asked the users to put on our physioHMD prototype and repeat the expression for 12 times for 5 seconds with intervals of 3 seconds. The captured data is then pre-processed before feeding into the network. Notch filters are used to remove the power line interference at 60Hz and 120Hz, and a high-pass filter is applied to cut off the low frequencies below 30Hz. We then label the time sequence sEMG data for each expression.

A 0.5 second time window is used to segment the multichannel time series data into subsequences. Every subsequence is a training or testing sample. The label for a sample is decided by choosing the principal type, which takes the maximum percentage in marker vector. Then follow a one-hot encoding [17] to re-encode the labels.

We take advantage of data augmentation [13] paradigm to reduce the effects of over-fitting. The augmentation generates sEMG signal translations and horizontal reflections increasing the size of our dataset. Whenever we collect different expression samples, we get neutral expression samples in addition to the specific expression being measured, this way we have mostly neutral samples in our dataset.

Method	Natural	Happy	Sad	Excited	Angry	Flirt	Quiver	Rage	Sarcastic	Shock	Snarl	Wink
Kats.	95.7%	98.9%	76.2%	—	80.0%	—	—	—	—	92.1%	—	—
Ours	97.2%	98.8%	79.4%	97.1%	97.6%	54.4%	74.0%	96.8%	84.9%	79.3%	97.9%	99.2%

Table 1: A comparison of facial expression recognition accuracy between Katsuhiro's method and our method

We use 0.5 dropout rate to avoid over-fitting [26] in the training process. From this, we get a learning rate of 0.001 this parameter tells the optimizer how far to move the weights in the direction of the gradient for a mini-batch. In 30 minutes and 800 iterations, our optimized network sees a classification accuracy in the training set of 99.8% and 92.3% in the testing dataset.

Skin conductance response (SCR) is considered to be useful as it signifies a response to internal/external stimuli. We follow Kim's et al. [14] method for SCR extraction from EDA signals by reducing the sampling rate to 20 samples per second, differentiation and subsequent convolution with a 20-point Bartlett window. This procedure yielded the output waveform shown in Figure 5b for the input signal shown in Figure 5a. The occurrence of the SCR was detected by finding two consecutive zero-crossings, from negative to positive and positive to negative. From this, we get the SCR and the peak which does not show exponential decay, depending on the context (e.g., if two SCRs occur close together in time, the first response may not decay before the second begins, yet this is not considered an artifact)

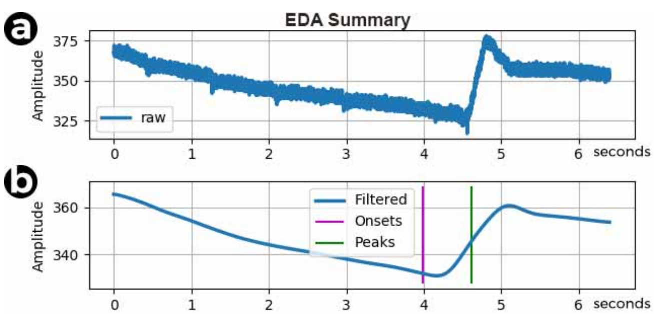

Figure 5: Six seconds of EDA signal recording showing a signal peak due to abrupt arousal. a) Typical waveform of EDA under emotional stimulation. b) Output signal from detection module from signal in a).

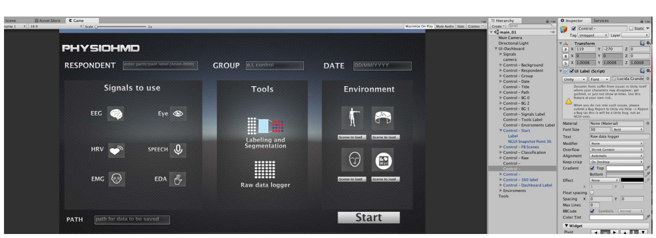

Figure 6: Unity package main dashboard, where users can select signals to measure, methods in which to segment data, and environments to test within.

