VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2022.1.08
Vibrations in Physical Systems, 2022, 33(1), 2022108

The Multidisciplinary Integration of Knowledge, Approaches and Tools: Toward the Sensory Human Experience Centres

Massimiliano MASULLO, **Luigi MAFFEI**

[1] Università degli Studi della Campania "Luigi Vanvitelli", Department of Architecture and Industrial Design, via San Lorenzo - 81031 Aversa (CE), Italy

Corresponding author: Massimiliano MASULLO, email: massimiliano.masullo@unicampania.it

Abstract The technological progress of the last decades has significantly contributed to the development and innovation of several areas, such as engineering, architecture, and medicine, providing new possibilities to measure, control, simulate and assess most of the physical phenomena of the environment, and the corresponding reactions of the individuals. This has shifted the attention of researchers toward the need to understand, in depth, the mechanisms which influence the perception and well-being of humans in complex environments (e.g., cities, urban parks). In this light, it can be expected that the first-person experiences will be assumed as the new frontier of future decision-making and design processes, as they may involve representatives of local communities and groups of interest. This approach leads to a multidisciplinary integration and contamination of the scientific competencies for all research groups involved in the so-called holistic research. Overcoming the concept of noise that has dominated until the end of the last century and considering the environmental sounds as a 'resource' rather than a 'waste', with the introduction of the Soundscape approach, psychologists and sociologists have provided several tools (e.g., questionnaires, scales, tasks) to measure the perceptual, emotional, and cognitive reactions of the individuals when they are exposed to the sounds. Different multidisciplinary research groups are involved in studies that adopt, refine, or propose new investigation tools, to assess, modify and manage the sound of cities, and their effects on the satisfaction and well-being of the population. Moreover, the huge development of miniaturised and powerful hardware and software of the last decade allowed the reconstruction of audio-visual scenarios with a very high degree of realism and the possibility of interacting ecologically with the virtual environment in a fully functional immersive experience. The recent possibility to measure the physiological and neurological reactions of the individuals has opened a further road to extend the knowledge about the effects of noise and the weight of the other physical factors on the populations. A scheme of Sensory Human Experience Centres, where approaches, tools, competencies of various disciplines are integrated, is presented. These kinds of centres could represent, in future, the places where they concentrate the selection and validations of design alternatives (e.g., product, building, city and infrastructure scale) at the local and national levels.

Keywords: multidisciplinary, multisensory, experiences, approaches, virtual reality.

1. Introduction

The technological progress of the last two decades has contributed to transforming the way to face many issues related to medicine and engineering, making available new tools and devices [1-4] to measure, analyse, model, and simulate existing or future situations. From 1996-2018 only the nanotechnology sector has counted about 152 000 publications and 4 000 patents [5].

Despite some ethical, legal, and social implications [6] of the use of this technology, especially for the environmental, health, and safety's monitoring [5, 7], nanotechnology applications it is impacting an incredibly wide range of industries and markets, such as defense [8], medicine [9, 10], agriculture [11], energy saving [12]. They are also promoting the development of powerful, and energy-efficient computers to process a large amount of data and simulate complex situations [13], and smaller and lighter devices [14, 15]. Virtual Reality (VR) and wearable devices [16] are the products that the growth of this technology has mostly spread. More in detail, since the first commercial prototype of Head Mounted Display (HMD) of 2013, and thanks to the rapid development of game engine platforms [17] that allow simulating the virtual environments and interactions, Virtual Reality has grown dramatically. The key aspect of this tool is its high ecological validity [18-20]. Today VR has applications in several sectors, such as architecture and design [21-24] (figure 1 - left), engineering and manufacturing [25], safety [26] and in clinical medicine [27, 28].

On the other side, wearable devices gained attention, as well, not only due to the integration of body sensors that provide health monitoring [29,30], but also because of the great interest toward the biofeedback signals [31, 32], i.e. electroencephalogram (EEG), electrodermal activity (EDA), heart rate variability (HRV) Visual Attention Feedback (VAF), and to their association with environmental parameters [33-37] (figure 1 - right) and self-reported measures of people well-being [38, 39].

Figure 1. Virtual reality environment built during the FP7-PEOPLE-2011-ITN EU project SONORUS The Urban Sound Planner (left) [22, 23]. Images of a virtual reality industrial simulator, lab experiment with biofeedback monitoring (right) [36].

