PhysioVR: A Novel Mobile Virtual Reality Framework for Physiological Computing

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***Abstract*— Virtual Reality (VR) is morphing into a ubiquitous technology by leveraging of smartphones and screenless cases in order to provide highly immersive experiences at a low price point. The result of this shift in paradigm is now known as mobile VR (mVR). Although mVR offers numerous advantages over conventional immersive VR methods, one of the biggest limitations is related with the interaction pathways available for the mVR experiences. Using physiological computing principles, we created the PhysioVR framework, an Open-Source software tool developed to facilitate the integration of physiological signals measured through wearable devices in mVR applications. PhysioVR includes heart rate (HR) signals from Android wearables, electroencephalography (EEG) signals from a low-cost brain computer interface and electromyography (EMG) signals from a wireless armband. The physiological sensors are connected with a smartphone via Bluetooth and the PhysioVR facilitates the streaming of the data using UDP communication protocol, thus allowing a multicast transmission for a third party application such as the Unity3D game engine. Furthermore, the framework provides a bidirectional communication with the VR content allowing an external event triggering using a real-time control as well as data recording options. We developed a demo game project called EmoCat Rescue which encourage players to modulate HR levels in order to successfully complete the in-game mission. EmoCat Rescue is included in the PhysioVR project which can be freely downloaded. This framework simplifies the acquisition, streaming and recording of multiple physiological signals and parameters from wearable consumer devices providing a single and efficient interface to create novel physiologically-responsive mVR applications.**

Keywords—physiological computing; virtual reality; smartphone; Heart Rate; EEG; EMG, Wearables, framework, Open-Source (key words)

I. Introduction

Advances in virtual reality (VR) technology over the last few years indicates that 2016 is the year when VR goes from virtual to reality [1]. VR comprises a collection of technologies (3D displays, motion tracking hardware, input devices, software frameworks, etc.) which aims to create a medium, composed of interactive computer simulation creating the feeling of being immersed [2]. The evolution of consumer grade hardware (such as Oculus Rift and HTC Vive) as well as the maturity of software platforms to create and display VR contents suggests that this field could be the next big wave of computer technology [3]. Interestingly, the Goldman Sachs Group published a report showing that for 2025, the VR market will raise around $ 80 billion [4] highlighting a wide diversity of applicable domains: from not only video games to education but also embracing healthcare and even engineering. The so called "second wave of VR technologies" took place with a 2012 Kickstarter project named Oculus Rift which had the purpose to provide an affordable high-quality Head-Mounted-Display (HMD) to the general consumers and achieved the goal of $ 250 000 in less than 24 hours [3]. The novelty of this HMD was the *immersivity* proposed in relation with the price offered. In comparison with some approaches which do not use HMDs to screen the virtual environment, the use of these headsets creates a complete sense of presence [5] and increases user interaction and immersivity by the means of incorporating stereoscopic 3D viewing and head tracking technology [6].

Consequently, mobile HMDs have the benefit of being wireless and being able to be used without additional PCs. The smartphones technology has been a supportive platform for the development of the mVR, which uses smartphone cases and additional lenses mounted at a reasonable distance to produce mobile and low-cost HMDs. The mVR market has been led by the ingenuous Google Card Board, a VR kit introduced by Google in 2014; where users just simply slide in a smartphone into a $2 cardboard box and experience VR in an omnipresent manner [3]. Although, mVR seems to be very promising to spread out the technology around several scenarios, the lack of interaction pathways and controls to interact with the applications are broadly restraining the capability of this VR approach [6]. Since the touch screen of the mobile phone is used as VR display, there are not too many options available to provide controls for mVR applications.

One of the most innovative and potential human computer interaction (HCI) paradigm to extend users' communication pathways is physiological computing which connects brain/body signals to machines [7]. Physiological computing principles show great potential in creating highly robust and responsive systems via effectively reading/interpreting emotions through wearable sensors [8]. Despite the advances in immersive and mVR during the past years, the inclusion of

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body signals to facilitate the interaction in VR experiences and/or provide strategies to make them physiologically-adaptive to users' emotions still remains as an open challenge [9]. Although there are many wearable sensors developed to facilitate the collection of the various physiological signals [10], not all of them support connectivity with mobile devices such as smartphones or tablets. Furthermore, for those devices supporting connectivity with mobiles, interfacing them with VR software tools (such as game engines) might involve days of work [11] mainly because the need of specialized knowledge and the lack of standardization between the sensors. The inclusion of physiological signals in immersive VR might significantly improve the interaction through enhancing the human-machine interfacing and augmenting the naturalness, fluidity and the intelligence of the communication [12]. Furthermore, physiological data collected during the experiences could be utilized in order to have better understanding of the users' emotions and behaviors during that particular interactive session. [13].

