The EXPERIENCE project: automatic virtualization of "extended personal reality" through biomedical signal processing and explainable artificial intelligence

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The transformation of communication media has revolutionized social interactions, incorporating audio and video into our lives. Despite the recent availability of virtual reality (VR) technology, its widespread adoption faces obstacles. Technological challenges in creating VR environments and scientific confounding concerning inter-individual variability in responses to virtual simulations are key factors hindering its broader integration. The EXPERIENCE project makes real the complex interplay between multisensory perception, emotional responses, and extended social interactions by allowing the public-at-large to create their own VR environments automatically through portable devices (e.g., smartphones/tablets) without the need for technical skills. The VR environment augmented by an individual's physiological responses, psychological and cognitive descriptors and behavioral outcomes defines the individual's subjective experience, namely, an individual's *Extended-Personal Reality* (EPR). The virtualization of a person's EPR provides a holistic and quantitative environment that can be shared with others to transfer personalized psychological and emotional responses. Additionally, EPR assessment enables subsequent manipulation of the VR through explainable artificial-intelligence routines merging multisensory biofeedback, individualized perception of time-space, and neuromodulation. This technology can be exploited in a plethora of innovative scenarios, including mental healthcare, gaming, e-learning, and neuroeconomics, also leading to the creation of a new market for sharing and selling (virtual) *experiences*.

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Introduction

The way we communicate in the 21st century is pervasive and extensively leverages in social communication and collaboration, entertainment, training activities, marketing and promotions, and healthcare [1]. Immersive VR creates interactive computer-generated worlds, which fully substitute sensations and perceptions of the real world with those of digital content.

VR produces a realistic perception of being situated and immersed in fabricated life-sized environments, producing sensory experiences that may be nearly impossible to recreate in real life. For example, the British Museum in London reproduced a 4,000-year-old house to educate and attract new visitors to objects they would otherwise only encounter behind glass casing. VR already promised to revolutionize the experience of sport events, putting viewers on the starting line and in the pits at last year's Daytona 500, as well as on the pitch at the National Hockey League. VR has also proven its effectiveness in several psychological treatments, giving rise to what is known as "Virtual Reality Exposure Therapy" [2]. This therapeutic strategy allows for the creation of a safe virtual space where the patient can be exposed to the frightened object or condition without feeling threatened, as well as to approach traumatic or phobic situations gradually to mitigate stress and anxiety [3]. Furthermore, avatar-based therapy showed promising results with auditory hallucinations [4]. However, while systematic reviews show that VR is effective at delivering exposure-based therapy for several anxiety-related disorders as well as mood disorders such as depression, the potential of VR technology has yet to be fully exploited in standard clinical practice. Most VR-based treatments are merely adapted versions of standard psychotherapy.

Previous studies have endeavored to automatically generate VR environments from real images and videos [17]-[21]. While some have been successful in creating specific environments, such as animatable 3D models [17], avatars [18], and virtual museums [19], they often demand advanced technical proficiency and substantial computational resources for their generation [20, 21]. Consequently, several barriers hinder the widespread integration and full realization of VR in everyday life, particularly for the public who may not have the means to create VR environments as easily as photos or videos. Additionally, to effectively elicit diverse perceptual and behavioral responses - much like real environments - VR scenarios should be personalized and adapted to the particularities of an individual.

To contribute solving these challenges, the EXPERIENCE project[1] provides the technology, scientific rationale, and data processing tools for the automatic creation of VR. A VR environment is equipped with psychological, cognitive, neurophysiological, and behavioral information for further processing. The automatically created VR may be shared with other

[1] www.experience-project.eu
https://cordis.europa.eu/project/id/101017727

persons, effectively communicating the provider's emotions. Key components of the EXPERIENCE project are depicted in Figure 1. The automatic process of generating VR scenarios can be achieved through the utilization of cameras or by leveraging neurophysiological data. These elements contribute to the definition of an individual's Extended-Personal Reality (EPR). This encompasses the augmented VR environment, along with the individual's physiological responses, psychological and cognitive attributes, and resultant behavioral outcomes.

