EDITORS: Andre Stork, andre.stork@igd.fraunhofer.de
Rahul C. Basole, rahul.basole@accenture.com

This article originally appeared in
IEEE Computer Graphics and Applications
vol. 41, no. 6, 2021

DEPARTMENT: GRAPHICALLY SPEAKING

Affective Virtual Reality: How to Design Artificial Experiences Impacting Human Emotions

Federica Marcolin, *Politecnico di Torino, 10129, Torino, Italy*
Giulia Wally Scurati, *Politecnico di Milano, 20156, Milano, Italy*
Luca Ulrich, Francesca Nonis, and Enrico Vezzetti, *Politecnico di Torino, 10129, Torino, Italy*
Nicolò Dozio and Francesco Ferrise, *Politecnico di Milano, 20156, Milano, Italy*

Computer graphics is—in many cases—about visualizing what you cannot see. However, virtual reality (VR), from its beginnings, aimed at stimulating all human senses: not just the visual channel. Moreover, this set of multisensory stimuli allows users to feel present and able to interact with the virtual environment. In this way, VR aims to deliver experiences that are comparable to real-life ones in their level of detail and stimulation, intensity, and impact. Hence, VR is not only a means to see, but also to feel differently. With the spreading of VR technologies, there is a growing interest in using VR to evoke emotions, including positive and negative ones. This article discusses the current possibilities and the authors' experience collected in the field in trying to elicit emotions through VR. It explores how different design aspects and features can be used, describing their contributions and benefits in the development of affective VR experiences. This work aims at raising awareness of the necessity to consider and explore the full design space that VR technology provides in comparison to traditional media. Additionally, it provides possible tracks of VR affective applications, illustrating how they could impact our emotions and improve our life, and providing guidelines for their development.

IT IS nowadays widely accepted that emotions rule the world. Most human decisions and actions cannot happen without the influence of an emotional factor. They affect our behavior and decision-making processes in a way that can be good or bad for ourselves, others, and society. Any situation can affect our emotions, and our own emotions can worsen or improve a situation, changing our responses. Emotions mediate and modulate our actions and reactions: this power has been widely acknowledged, not only by researchers but by the whole of humankind.

For this reason, humans have always engaged in the development of artifacts and technologies raising emotions in various fields (e.g., artistic, technical, and medical). This creative activity is not a mere personal expression but often aims to influence people's attitudes, thinking, and acting through emotional experiences. In fact, these experiences can change the way we see and manage past events,[1] current issues,[2] and future perspectives.[3]

Computer graphics and interactive technologies have greatly enhanced this opportunity, widening and enriching the emotional design space. In particular, VR

0272-1716 © 2021 IEEE
Digital Object Identifier 10.1109/MCG.2021.3115015
Date of current version 10 December 2021.

can provide immersive experiences, allowing users to embody other people and living beings,[4] facing a wide range of situations that can be dramatic,[1] relaxing,[2] scary,[5] or exciting.[6] Similar contents raise more intense emotional reactions when delivered through immersive VR compared to other media or technologies (e.g., PC screens, traditional videos).[7,8] Researchers and professionals acknowledge the potential to raise emotions through VR from various fields (e.g., design and engineering areas, psychology, and medicine), various industries and enterprises, and governmental and nongovernmental organizations. Addressing emotions in VR can support environmental education, stakeholders' and practitioners' decision-making, and fundraising campaigns. It can improve employees' or patients' moods, inducing relaxation, and treat past traumas and phobias. The interest in affective VR is growing and is predicted to play an increasingly determinant role in the next years, improving human life and behavior. Nonetheless, for designers, the development of emotional VR experiences is not a straightforward process.

In this work, we explore the wide design space offered by VR tools, relating it to emotional mechanisms and aspects, providing basic hints for VR designers. Relying on our experience, we describe different directions and applications designers can choose when creating emotional VR scenarios. The aim is to summarize why designers should engage in affective VR design, which sets of issues they could target, and how different design factors can be modified and calibrated.

VR DESIGN SPACE AND EMOTIONAL SPACE

The ability of VR in raising intense emotions is due to a series of specific properties of VR tools compared to other media and technologies. These properties can be used and modulated in many ways according to the kind and intensity of emotional response the designer wants to achieve. Moreover, different aspects should be considered when raising an emotion, connecting the wide VR design space and the complex emotional space, relating design factors and decisions to emotional dimensions.