Besides, the development of wireless communications has favoured the installation and the use of many fully connected sensors, able to communicate with each other and with the external surroundings, in what is known as the Internet of Things (IoT) [40]. Their applications in controlling transportation and energy infrastructures, buildings and other home devices allow the environmental and urban monitoring, people healthcare, energy cost management, building/home automation [41]. While the rapid developments in IoT have increased the number of connected devices leading toward Smart City, Home and Transportation concepts, its growth is still negatively affected by cybersecurity risks and privacy concerns [42, 43]. The development of IoT applications has exponentially increased the amount and dimensionality of the available data. The increasing demand for intelligent virtual assistants to increase client satisfaction levels has contributed to the development of new multidisciplinary technology, artificial intelligence (AI). Today, AI is adopted in several sectors and integrates cognition, machine learning, emotion recognition, human-computer interaction, data storage, and decision-making [44].

2. Paradigms' changes in physical disciplines

In the same decades, has been discussed the limitations of the existing approaches and models, mainly focused on the adverse effects of the environment on individuals, e.g., thermal discomfort, noise annoyance, disability and discomfort glare; and on the use of tables of data or coloured maps to describe existing or future situations. Beyond these classic models, some researchers proposed using new paradigms which investigate the hedonic attributes of the human perception and positive influence (distraction, restoration, being away, fascination) of some environmental cues in everyday life.

In thermal comfort studies, the major paradigm shift was from the physically-based determinism of Fanger's comfort model toward the mainstream and acceptance of the adaptive comfort model, which considers physiological, behavioural, and psychological. Another relevant shift concerns the language used to study the air movement, which passed from overwhelmingly negative (draft, nuisance) to positive hedonic aspects, such as aerodynamic pleasure, breeze, air aesthetics, and thermal delight [45]. The hedonic component of thermal perception is believed to play a role in initiating and/or activating behavioural thermoregulation. Furthermore, in 2010, de Dear [46] revisited the concept of Alliesthesia (Greek: allios=changed, esthesia=sensation) proposed in 1971 by Cabanac de Lafregeyre [47] to describe the amount of thermal pleasure or displeasure aroused in non-steady-state environments acting on those factors that can modify the internal state. In 2015 [48], he found that positive pleasure can be associated with temporal thermal transients and prospect a new road of design and engineering.

In environmental acoustic research, since the end of the last century, some researchers distinguished between the traditional environmental noise management approach, which involved an objective energy-based model of the acoustic environment, from a new subjective listener-centred model where the sounds were conceived not only as a waste but as a resource [49, 50] for the community, able to engender pleasantness and improve the quality of life of inhabitants. This paradigm shift originates since, in the 70s, Schafer coined the term soundscape [51, 52], prospecting a new way to consider the sound. This new approach, the Soundscape approach, integrates the knowledge and skills of the many disciplines and is mainly based on the opinions and experiences of the space users [53-56]. Definitions and framework of the soundscape [57], the data collection methods and the reporting requirements [58], and the data analysis [59] have been described in the standards series ISO 12913. The framework of the soundscape shows in brief that context plays a major role in people's perceptual construction of soundscapes. A deeper description of the elements of the context that may potentially influence a person's experience of the acoustic environment was provided by Herranz-Pascual et al. [60]. The multidisciplinary approach has broadly stimulated the scientific community in using sounds as an element of design for outdoor, i.e., urban parks [61-63], plazas, [64], and indoor [65] contexts, as well as the presentation of the research project on this topic. More recently, researchers are using new technologies to design and predict the effect of soundscape in realistic virtual contexts [66, 67, 22-24].

In lighting design, a change of paradigm refers mainly to the *pre* and *post* LED use, where the debate about the potential benefits of light sources with higher ratios of scotopic to photopic lumens (S/P ratio) and CCT, pre-LED [68], was overpassed by the interest toward the integrative lighting [69], also known as "human-centric lighting" (HCL), "circadian lighting", and "biodynamic lighting". This last wider approach aims at adapting buildings' lighting to individuals' physical and mental health-related to the image forming (IF) and non-image-forming (NIF) responses to light [70]. Where IF response refers to biological processes between the rods and cones and the brain after light reaches the retina, and NIF response refers to the intrinsically photosensitive retinal ganglion cells (ipRGCs), the human eye photoreceptors revealed in recent biological studies [71]. While IF effects have widely been studied in lighting science, actual knowledge about NIF response to light found that human eyes' ipRGCs are responsible for circadian clocks regulation, alertness, performance, and mood [72]. Considering the aims of the integrative lighting [73], the increasing interest toward a lighting design going beyond the physical visual experience, and the advancement of the tools and devices for vision, which have made the virtual visual experience very realistic, several researchers focused their research on perceptual experiments in immersive virtual environments [74, 75].