Game Engine Integration

To facilitate the integration, we have encapsulated it into a Unity3D package. By encapsulating the platform, less experienced users can drop the package into an empty or already built environment and access our tools. The sample scenes included within the package are set with default configurations that can easily be customized with the exposed parameters in the editor. The main scene is a dashboard (Figure 6) for the person running the study, and here the user can select the signals of interest, choose our data segmentation tool, or merely record raw data. Once those parameters are selected, the user can choose to use one of the demo scenes. Lastly, the user can also choose to take information from external API or SDKs. We show those utilities by integrating aGlass SDK [1] to provide a point of regard (POR) data and Beyond Verbal affective speech recognition. These demo scenes were created with the intention to meet most user cases in XR behavioral research.

1. A full body inverse kinematic (IK) scene, where the user can have a room scale experience while embodying a full-size avatar.
2. A mimicry scene where a 3D avatar replicates the facial expressions made by the user wearing the HMD.
3. A 360° scene where 360° video is played.
4. A scene with a particle system that can instantiate animals or objects that the user might have a phobia.

PLATFORM EVALUATION

We conducted a set of tests to evaluate the accuracy and of our system and the signal quality vs. ergonomic comfort levels once worn by the user. We were mainly interested in testing the robustness and usability of the prototype for long periods of time in multiple scenarios. 8 participants (four females and four males), 18-32 years old for 12 different expressions As part of the data collection procedure, we asked the users to put on our physioHMD prototype and repeat the expression for 12 times for 5 seconds with intervals of 3 seconds. We also tested each electrode on the following parameters: level of comfort, signal quality, and shelf life. After wearing the headset for 15 minutes for each face-pad, we asked the user to self-report on the level of comfort.

Qualitative Analysis

The training and identification processes were done for each individual. The recognition accuracy values of the facial expressions are shown in Figure 7. This figure shows the testing confusion matrix, which shows the different performance of each expression. Due to obvious signal patterns and high-intensity signal amplitude, Happy, Excited, Angry, Rage, Snarl, and Wink have the highest recognition accuracy.

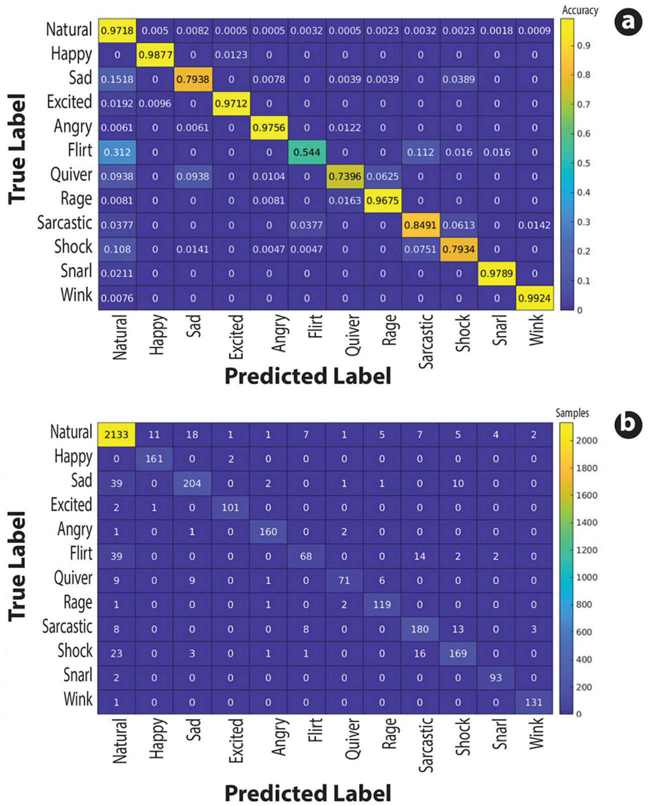

Figure 7: Confusion matrix. a) Confusion matrix of prediction accuracy. b) Confusion matrix of prediction amount.