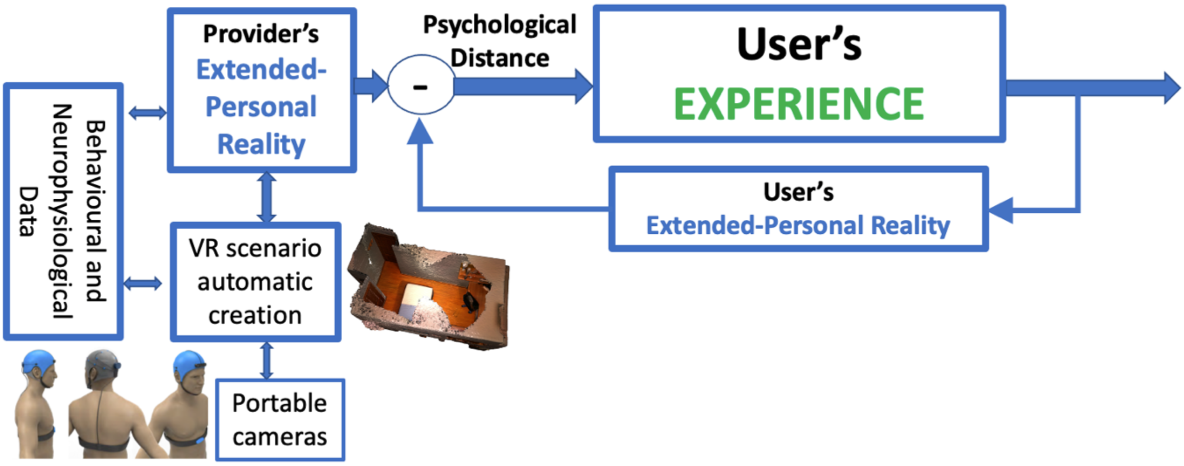

Figure 1: Block scheme showing the principal components of the EXPERIENCE system

EXPERIENCE involves several academic partners, including Università di Pisa (Italy), Università di Siena (Italy), Universitat Politecnica de Valencia (Spain), Università di Roma "Tor Vergata" (Italy), University of Padua (Italy), and Karolinska Institutet (Sweden), as well as research centers such as Centre Suisse d'Electronique et de Microtechnique (Switzerland), Comissariat à l'Energie Atomique et Aux Energies Alternatives (France), and the Quatechnion (Spain) enterprise. Consortium expertise is highly interdisciplinary, ranging from microelectronics, biomedical signal and image processing, and artificial intelligence to cognitive and affective neuroscience, and psychiatry and experimental/clinical psychology.

Overview on the automatic creation of VR scenarios

What is currently needed to create a VR scenario? Most VR scenarios are created manually by a graphic designer using standard 2D/3D graphic design tools. This procedure can be very expensive and inefficient. An alternative for obtaining VR environments from real scenarios is the use of photogrammetry techniques. These techniques start from the images captured by a camera and, using artificial vision techniques, provide a 3D model of the scene. Any element (i.e., objects) of the reconstructed 3D scenario must be completely customizable by the user (in appearance and form) in a simple way. If done manually, such a process may be time-consuming to guarantee a photorealistic 3D model (multiple days using standard hardware equipment). Likewise, photogrammetry techniques do not take advantage of depth information and generally use only color information. This prevents the user from obtaining more information about the light of the 3D scene. Currently, reconstructed 3D models are not automatically customized. Immersiveness depends on both VR software and hardware and can be specifically measured using variables from, e.g., scene context. Indeed, an automatic creation of VR environment would allow to fully record experiences and make them available for a re-experience in VR, therefore opening radically new communication and social interaction scenarios.

Using simple hardware like tablet or wearable cameras, EXPERIENCE aims to enable any non-expert user to perform 3D customization through detection-and-pose estimation of 3D objects, 3D-object retrieval, semantic analysis of the scene, and style transfer. The proposed artificial intelligence (AI)-based methodology is summarized in Figure 2.