Body vibration aboard transportation means [76] and hand-harm vibrations [77] experiences can be already well simulated using 3 or 6 degrees of freedom multi-axis shakers once the stimulus has been simulated or recorded in existing situations. On the contrary, haptic experiences (manipulation, motion, objects, grasping, touching) are still limited to real experiments. In fact, although recent technologies helped to shift the paradigm of haptics interaction through desktop haptics, surface haptics and wearable haptics, this interaction still fails in several aspects. More powerful haptic devices and cross-disciplinary endeavours should be done to fill the gap and achieve equivalent sensations and interactions between the virtual and physical world [78].

Like most previous research disciplines, to control the smell experience, it is important to monitor the objective parameters that characterise a specific odorant volume or environment (i.e. concentration, intensity and persistence) [79, 80]. The previous objective parameters can be correlated with further perception-based ratings describing the character and the quality (e.g. character, hedonic tone and annoyance) of the olfactive experience [81, 82]. The paradigm shift in this field is strongly connected to reproducing and controlling the odorants during the experience [83].

3. Multisensory experiential assessment in urban planning.

The convergence of different scientific disciplines in overpassing the old deterministic paradigms toward more human-centred approaches and the new tools and devices that allow building ecological realistic (virtual or hybrid) immersive experiences, and monitoring human reactions, represent the central elements rethinking the process of assessment. For instance, urban planning could allow the communities interested in new projects to play a key role in the decision-making process. Adopting an experiential assessment could overpass most of the issues highlighted previously. First, inhabitants' social and economic context could be considered by involving representatives of local communities and the group of interest. Secondly, the issues and preferences connected to the multisensory perception and interaction of the auditory, visual, thermal and lighting sphere, which emerged more or less evidently in several studies [84-91], will be lived through holistic, physical or digital experiences, without filters and misunderstandings. In analogy with the Soundscape Framework ISO 12913-1 [57], figure 2 depicts the framework of the holistic experience.

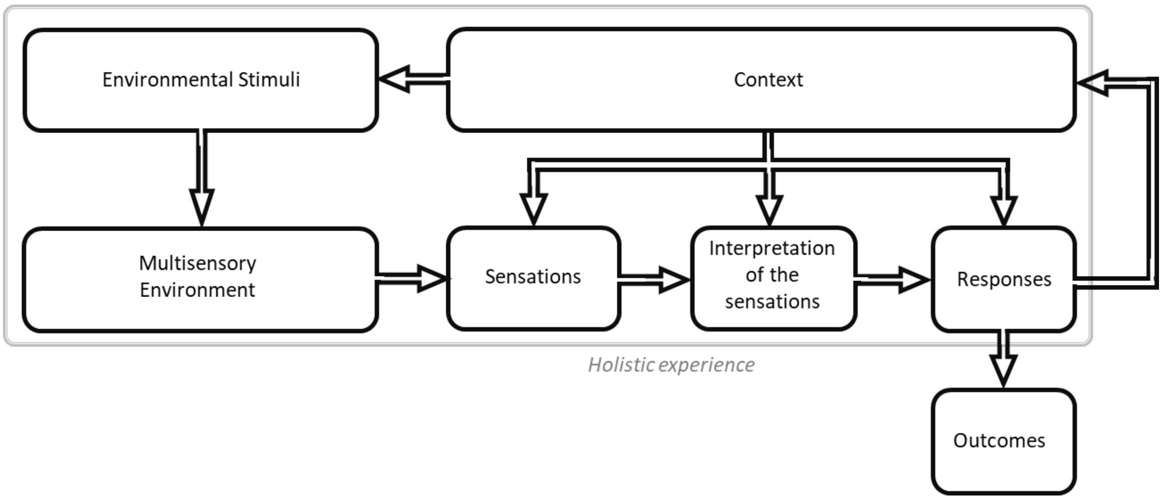

Figure 2. Holistic experiential framework.