VR Design Space: Playing With Immersion, Presence and Agency, and Multisensory Stimuli

VR specific properties have been widely described and investigated to enhance users' involvement and engagement and make the experience more realistic and credible. These concepts have been defined and extensively discussed, for instance, by Slater and Wilbur,[9] Schuemie *et al.*,[10] and Skarbez *et al.*[11] Considering their relationship with emotional aspects, the most relevant properties we discuss here are as follows:

- immersion;
- presence;
- agency;
- embodiment and body ownership;
- multisensory synergetic stimuli;
- dynamism and animations.

Immersion is perceptual and psychological, which describes how users feel enveloped and interacting with the environment,[11] whereas presence is defined as "the sense of being there."[9] The term immersion is also used to refer to the kind of technology used (i.e., immersive HMDs, nonimmersive PC screens) as an objective feature of the system.[9] Presence and immersion can increase the affective response,[2] but it is also true that affective contents can increase presence.[12] This is not surprising, as these concepts also regard the psychological dimension; immersion is a psychological state of feeling involved by the experiences and stimuli into the virtual space.[11] The relationship between presence, immersion, and emotions is represented in Figure 1.

Agency is the sense of being the one causing or generating action; it is related to embodiment and body ownership, the sense of being the one undergoing an experience and own the body that is providing sensations.[13] Agency makes users feel able to affect the virtual experience and take decisions, including control of their own movements and navigation. It can be regulated to support self-efficacy[14]—or rather to cause frustration. Agency and body ownership can enhance emotions (e.g., increasing anxiety when avoiding knives).[15] However, presence and emotions can also be elicited with low agency level (e.g., passive VR 360° videos).[2] The VR space can be used to mix, blend, and deliver multisensory stimuli (visual, auditory, tactile, and olfactory). Importantly, their combination and interaction result in a synergetic effect and significantly contribute to increasing presence, making VR experiences closer to real ones.[16] Multisensory VR regards using a great variety of elements, colors, sounds, objects, and smells. These elements are also used to deliver reproductions of movements and animations into the VR environments. All these aspects can be designed to obtain a specific emotional outcome.[17]

VR Emotional Space: Linking Emotional and Design Factors

The first obvious step to design a virtual environment with a specific emotional effect requires defining the emotion to be stimulated. Traditional emotions that

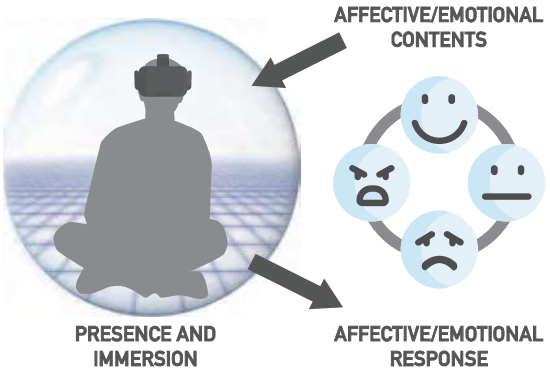

FIGURE 1. Relationship between presence, immersion, and emotions. Affective and emotional contents can increase presence and immersion, which can increase affective and emotional responses: this can enhance the contents' effectiveness.

have been widely studied and addressed in these years are the well-known "basic emotions,"[18] including *anger, disgust, fear, happiness, sadness,* and *surprise*.

While these basic emotions are well known, the first difficulty an affective VR designer has is that, beyond these basic emotions, there are several more complex emotions. In addition, many emotions seem similar to the six basic emotions but they have different names and characteristics. The first step is to correctly identify the characteristics of the specific emotion the designer wants to arouse.

Each specific emotion is activated by certain mechanisms, and the designer must understand which mechanisms to activate and how to avoid arousing the wrong emotion. Some emotions can also be correlated or alternate during the use of a VR environment.

Once the emotion is selected, designers can choose *ad hoc* elements from the design space to make the VR environment evoke that one specifically.

Furthermore, it is possible to adopt three numerical dimensions to represent the emotions. These dimensions describe the *PAD/VAD emotional state model* developed to describe the emotional states.[19]

These three dimensions are as follows:

- pleasure/valence (positive versus negative experience);
- arousal (the degree of the activation of the emotion);
- dominance (feeling in control versus under control of the situation).