For Sad, Flirt, Quiver, Sarcastic and Shock, because of the similar signal pattern with other expressions and weak signal amplitude, we obtained lower accuracy relatively. Compared with the state-of-the-art results, our platform can deal with more complex expressions and shows better performance in recognizing the basic ones which Katsuhiro et al. also showed in their paper [27]. Table 1 compares the facial recognition model's accuracy of Katsuhiro's et al. research in comparison to our facial recognition model.

Ergo-Electronics Evaluation

We tested our prototypes and compared the three different face-pad electrodes: the gold-plated pads, standard Ag/AgCl electrodes, and hydrogel-based electrodes. We tested each electrode on the following parameters: level of comfort, signal quality, and shelf life. For the experiment, we asked the participants to evaluate comfort levels, we asked the participants how comfortable each type of electrode on the face pad was while creating different facial expressions in the HMD during a trial. We used a scale of 1-5, where 1 is uncomfortable and 5 is maximum comfort. We also used a standard face pad as a the neutral reference. Hydrogels match closely to the standard facepad in terms of comfort whereas gold plated electrodes were the least comfortable for the participants. Table **??** gives a summary of the average comfort felt by the participants, the average signal gain and the shelf life of each electrode.

Faceplate	Comfort	Signal Gain(dB)	Shelf Life(months)
Facepad	4.5	NA	NA
Gold Plated	3.1	0	>12
Ag/AgCl	4.1	-1	<6
Hydrogel	4.4	+7	<1

Table 2: Comparison of Comfort, Signal Quality and Shelf life of different electrodes

Further, we compared the signal-to-noise ratio of the signals acquired by each different electrode and evaluated the signal gain with reference to the gold-plated electrode. We found the Ag/AgCl electrodes had -1dB signal gain and hydrogels had +7dB signal gain on average with the same expression. The shelf life of gold plated electrodes is estimated to be >1year whereas the shelf life of Ag/AgCl and hydrogels is <6months and <1month respectively. The hydrogels also require frequent treatment with saline solution for keeping the signal quality high. Also, based on observations during signal analysis from all three different electrodes, we found that hydrogels and Ag/AgCl had better mechanical contact compared to gold-plated electrodes because they protrude from the facepad. Hence, we concluded that hydrogels will be suitable for physiological data acquisition where high signal quality and comfort is desirable. Ag/AgCl electrodes will be desirable where both contact requirement and cost are constraints. Gold plated electrodes will be desirable where longevity and minimum cost are required.

DEMO SCENES

We present four demo scenes that demonstrate the capabilities of the PhysioHMD system. First, a demo that uses the system to create more expressive avatars in a social VR setting. Then, a demo that maps user's real-time expression and emotion into the user's VR avatar. After that, a demo scene presents stimuli for uses in VR exposure therapy settings that offers gradual hierarchies of fearful stimuli. At last, a 360 video scene that monitoring the user's reactions towards the VE content and modulates the scene based on the user's response.

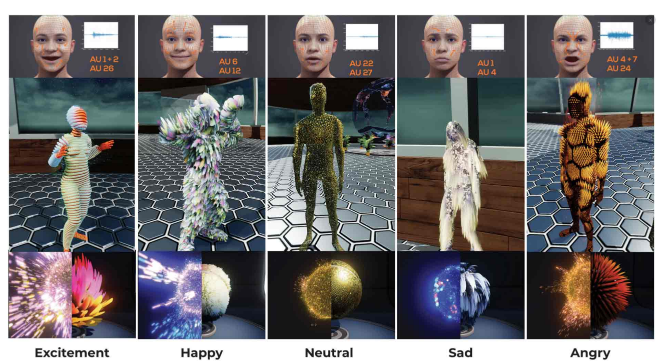

Figure 8: The depiction of the range of possible transformations and qualities for an avatar's emotional expressions with a particle system. The figure shows the particle system's variations in particle size, density, brightness, and color which can all adjust to express the emotions of the user visually.