The benefits of this kind of process are clear, especially for big and complex projects, and consist mainly in avoided costs for the administrations and investors, and in the increases and best engagement of local authority teams, communities and users in the design processes, making understandable complex architectural and engineering interventions and alternatives.

Besides the previous advantages, this kind of approach will also shorten the distances among the various disciplines involved, fostering the mutual scientific and technical contamination among physicians/engineers, designers and planners, sociologists, psychologists and economists during all the phases of the design process.

4. Toward Sensory Human Experience Centres

Figure 3 shows a framework of new centres, here named Sensory Human Experience Centres, where it is expected that it will be possible to simulate future design scenarios to get feedback from human holistic experiences. The figure shows the data flow, the procedural phases and the possible complexity levels of the virtual-hybrid experience, and the skills involved in the assessment and decisional process.

The framework should be seen as an extension of the most traditional design process, as seen from the left column. This means that future project teams should be able to project not only according to the existing national/international regulations and standards but also demonstrate the project's sustainability taking into account the human feedback: reactions, expectation, acceptance, and suggestions of the local communities and users. The input used for the modelling and simulation of buildings, landscape, traffic, climate, noise and lighting will be used, as well, to create the VR or hybrid experiential scenes.

In analogy with the research of Vergara et al. [92] on the design of VR learning environment, one of the first issues to perform an experiential assessment is the need to define which projects will encompass this new process. The definition of the number of interested inhabitants or users (e.g., small, medium, big) and intrinsic typology of the projects could suggest situations where the weight of the human component cannot be neglected. Once the project's group is identified, the main objectives of the experiential assessment should be defined, i.e., "which is the level of acceptance and impact on the population?", "which is the best alternative among those proposed?" what are the effects on human well-being?".

The next step is to define the level of realism of the experience. Must be defined: 1) the senses and stimuli to be included in the experiment; 2) the levels of detail of the different cues; 3) the interaction level (e.g., participant seated, driven or free exploration) between participants and scene. Llorca-Bofí and Vorländer, in [93], presented a comprehensive framework on audio and visual cues and discussed two extreme applications that combine different modules in a final 3D scenario for perception research.

More complex is the control and calibration of the odours parameters. As it affects significatively the vision, in the Sensory Human Experience Centres framework, the lighting has been kept separate from the Vision and put at a wider level of detail. In fact, depending on the level of detail used to simulate the light emission (e.g., omnidirectional light, directional light, IES profiles), the scene vision (surfaces, objects, materials, shadows) may change dramatically. However, while the equipment (binaural dummy head) and the audio calibration procedure are clear and independent of the playback system (headphones or spatial audio), those for lighting calibration are still not well defined. On the other hand, considering the integration

of physical cues, the calibration and control are well defined for the microclimate (temperature, relative humidity, air velocity, mean radiant temperature) and, once defined, the simulators' characteristics for the HAV and WBV vibrations.
The activation of some of these physical stimuli can be "steady" or activated by VR events programmed in the scene using Arduino interfaces [94].