One of the main limitations of the PAD/VAD emotional state model is that there is no perfect correspondence between valence, arousal, and dominance (VAD) values and a specific emotion. There are numerous valence–arousal diagrams in the literature with emotional labels placed in a point or area. In analyzing these diagrams, it turns out that the placement of labels is not always the same when analyzing different articles. Furthermore, in a minimal space of the valence–arousal diagram, there are sometimes many emotions.

Once the limitations of this model are known, designers can manipulate these three dimensions, combining features that affect each of them in the desired way using the VR design factors described earlier.

For instance, agency essentially corresponds to the feeling of being in control when performing actions,[13] so it might be related to dominance.

Stimuli and media can be related to emotions, valence, and arousal. For instance, bright, saturated colors are associated with emotions having positive valence and high arousal (e.g., excitement), whereas dark, unsaturated ones are associated with low arousal and negative valence (e.g., depression).[17] Dynamism, movements, and animations also have emotional meaning: different speeds and directions can raise anxiety or, instead, relaxation.[17]

Considering presence and immersion, they can influence emotions' intensity and, consequently, the VR tool's efficacy. Low presence rates can be linked to weaker affective responses.[20]

The link between all these factors in the design and emotional space is represented in Figure 2.

These considerations guide the virtual environment's design and affect the use/choice of technologies to deliver the stimuli, navigate the environment, eventually control a virtual avatar, and detect users' actions and reactions. These devices include visual, auditory, haptic, and olfactory displays, controllers, sensors, and actuators. For instance, immersion is affected by the use of technologies: adopting headset provided with headphones can provide a higher immersion than using a PC screen.[2]

VR DESIGN OPPORTUNITIES AND DIRECTIONS

VR tools allow us to explore and connect extremely wide design and emotional spaces, with a great variety of possible applications. In particular, there are three main directions to develop VR environments, which are as follows:

- understanding, recalling, and reviewing the past;
- improving the present: affecting current mood and activities;
- prepare for the future and change our intentions.

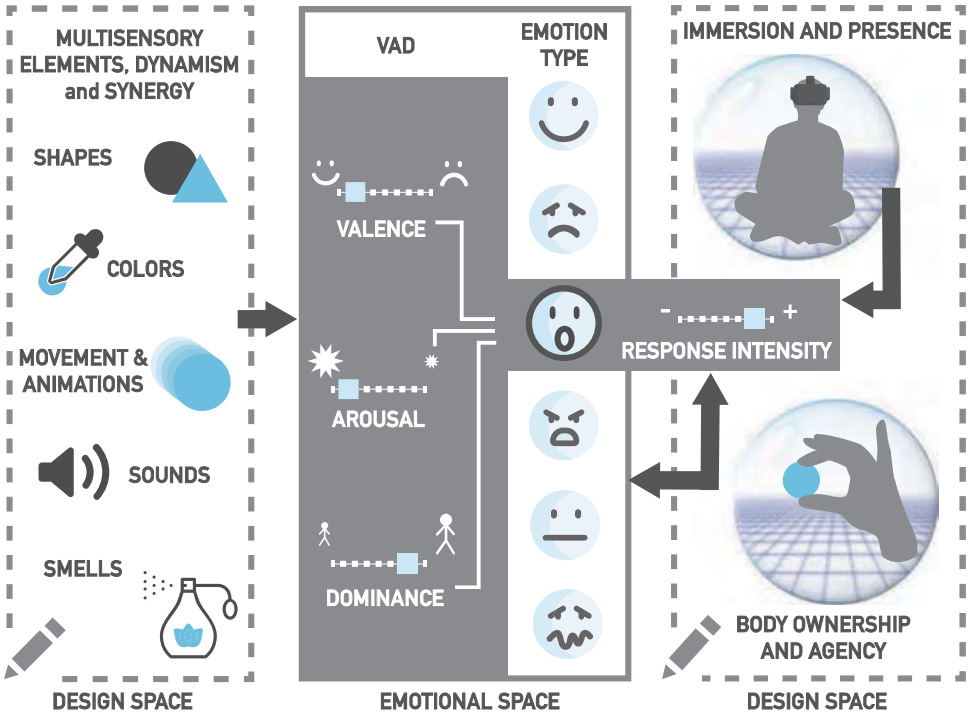

FIGURE 2. Relationship between emotional (PAD/VAD, emotion-type, and intensity) and design space (sensory elements—on the left, and VR properties—on the right). Multisensory elements, dynamism, and synergy affect VAD raising an emotion. The intensity of the affective response can be increased by VR properties (immersion, presence, agency, embodiment, and body ownership).