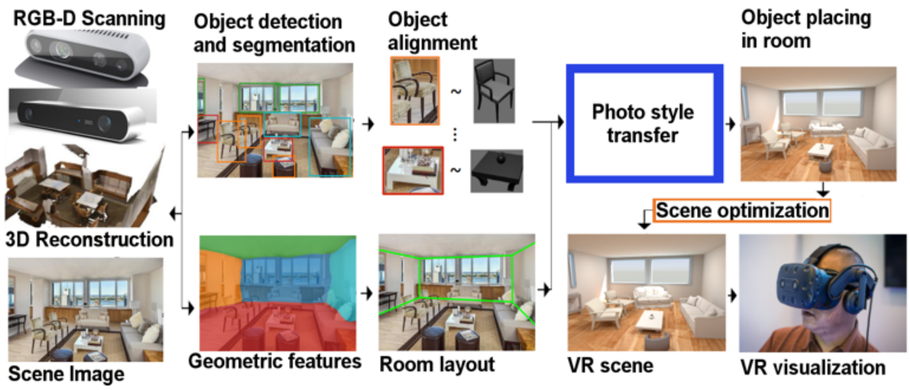

Figure 2: Main components of the EXPERIENCE AI-based methodology for automatic VR environment creation

Once the image and depth are collected, a dense 3D scene can be reconstructed using pose estimation algorithms such as BundleFusion, which is a real-time 3D reconstruction algorithm using on-the-fly surface reintegration of the RGB image [5]. Once the 3D reconstruction is performed, the point cloud is preprocessed through denoising, mesh simplification, and mesh alignment. Then, an automatic 3D scene understanding step identifies the different objects in the scene while extracting the boundaries of the captured scene. Specifically, once the objects in the scene have been detected, the different regions are segmented to obtain the different instances representing each object. Indeed, object detection is one of the most fundamental and challenging problems in computer vision and is based on detecting visual object instances of different classes, such as cars, people, animals, and floors. Using these labels, a realistic scene is then rendered where previously modelled objects can be replaced. Other important steps comprise layout estimation, which provides information about the boundaries of the scanned environment, and the style transfer algorithm, which blends the objects with the real scene and changes the overall appearance of the 3D scene [6]. The automatically virtualized scenario is then precise, photorealistic, and efficiently adapted to multiple VR systems. Additionally, EXPERIENCE proposes sketching techniques to simplify most of the scene's regular surfaces (e.g., planes, cylinders).

EXPERIENCE also aims to automatically generate VR environments faithfully representing a person's recall from their neuromonitoring data, including, e.g., functional magnetic resonance imaging, magneto/electro-encephalographic data. To this end, deep generative models able to capture and disentangle most of the complexity of the 3D multisensory input that generates brain responses, hence flattening and evening out the "perceptual manifold" like human brains might do, are devised. The EXPERIENCE automatic VR generation procedure described above significantly reduces the complexity of this task: on the one hand, the generative architecture has an augmented training set comprising hierarchically organized, VR specific, uniquely realistic features that, by design, have been engineered to embed maximum realism at multiple scales. On the other hand, the real images from which these VR environments are created can be incorporated in the training set, as well as to the deep models that have automatically generated these features as well as the full VR scenes. This is akin to training an encoder-decoder architecture not only by using information contained in pictures but also by incorporating countless paintings representing the same scenes, physical knowledge about the cameras and lenses that were used to capture the image, their settings, and the environmental conditions (such as lighting) in which they were captured. The generative architecture will also be able to recapture the image an unlimited number of times while tweaking camera settings and will have the painters repainting the scene a potentially infinite number of times. This represents one of the most sophisticated data augmentation techniques to date.