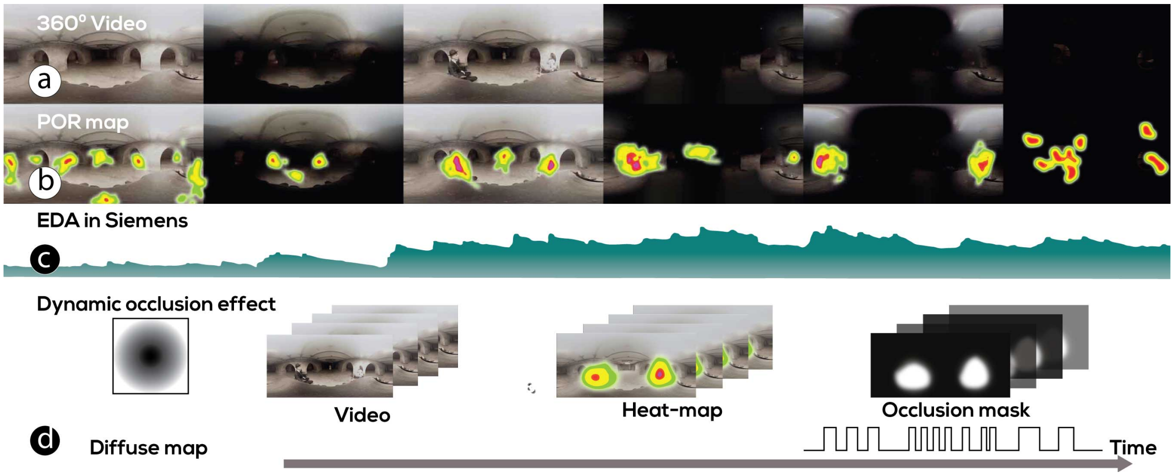

Figure 9: a) Frames from the 360 experience. b) Heat-map from point-of-regard (POR) from user's gaze. c) Electrodermal activity in Siemens. d) Diagram showing how the occlusion shader works.

Figure 10: The user's real-time expression and emotion are mapped into the user's VR avatar. Natural, Happy, Sad, Excited, Angry, Flirt, Irritated, Rage, Sarcastic, Shock, Snarl, Wink.

Affective Avatars

The first of the two affective avatars scenes show how the system can allow users to express emotions in abstract ways using full-size avatars in a virtual environment while embodying a full-size avatar using an IK system with our system (Figure 8) The affect of the user is represented visually in two different ways: (1) the fur of the avatar can grow when arousal is high and (2) the color of the avatar can intensify in brightness or change color to highlight when the user is in a high arousal situation. More detailed information can be found in our paper Emotional Beasts [4]

Within this application area, we are looking to provide agency and express affect in VR through avatars to produce the compelling human-to-human connection. The second scene expresses affect through facial expressions (Figure 10) this is done by mapping the facial expression of the user wearing PhysioHMD into a 3d rigged model avatar. We investigated mimicry due to its relevance in areas, such as autism spectrum disorder research [9]. Participants played an imitation game with both a socially engaged avatar and socially disengaged avatar. This application presents a direct mapping of the user's facial expressions and affect state onto the VR avatar.

Dynamic Occlusion

Monitoring the user's reactions towards the VE content has been a hot topic [18], as it enables the generation of personalized VR experiences. Our demoscene uses of arousal levels to provides real-time, reliable information about the user's reception of the content and can help the system adapt the content seamlessly. In our 360 video demo player scene, we use the gaze data and SCR data to increase the levels of arousal in the users. Figure 9 shows how our demo takes standard footage from people in a basement and makes a darker flashing more dramatic 360 captured video, similar to those seen in horror movies.