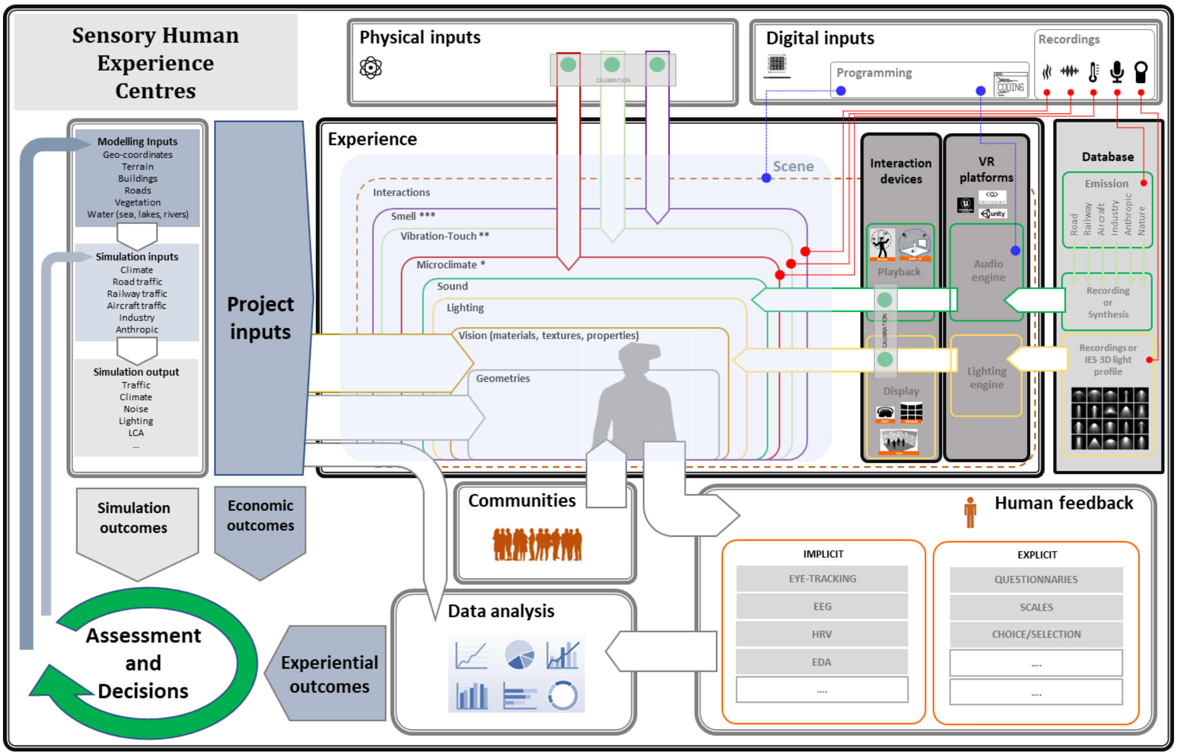

Figure 3. Sensory Human Experience Centres framework.

Among the most diffused platforms in implementing VR scenarios, Unreal Engine and Unity are the most used. Although these game engines have their own visual and audio engines, which are continuously updated to improve their realism, they still lack to reproduce some important physical effects [95]. On the other hand, they allow installing physical-based rendering plugins, or develop specific ones by programming in C sharp (Unity) and Blueprint (Unreal Engine). Vorländer and the colleagues of the Institute of Technical Acoustics (ITA) of RWTH Aachen University, after introducing the auralization technique [96] in building acoustics [97], have designed and integrated into Unity an auralization framework that implements a sound insulation model based on the ISO 12354-1 [97-99]. Other authors have proposed further implementations in room acoustics with other platforms [100, 101]. However, while lighting engines in Unity and Unreal Engine allow using IES profiles' files, which provide all the emissive characteristics of the light sources, all the audio engines and plugins use wave files as input of audio processing. This means that besides implementing a physically based rendering for audio, also in outdoor contexts, it will be indispensable to have available audio databases to introduce background or foreground sounds and simulate the sound emission of the transportation and anthropic sounds. While IoT and artificial intelligence can help the manual, or automatic, implementation of the sound databases of the environmental and anthropic sounds for the simulation of the emission of transportation means. Some authors have already developed models for synthesis or auralization [102] for road traffic [103,104], railway [105, 106], aircraft [107, 108] noise. Figure 4 shows the block diagrams of two noise auralization models for passenger cars [103] and aircraft [107] noise.

Implementing all these auditory cues is necessary to get a dynamic and plausible auralization of the sound environment.