This paper describes the functionalities of the Open-Source framework called PhysioVR, which has been specifically developed o facilitate the inclusion of physiological signals and parameters in mVR applications such as interactive experiences and videogames. The PhysioVR framework can be used to develop applications in three main domains of physiological computing systems: a) to provide physiological input control, b) to create physiologically-adaptive systems (biocybernetic loops [7]) and c) to support ambulatory monitoring [14]. PhysioVR supports heart rate (HR) data from Android wearables, a brain computer interface (BCI) headset and an electromyography (EMG) armband. More sensors can be easily incorporated into the framework which is available online. Although PhysioVR is specialized for mVR projects, the framework can be easily extended for VR applications with wired HMD (such as Oculus Rift). Moreover, PhysioVR includes a Unity3D (a game engine software) API created to facilitate the integration of PhysioVR with the game engine. Finally, we developed a demo videogame called EmoCat Rescue which encourages players to regularize their heartbeats in order to find a cat lost in a forest treetop.

The next section describes some of the main systems created to incorporate physiological signals into VR projects. Explicitly, we are interested in analyzing the software and hardware tools used as well as the limitations.

II. Related Work

Past investigations have shown diverse software approaches to integrate physiological signals in VR projects, videogames and interactive experiences. The PhysSigTK [15] is a toolkit for making low-cost physiological computing systems accessible in the Unity3D game development environment. The toolkit includes a set of sensors to record Electrocardiography (ECG), Electrodermal (EDA), Electroencephalography (EEG), respiration rates and body temperature. The devices included were selected considering criteria such as ease of use, availability, price, software support, responsiveness and low-level access data. The authors also included functionalities for pre-processing and analyzing physiological signals. The toolkit is freely available online and it is specifically used in teaching experimental game design allowing research in affective trajectories (intricacies of gameplay experiences) [16]. A broader approach was found in the Rehabnet Control Panel [17], a distributed architecture aiming to promote rehabilitation through serious videogames. The software includes an extensive list of supported hardware such as motion tracking systems, sensors embedded in mobile phones, eye trackers, virtual reality headsets and electrophysiological sensors. The software simplifies interfacing a large number of existing physiological sensors with third party VR applications by making use of the Virtual-Reality Peripheral Network (VRPN) [18] and the UDP (User Datagram Protocol). The Rehabnet Control Panel has been used to develop serious games for rehabilitation and neurorehabilitation and its integrations with the experimental BCI software OpenViBe [19] has facilitated the inclusion of HMD for neurophysiological experiments. Thus, BCI experiments using immersive VR can be interfaced with a unique integrated software tool which allows the recording of multiple session parameters such as physiological signals, visual stimulus, game events, etc. [20].

Finally, a tool specifically created to facilitate the acquisition and streaming process of BCI signals MuLES [21] was found. This software aims to create a standard interface for portable and low-cost EEG headsets in order to accelerate the development process in BCI applications. MuLES was developed using the LabVIEW [22] graphical programming environment and allows the acquisition, streaming and recording of EEG data through the TCP/IP transmission. Although the software was not made for VR applications, the authors mentioned the importance to include more software frameworks (such as Unity3D) to expand the contexts wherein MuLES can be utilized. To conclude, although the explored software tools showed versatility to integrate multiple physiological and neurophysiological signals to develop interactive applications, we noticed that they are specifically created to run in PCs, therefore limiting the use of mobile, low-cost and wireless HMD for mVR applications. In order to transform VR in a truly unobtrusive and ubiquitous technology, novel physiological computing software tools should empower mobile devices with sophisticated functionalities facilitating the integration and rapid prototyping of physiologically driven/adaptive systems.