To direct the user's focus to the people within the video, we then modulate a surfaces shader dynamically that occludes locations informed by the POR data from the gaze tracking system as areas that are not of interest to the user. We used the detected SCR and peaks values to pulse with modulation the occlusion shader. Formula 1 shows the simple equation that drives the visibility guided by the user's affective state.

$$D = \frac{kA - Ymin}{Ymax - Ymin} \tag{1}$$

1: D is Duty Ratio of the PWM signal. A is the amplitude of EDA signal. k is the constant coefficient, Ymin and Ymax are the minimal and maximum value about the PWM signal.

The POR data is collected by dividing the HTC vive HMD screen into two halves, and each half screen is used for one eye. So, for monocular eye aGlass module, the coordinate is mapping to the half of the screen which size is half of the HTC HMD screen (1080 pixel * 1200 pixel). The coordinate system is normalized, the coordinate of top left is (0, 0) and the coordinate of the right bottom corner is (1, 1). For example, the pixel coordinate of HTC Vive screen where aGlass [1] coordinate (0.5, 0.5) map to is (540, 600). Then this coordinates (POR) are mapped onto a plane at a specific location within the eye tracker coordinate system.

Adaptable Exposure

We explored the usage of our system in a phobia treatment scenario where we present a subject stimulus of a feared object using a particle system. The images (sprites) spawned through the particle system can be modified (speed, size, the rate of spawn, movement) in the Unity inspector to increase or decrease the arousal level of the user. This demo shows a participant with entomophobia and her response to the stimulus of the spawning of more insects. The images (sprites) spawned by the particle system can be modified in the Unity inspector, allowing the organizer of the study to control the virtual animal by choosing different functions (e.g., increase/decrease the number of animals; increase/decrease the size of animals; make the animal move continuously or randomly; make the animal stay still). *(footage of the demo can be found in the video footage that accompanies this video)*

Taking data input from the EDA signal, control changes were sent to the particle system and synchronously relayed to trigger occurrences in the behavior of the critters in the scene meant to represent or provoke arousal in the participants. Three levels of participant arousal were determined to range from low to high. Such levels were established based on simple rules regarding how the data from the sensors changed in the short, medium and long-term. Since EDA readings can vary significantly from one participant to another, where possible, the control system was designed to change the criteria on which these rules were based to more accurately reflect the arousal levels of the user group throughout the installation.

LIMITATIONS AND FUTURE WORK

The applications presented in this research aimed to expose advantages in using physiological computing tools that involved multi-modal sensing for VR psychotherapy, behavioral studies or expression explorations, but there are many features we plan to add in upcoming versions.

- More studies need to be done to thoroughly understand the role of our tool with the rest of our target community. We plan to host workshops with psychology, cognitive science department as well with HCI groups to build a community.
- Current Unity3d sample content still requires the user to have a basic understanding of the game engine, which could lead to frustration for those unfamiliar with Unity3d. We plan to improve our UI and the system as whole further so the platform can be run as an executable system without losing access to parameters in the editor.
- We are working to incorporate signals like skin temperature and respiration used by some of the literature referenced in the related work section.

For future work, the performance of our CNN on the raw data from more than four channels in the dataset should be investigated. Since the dimensionality of the data is high, an effective channel selection algorithm is necessary. Secondly, the relationship between our CNN structure and its performance is of interest for finding appropriate trade-offs between solution quality and training time. For these reasons, we would like to expand the PhysioHMD platform to a broader community to help grow the quality and quantity of the data.

CONCLUSION

In this paper, we introduced PhysioHMD: a sensor and computing platform developed to support the analysis of multi-modal data related to the behavior and responses of a user utilizing XR technology to enable evaluation and customization of virtual experiences. The toolkit is intended to assist both researchers and non-experts in the arduous task of collecting and processing physiological signals and creating experiences in a game engine. The software provides signal processing methods and data logging for physiological signals in order to provide researchers with accurate, real-time information regarding a user's response to content in a virtual environment. Our intention is to grow a community that contributes to HCI and XR technology research through the pluggable open source platform.

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