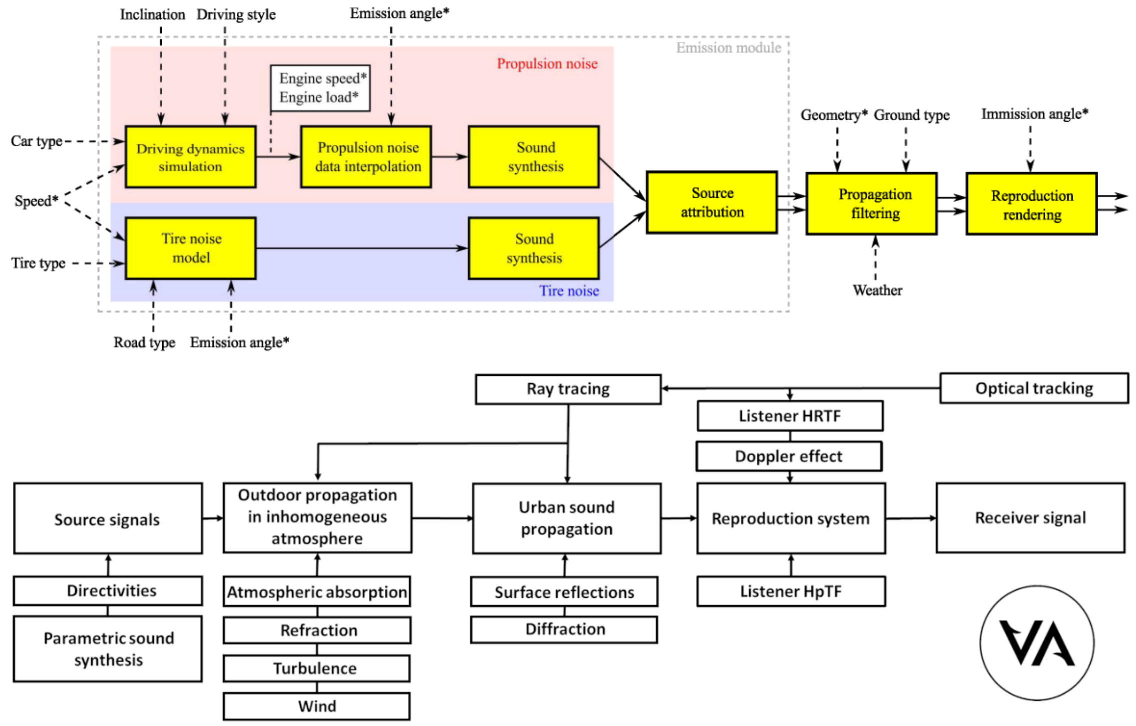

Figure 4. Auralization block diagrams of passenger cars (upper) [103] and aircraft [107] (lower) noise.

Creating the virtual or hybrid experience of the future scenarios is only the technical part of the setup and organization of Sensory Human Experience Centres. In fact, engineers and architects will be involved in the preparation of the project and the graphic and physical simulation of all relevant variables of the context (i.e. sound, vision, lighting, microclimate, air quality). Sociologists will lead to the local communities' selection and involvement. Psychologists will select the material (questionnaires, other tests/scales) to administer to the communities' representative, prepare the experimental design, and manage the experiments. Experts in the economy will estimate the costs for the alternatives. Data analyses and the process outcomes could be shared among most professionals included or specialists in statistics.

5. Discussion and conclusions

This paper has highlighted how several disciplines have changed their approach in assessing the effects of new projects and interventions in the last two decades. Most of the disciplines involved in studying the physical transformation of the environment and the effect on the individuals are shifting their approach from a negative (e.g., pollution, adverse effects) and monodisciplinary toward a positive (e.g. soundscape) and multidisciplinary (e.g. restoration, well-being) approach. The availability to use innovative technological tools and devices to simulate future scenarios and measure human feedback is now stimulating a renovation of the skills, making them broader, contaminating several other research fields.

It is expected that in the next future, most of the projects which interest large or sensitive communities, maybe all, could be performed within new spaces dedicated to reproducing holistic and predictive experience, which we named Sensory Human Experience Centres.

However, several issues must be solved before walking this road. One of the most important is the definition of the eligibility criteria of the digital platforms to use for the implementation of the virtual scenarios, which are the minimum requirements of the acoustics and lighting's engines or plugins. Independently from the platform selected, all of them must be able to simulate the most important physical effects of the (sound and lighting) propagation during the human interaction, also considering the combinations with other relevant stimuli. Similarly, the algorithms selected for the sound synthesis of the emission transportation sources should satisfy some criteria. In this sense, it is expected that instead of developing lots of algorithms, as done for the national noise emission models on the environmental acoustics, the efforts should be focused on few proposals.

From the point of view of implementing realistic lighting simulations, several efforts must be made to develop proper calibration procedures [108]. This should be done at least for HMD.

All issues mentioned above have highlighted the need to standardize, as possible, the devices, modules, and procedures making VR ready for a new EXperiential Reality (ExR), where it will be possible to define the accuracy level of all experiences.

As they involve several skills, ExR tools should also provide a database of the most common and validated tools used in psychology and sociology, and the most appropriate statistical analyses. Regarding the biofeedback measures, it is expected that in an early phase of the implementation it could be more a prerogative of the research sectors than of the assessment process.

Lots of research must be done in this direction. This will allow a general change of paradigms in assessing how humans perceive changes in the surrounding environment and will foster the scientific contamination among the disciplines involved in the design of the experiential reality (ExR).

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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