The Extended-Personal Reality and creation of virtual senses

The extended-personal reality (EPR) of a person is all the different ways their body and mind respond to a virtual reality situation. This EPR can be shared with others, so they can experience the virtual reality as if they were there themselves. More specifically, the EPR is defined as the set of all neurophysiological, psychological, cognitive, and behavioral responses occurring in a given VR situation. This set includes the individual's mood and emotional state, as well as general psychological state. The provider's EPR thus virtualized may be shared with other individuals (the users), who may explore the recorded VR environment. As in real life, given the same situation or context, the provider and the user's experience of the same VR may differ. Essentially, an objective level of stimulation does not translate into an identical level of neurophysiological response. Additionally, the neurophysiological response in one individuals will not necessarily reflect the same psychological response in another. Thus, an identical level of neurophysiological activity in two individuals do not necessarily translate into the same psychological response (e.g., emotional, or cognitive). EXPERIENCE addresses this "subjectivity gap" in different ways. It explores how time and space interfere in vision, in somatosensory, and in multisensory integration similarly to audiovisual integration [10] related neurophysiological mechanisms [11]. Consequently, distinct spatiotemporal patterns should be used in VR to induce similar stimuli perception across individuals, minimizing in turn the so-called *psychological distance* between individuals [12]. While exploring the recorded VR environment, the receiver shall effectively feel the provider's mood and psychological states. For this, EXPERIENCE will employ novel multisensory manipulation, including a controlled delivery of illusory or conflicting multisensory (visual, audio, and haptic) and multimodality (time, space) cues. In summary, VR may differ between provider and receiver, but EPR will be closer, essentially reducing the psychological distance between them.

To synchronously collect audio/video information of the scene to be virtualized together with a comprehensive set of neurophysiological signals, a head-mounted, comfortable, lightweight wearable system for audio/video and physiological/biometric monitoring was developed. This technological pillar comprises new wearable devices for recording the user's EEG, ECG, respiration, environment vision and sound, movement, and hand kinematics, as well as to mark/annotate significant events. EXPERIENCE wearable technology integrates dry passive (no battery) electrodes, which are easy to use and produce high-fidelity signals without skin preparation and gels. This configuration has the advantage of improving the safety of the user and the simplicity of the centralized battery recharge. Dry flat-ended finger electrodes improving contact scalp through-hair will allow high signal quality, despite the presence of hair. An EEG cap will enable accurate placing of the EEG sensors according to the 10/20 International System. The cap is connected to the data acquisition module dedicated to EEG reading and transmission to the recorder on a belt or harness. The cap cohabitates with a head band integrating a depth camera and microphone, enabling environmental recording. The image is encrypted before being recorded, thus protecting privacy throughout recording sessions. To optimize wearability, a specially designed harness embeds the EEG digitalization module, the recorder, the ECG electrodes and the wiring, enabling the recording of the raw EEG, ECG, and motion signals in an easy and comfortable way.

Clinical scenario

Diagnostics

The EXPERIENCE framework aims at providing objective tools to support diagnosis of psychiatric disorders, such as depression and anxiety disorders. Diagnosis in psychiatry is mostly based on semi-structured interviews or questionaries in which the professionals ask patients about symptoms and behaviors they may have experienced. For example, for a diagnosis of major depression, patients should show, for at least two weeks, a minimum of five out of nine symptoms, and at least one of these should be depressed mood or lack of pleasure in daily activity. Diagnoses for all the other psychiatric disorders follow similar rules. This approach relies on subjective observations by health professionals, requires a significant amount of highly specialized human resources, and implies a diagnostic consensus with low specificity. Indeed, there is no objective test or measurement accurate enough to be used in clinical practice to validate a diagnosis [15]. Exemplarily, in affective disorders, subjective retrospective evaluation which represents the gold standard for diagnosis and severity assessment were shown to be affected by memory bias.

The EXPERIENCE framework extends beyond standard psychometric questionnaires by incorporating behavioral and physiological data derived from VR-based tasks. This comprehensive approach aims to capture features indicative of affective disorders within the individual's EPR. For example, distinctions in performance specific to certain disorders within neurocognitive domains, such as memory and executive functioning, can be translated into immersive VR experiences, enabling the assessment of dysregulated time perception and other facets of decision-making using tasks like gambling. Additionally, patients may be prompted to manipulate their perception of space-time, allowing for the quantification of the dissonance between objective reality and subjective perception, which may serve as a gauge for symptom severity (e.g., anticipatory anxiety, cognitive deceleration). Consequently, an in-depth analysis of the EPR features may uncover latent indicators capable of predicting the onset of psychiatric conditions.