III. PhysioVR Framework

The PhysioVR framework is an Open-Source software tool created to robustly enable the inclusion of physiological parameters in mVR solutions using wearable devices connected to a smartphone. The role of the smartphone in this framework is two folded: 1) as a screen for the HMD using the screen-less cases and 2) as a personal server for data streaming [23]. PhysioVR handles the communication between various physiological devices and makes extractable data accessible for client applications. The PhysioVR supports an initial set of physiological devices, however more sensors can be easily added to the framework. PhysioVR is composed by 2 different software layers called PhysioSense, which synchronizes the devices and stream the data and PhysioAdapt, a Unity3D API to receive and adapt the physiological signals. Besides, PhysioVR includes two additional features to provide an external control (*PhysioWOoz*) and for data recording (see Figure 1).

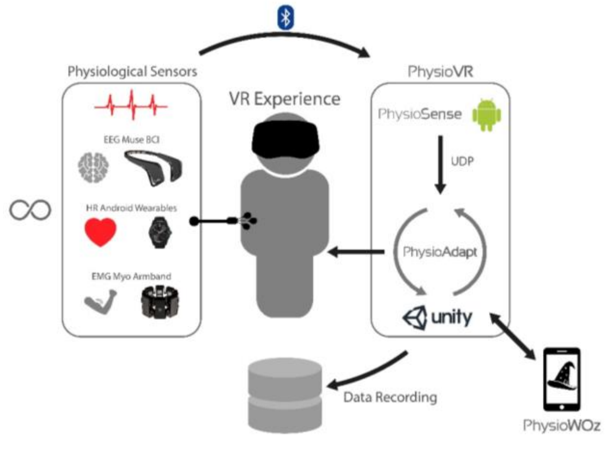

Fig. 1. Architecture of PhysioVR. The physiological sensors are connected to the smarthphone using the PhysioVR App and the communication with external client applications is done via UDP.

A. *Physiological Signals*

Currently, the framework allows an integration of three different physiological signals. Table 1 summarizes the physiological sensors and signals included in PhysioVR listing the parameters that can be acquired.

TABLE I. DEVICES SUPPORTED BY PHYSIOVR INCLUDING THE PHYSIOLOGICAL SIGNALS THAT CAN BE ACQUIRED AND THE LIST OF AVAILABLE PARAMETERS.

Physiological Sensor	**Signals**	**List of parameters**
Android Wearable Sensors	Heart Rate Accelerometer Gyroscope	Heart Rate X-Y-Z Axis Acceleration X-Y-Z Axis Rotation
Muse BCI	EEG Accelerometer	Raw EEG Data Alpha Related Elements X-Y-Z Axis Acceleration
Myo Armband	EMG Accelerometer Gyroscope Magnetometer	Raw EMG Data X-Y-Z Axis Acceleration X-Y-Z Axis Rotation X-Y-Z Magnetic Field Direction

- Heart Rate (HR): PhysioVR includes an approach to acquire HR signals from any Android wearable device [24] such as armbands, smartwatches, headphones or camera-based sensors. Additionally, we included the possibility to use the information from activity tracker sensors embedded in the Android wearable such as accelerometers and/or gyroscopes.

- EEG: the Muse BCI sensor [25], a wearable and low-cost brain sensing headband was chosen to import the EEG signals from 4 dry electrodes (AF3, AF4, TP9, TP10) as well as a 3-axes accelerometer. The sensor includes data called alpha related parameters which are four variables derived from the alpha rhythms (brain waves associated with relaxation) [26].

- EMG: the Myo Armband is a wearable gesture recognition device equipped with 8 EMG sensors and also has a nine-axis inertial measurement unit (IMU) which contains a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer [27].

The sampling frequency (SF) of each sensor can be modified avoiding both delays in consequence of unnecesary or redundant information and loss of data packages.

B. *Signal Acquisition and Data Streaming Layers (PhysioSense)*

Acquisition from the supported hardware is done via drivers, SDKs and APIs supported for each individual device. The sensors are interfaced with the smartphone via Bluetooth protocol and then, integrated in an Android App using Android Studio 2.0. Users have to individually synchronize each sensor before opening the PhysioVR App. Consequently, a quick glance to the data from each sensor is allowed through a simple graphical user interface (GUI). The GUI contains two different panels: a) input device setup which is used to choose the sensor that will be streaming the data and b) signals current state which is a console used to show the available parameters once each sensor is connected. After completing the sensor connection, the App can run as background process in the smartphone facilitating the integration with an external application.