To achieve this, a battery of behavioral and cognitive assessments, identified through a meticulous review of existing literature (including RVIP, TMT, 2-back test, WCST, metacognitive sensitivity, curiosity, persistence, engagement with emotionally charged stimuli, and mood induction), has been integrated with physiological metrics (e.g., ECG). These measures are seamlessly integrated into a specially designed Virtual Reality serious game. Through the application of Machine Learning algorithms, as registered in trial ISRCTN16396369, the system has been scrutinized for its ability to distinguish between individuals exhibiting varying degrees of depression. Those measures found to correlate with heightened depression symptoms will subsequently be integrated into the EPR framework.

Treatment

EXPERIENCE offers multiple avenues to treat affective disorders. It enables the presentation of personalized stimuli tailored to specific emotional targets, thereby facilitating the restoration of healthy emotional processing. Additionally, it allows to modulate the patient's emotional responses by employing techniques like biofeedback and guided relaxation. These features represent a groundbreaking advancement in psychiatry, leveraging real-time neurocognitive feedback adjustments to fine-tune therapeutic stimuli during sessions. For example, in VR-based exposure therapy for social anxiety, stimulus intensity could be automatically calibrated based on the patient's level of fear. Furthermore, the use of a highly customizable VR system offers an enhanced tool for anxiety treatment through personalized and realistic exposure.

On a different note, EXPERIENCE's innovative emotion elicitation can expedite therapeutic progress by inducing positive emotions alongside exposure to feared stimuli. For instance, the common negative perception bias among depressed patients may improve when experiencing stimuli through an EPR linked to a positive mood. EXPERIENCE also provides a naturalistic platform for applying gamification to mood disorders. Gamification, the use of game-like exercises to address psychopathological symptoms, has already been successfully implemented for eating disorders, anxiety, and mood disorders. Finally, time perception manipulation may potentially yield direct therapeutic benefits. While this hypothesis is intriguing, no studies to date have endeavored to modify subjective experiences as a means of treating patients with affective disorders.

Ethical considerations

The democratization of VR technology, enabling easy creation of personalized and immersive experiences, presents exciting possibilities. However, it also raises crucial ethical considerations. The potential for manipulative use of collected psychological, cognitive, neurophysiological, and behavioral information demands ethical guidelines and oversight to prevent nefarious purposes. Applying VR to psychiatric patients requires responsible usage, considering informed consent, emotional safety, and potential heightened responses. Additionally, accidental discovery of mood and emotional disorders in supposedly healthy users using the VR system poses ethical challenges, necessitating support and privacy respect. Addressing bias and discrimination in processing such data is vital. By adhering to such ethical guidelines, we can navigate these complexities responsibly, unlocking the potential benefits of VR in several real-life applications.

Discussion and Conclusion

It is EXPERIENCE's ambition to provide the foundation for a radical shift in the way VR, extended social interplay, cognition, and neurophysiology are conceived and exploited at the level of the individual. A VR environment may also be automatically generated from personal neurophysiological data and is equipped with psychological, cognitive, neurophysiological, and behavioral information that constitute the person's extended-personal reality. The unique multivariate approach linking extreme vision and psychophysiology is expected to provide objective data for assessing the user's emotional state, as per an emotion model. Indeed, due to the nonspecificity of neural dynamics and behavioral information, emotion recognition based on a multifeatured approach is crucial.

EXPERIENCE fosters great technological achievements through highly integrated healthcare wearables able to fully monitor the user's EXPERIENCE, which will allow i) unique noninvasive, comfortable, and comprehensive data collection in naturalistic conditions; ii) automatic creation of VR environments integrating multimodal (video/audio/haptic) elicitation for personalized performance and use; iii) unique biofeedback capability; and iv) novel appealing experimental designs and VR scenarios to be exploited in biomedical research, particularly the diagnosis and treatment of affective disorders, as well as in commercial fields such as gaming, neuroeconomics, and e-learning.

While EXPERIENCE is optimized specifically for VR as a fundamental and self-sufficient part of the XR framework, we recognize its potential across all extended reality technologies, including also Augmented Reality (AR), and Mixed Reality (MR), to involve all senses and create immersive experiences. VR's capacity to generate fully simulated environments allows for controlled and intense user experiences, fostering deep immersion. Conversely, AR enhances the real world with digital overlays, seamlessly integrating digital content with the physical environment for context-aware interactions. MR combines elements of VR and AR, blurring boundaries between the virtual and real worlds, resulting in interactive and dynamic experiences. While our framework has the potential to enrich user experiences across the XR spectrum, applications other than VR would necessitate a distinct scientific characterization due to the unique attributes and advantages offered by each XR technology. Users' reluctance to wear a VR head mounted display may pose an obstacle to the widespread use of the EXPERIENCE technology. Comfort, motion sickness, and social stigma may contribute to this hesitation. To address this, we must prioritize user-centric design, explore alternative VR interfaces, and educate the public about the benefits and safety of VR technology. As future work, considering VR's unique strengths in contrast to the broader XR landscape, where AR and MR are gaining prominence, can help manage user expectations. Overcoming these challenges will enhance the acceptance and accessibility of VR experiences for a broader audience, unlocking the technology's full potential in various fields.

Since the perception of space and time are interdependent [7,8], both can be assessed and manipulated in VR [9]. As an illustration, consecutive and distributed tactile stimuli can be perceived as more temporally separated if the spatial distance between them increases [13]. While multisensory cues include audio and haptics, EXPERIENCE research primarily focus on video. As a result, audio and haptic cues in VR are mainly derived from audio recordings and kinesthetic/cutaneous measurements. It is worth noting that EXPERIENCE is proudly part of a collaborative initiative involving multiple consortia - the so-called SECTG - coordinating and complementing research aims and directions. In particular, the TOUCHLESS project [14] (www.touchlessai.eu) is specifically dedicated to haptic cues research, while the SONICOM project [16] (www.sonicom.eu) specializes in audio research.

Frequently, the deep dive into VR environnement lead to a distressing phenomenon known as cybersickness. This condition, which lacks an effective therapy, can be severely debilitating. However, recent research in the frame of the EXPERIENCE project suggests that non-invasive brain stimulation utilizing transcranial alternating currents can modulate vestibular oscillatory activity, offering relief for a majority of individuals during VR immersion [22].

AI algorithms play a pivotal role within the EXPERIENCE scientific framework. They are instrumental in automating the recognition of objects and in generating VR scenarios, as well as processing EPR-related data. Depending on the nature of the data and the learning tasks (supervised or unsupervised), a range of techniques can be employed, encompassing machine learning methodologies like tree-based approaches and ensemble learning, as well as neural network architectures such as Convolutional, Deep, Recursive Neural Network, autoencoders, snapshot neural ensemble, and their refined iterations. To ensure reliability, transparency, fairness, and trustworthiness in predictions, diverse interpretability logics are integrated into the AI engine. This approach not only facilitates seamless integration into real-world clinical decision-making processes, but also adheres to contemporary regulations governing personal data processing, including the General Data Protection Regulation.

To conclude, we mention that it is ambition of EXPERIENCE to initiate a radically new market, technology, and science for creating, customizing, and selling personal EXPERIENCEs. To illustrate, soon we envision the ability to craft and share highly evocative experiences, ranging from deeply relaxing and tranquil VR settings to profoundly stimulating ones. Imagine a tourist hotel virtually replicating its lobby and guest rooms, enabling remote users to 'feel' the essence of being there. Similarly, an architect could directly virtualize an indoor space by scanning it. Within this context, our emphasis on social interaction arises from the interplay between creators, who create immersive scenarios (such as a VR environment through EPR), and users, who relive them. This dynamic exchange lies at the heart of social interaction within the realm of EXPERIENCE. In this vision, our consortium has chosen to prioritize the challenges in mental healthcare, reserving other applications (e.g., e-learning, gaming) for future exploration and innovation. In the case of psychiatric patients, the induction of emotions through EXPERIENCE technology may enhance the efficacy of therapeutic interventions, especially when coupled with cognitive-behavioral therapy. For example, individuals grappling with negative perception biases, a common struggle for those with depression, might find relief through personalized stimuli delivered via VR simulations, tailored to, e.g., their own home environment, thus aligning with the principles of well-being therapy.

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