In order to facilitate the data streaming process, PhysioVR uses UDP (User Datagram Protocol) allowing the information transmission through a simple IP direction and a pre-defined port. Using UDP, a multicast (sending datagrams to a group of interested receivers) transmission of all the physiological signals and parameters can be done using a single port. Even though the PhysioVR framework was created to boost the integration of physiology in mVR solutions, the data can be accessed in the same handheld device as well as other external devices with UDP reception capabilities. Client scripts can be integrated in any programming language supporting basic socket programming such as C#, Java, Matlab, Python, etc. [28]. Moreover, users can remotely access the data and send back information enabling a bidirectional communication.

C. *Unity3D API (PhysioAdapt)*

PhysioVR can be integrated in a wide list of VR software tools supporting multiple programming languages with UDP connectivity. We decided to create a first third party application to connect PhysioVR with Unity3D which has been pioneering in the inclusion of mobile VR tools for developers [29] [3]. The Unity3D API called PhysioAdapt uses scripts to read the incoming data stream through any UDP port in Unity3D and make them available in the game development environment. Physiological data could be employed as an input control of any game parameter in Unity as well as to design physiological adaptation rules for the game dynamics [9]. PhysioAdapt also uses the Google Cardboard SDK [29] which expedites the inclusion of VR features such as stereoscopic virtual cameras and libraries for the head tracking sensors in order to minimize the effort it takes to developing mobile VR games.

D. Additional Features of PhysioVR

In addition to the above mentioned software layers, PhysioVR features two extended functionalities for the framework: PhysioWOz and a data recorder.

1) Wizard of Oz for External Control and Event Triggering (PhysioWOz): the Wizard of Oz methodology is an extensively used HCI-research approach which takes advantage of human intervention in order to simulate the system response “behind the curtain” [30]. Using the UDP communication, an external application can be developed in order to trigger events and/or create stimuli in real time, thus allowing a bidirectional communication with the VR experience. This feature is widely used in health applications such as exposure therapy using VR [31] creating a more controlled environment for the clinicians. Thus, PhysioWOz only requires the corresponding IP address along with the relevant UDP port number of the VR App created in order to send and receive any data in real time. This feature is extremely useful for real-time monitoring of the users’ physiological signals by plotting the parameters synchronously with events/stimuli [32]. This feature is available for both PhysioSense and PhysioAdapt.

2) Data Recording: PhysioVR incorporates a function to record physiological data and the events from the VR experience in a custom CSV file, making it straightforward to import the data for a post-processing analysis in specialized softwares (e.g. EEG: EEGLAB [33], HRV: Kubios [34], EMG: PhysioLab [35]). Therefore, the data recording feature facilitates to carry out a causality analysis to better understand how specific events/stimuli affects the VR experience in terms of physiological responses [36]. The data recording can be carried out using PhysioSense as well as PhysioAdapt.

IV. USE CASE: EMOCAT RESCUE GAME

In order to demonstrate the usefulness and ease of PhysioVR to integrate physiological signals in game design projects, we created a first videogame called EmoCat Rescue which encourages players to regularize their heartbeats in order to find a cat lost in a forest. EmoCat Rescue was developed as a proof of concept and it uses HR data from an Android smartwatch (LG G Watch R), a low-cost HMD with a smartphone (Samsung Galaxy S4), a gamepad and headphones, both connected to the smartphone via Bluetooth. The videogame was developed using PhysioVR with the PhysioAdapt module in Unity3D. First we used the PhysioVR App to synchronize the smartwatch and stream the HR data through UDP. Then, we used the functionalities of PhysioWOz to develop an external App which will monitor the HR, provide feedback about the position of the user and allow a manual triggering of some game events. Both, the EmoCat Rescue game and the external App, should be synchronized at the beginning of the experience by entering the corresponding IP address and the port.

In the game, the player embodies a cat-rescuer who has the mission to find a little cat which is lost in the woods. The figure 3 shows a player interacting with the EmoCat Rescue game and a screenshot of the virtual environment. The playtesting was carried out in a garden in order to improve the immersion and realism of the experience.

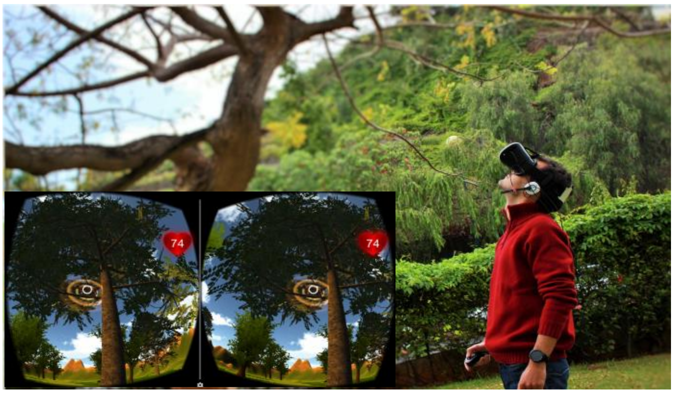

Fig. 3. Playtesting session carried out in a garden. A small screenshot of the EmoCat game is shown.

A. Exploration and Calibration

The player is situated in the middle of a forest with mountains, trees and shrubs and the in-game navigation inside the 3D environment is achieved by utilizing both the head tracking feature of the game engine and a Bluetooth gamepad. In the top-right corner of the screen, a small heart with the HR value was placed in order to provide a real-time feedback of the cardiac rhythm. During the first interaction minute, the EmoCat Rescue game collects the HR values (SF= 1 Hz) of players and establish a threshold to trigger events. Specifically, the physiological trigger will start a meow of the cat using stereoscopic sound. After some iterations, we decided to use 5% of the first-minute HR average as a physiological activator in the game. Thus, players are challenged to regularize their heartbeats by decreasing the HR below the threshold in order to activate the cat’s meow. EmoCat Rescue displays in-game messages in order to encourage users to carry out breathing exercises to effectively reduce the heartbeats. In case if the players are unable to reduce their HR levels, the cat's meow can be triggered manually through human intervention via an external App (PhysioWOz).

B. Searching and finding the cat

Once the cat’s meow is activated, players have to locate the cat by listening to the direction of the sound source (cat). The intensity of the meow respectively diminishes when the players navigate farther away from the cat. Players should navigate through the environment paying attention to the sound to continuously listen the cat that cat that is located on a tree branch. The game ends once the cat is precisely located and the player stares at it for 4 seconds. Subsequently a profile of the cat will pop up on the heads up display (HUD) and relevant information will be populated such as the name and attitude of the cat along with the number of days it has been on the tree. Finally, we have included an option to record the data during the interaction in the external App for a posterior analysis. Particularly the data of the players' in-game location in relation to the cat along with HR threshold and the triggering time of the "meow". These information is stored in the internal memory of the external App (PhysioWOz). Figure 4 depicts the post-processing of the data presenting the behavior of the HR during a 5-minutes session of a player.

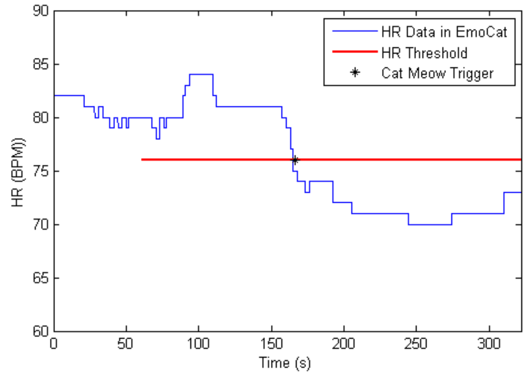

Fig. 4. Graphical representation of a 5-minutes session with the EmoCat Recue game. The HR Threshold was activated after the first minute. The player could overcome the threshold around 100 seconds after the visual feedback.

From the figure 4, we can observe the behavior of the HR from one user during a playtesting session. After the first minute, the player was informed of the threshold to trigger the cat meow (red line, HR= 76 BPM), then we employed in-game messages for encouraging the player to regulate their HR in order to find the lost cat. The player will be able to physiologically activate the cat meow around 100 seconds after the inception of the threshold, threshold; demonstrating the effectiveness of the EmoCat Rescue game to induce calmness in players by breathing techniques in order to reduce their HR levels, allowing the player to accomplish the final goal of the game.

V. Potential Applications

Although PhysioVR is a mobile VR framework created to facilitate the integration of physiological data in mVR applications, we envisioned the use of the framework in other scenarios such as mobile affective computing systems and game user research. This section provides an overview of other potential application of the PhysioVR framework in developing different solutions.

A. *Mobile Affective Computing Systems*

The combination of smart mobile devices and affective computing is called mobile affecting computing [37] which describes the investigation of minimally obtrusive systems created to collect, analyze and translate signals to understand users affections and emotions. Past investigations have used signals from smartphones such as the touchscreen, accelerometer, gyroscopes and microphones to interpret user’s emotions [37]. However, the widespread use of wearables in the last lustrum might facilitate the continuous recording of physiological data allowing a more accurate affective sensing process as well as mood and emotion detection. Since PhysioVR can connect and stream multiple physiological data from different devices through UDP, any external application running in a mobile device can easily use this data to produce affectively-responsive systems. Past investigations have shown the advantages of using multimodal physiological approaches for emotion recognition instead of interpreting human behavior from an isolated physiological phenomena [38].

B. *Tool for Game User Research*

The use of physiological measures for game evaluation embraces a collection of methods that facilitates researchers to better understand players’ reactions and behaviors during a game experience [13]. Although, the prices of sensors are rapidly falling, the use of physiological variables in game user research still requires a set of convulsionary skills of sensor related programming and the data acquisition process widely restricts further progress to be made. PhysioVR has three main features to facilitate the game user research process: a) allows a clean and minimally invasive collection of physiological data during the experience without hindering the interactivity, b) the PhysioAdapt facilitates the synchronization of the physiological signals recoded with the game events in Unity3D, thus allowing a causality analysis, c) the complete connection and collection process is carried out in a handheld mobile device which significantly simplifies the researcher work, especially in out-of-laboratory studies. Moreover, specifically in the mVR field, PhysioVR offers a unique approach on facilitating the collection of physiological signals during the interaction using wearable devices (in comparison with EEG caps, wired EMG or ECG systems) which enhances the convenience of mVR applications.

C. *Mobile VR System for Exposure Therapy*

VR systems for exposure therapy are characterized to be expensive, obtrusive and non-portable preventing a massive use of this technology in the clinical practice and/or at-home rehabilitation processes [39]. Additionally, the inclusion of equipment for physiological monitoring often leads to a significant increase in the economic cost of these systems [39]. PhysioVR might be a remarkable framework to develop mobile and sophisticated systems to carry out exposure therapy through VR. Firstly because the price of the HMD is significantly lower using screenless cases and smartphones, thus overcoming the initial investment issues. Secondly, the inclusion of physiological signals as input as well as for health monitoring control in VR experience, doubles the advantages for psychological exposure therapies. Finally, the PhysioWOz allows an external control which can be used by the therapist in order to trigger events and provide specific stimuli in a particular moment of the therapy, which is a remarkable feature in these types of psychological procedures [31].

VI. Conclusions and Future Work

PhysioVR explores the use of consumer grade wearable devices for physiological signal integration in mVR applications. Such methods receive increasing attention in several fields as gaming and healthcare since they possess the potential to become VR highly personalizable and ubiquitous technology. Here, we have presented the PhysioVR framework, its general architecture, functionalities and a case study of a physiologically-responsive mVR game. Moreover, we have included three potential scenarios that we envisioned in which

PhysioVR will have a substantial prospect as a software tool to simplify the inclusion of physiological signals. By empowering VR technology with novel physiological computing systems, PhysioVR strives to augment the interactivity and extend the capabilities of VR in order to reinforce and augment the human-machine communication. PhysioVR can be downloaded in: https://github.com/PhysioTools/PhysioVR.

As for our future contribution we are anticipating the inclusion of more physiological sensors in the framework, especially the multimodal do-it-yourself (DIY) tools such as Bitalino (http://bitalino.com/) and the e-Heatlh Kit (http://cooking-hacks.com/) which supports a wide range of physiological sensors. Furthermore, we are expecting to enrich the connectivity of PhysioVR with more third party applications and programming languages such as Matlab and Python as well as provide more demo projects for the PhysioAdapt (Unity3D API).

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