Considering the first direction, examples include treating past traumas[1] or recalling positive autobiographical memories.[21] A typical application of the second one is improving mood, reducing negative emotions, and increasing relaxation.[2] Another possibility is making everyday activities (e.g., learning) more engaging and satisfactory.[22] The third one regards preparing users for future challenging and stressful situations, and also changing intentions and behavior, for instance, making them more sustainable.[3] These directions allow us to individuate design opportunities and define a narrative tailored on the specific objectives. Designers do not only define VR elements and their relationships, they also guide the users into the VR environment to experience design and emotional objects with a specific path and order.

DESIGN PROCESS AND GUIDELINES

As we have seen, the number of variables that we can consider to evoke a specific emotion in VR are many. Sometimes in VR, working with multiple variables does not give out an *a priori* known output. For example, VR is multisensory, and combining a tactile stimulus with a visual and a sound one does not always give the expected result. Furthermore, the complexity increases when we consider that every simple stimulus will be connected to a specific symbolic and emotional meaning, and that this may not be understood or perceived uniquely by each user. Hence, several iterations and prototype testing should be required to refine the overall environment.

In order to create affective VR contents, the following simplified design process can be adopted. These steps must be considered sufficient but not exhaustive. The process might not be linear thus some of the steps might require more than one iteration.

The steps are as follows:

- choosing a direction (focus on past, present, or future emotional experiences);
- defining emotional space (valence, arousal, dominance, emotion typology, and intensity);
- defining the design space (sensory elements and their meaning in the overall VR experience);
- define a narrative (arranging elements in a given order shaping the experience);
- selecting input/output technology.

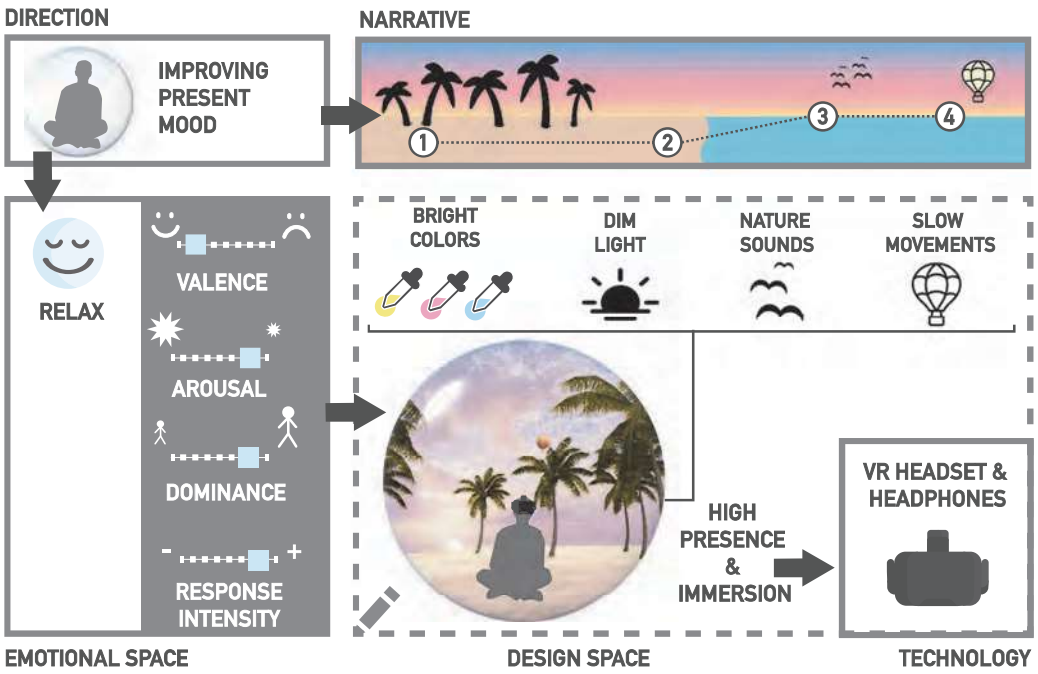

FIGURE 3. Design process for affective VR and its complexity demonstrated through an example.

Figure 3 is purely descriptive and illustrates the design process and its complexity. We used an example (designing for relax) to show the design process and its complexity.

As described earlier, a possible design direction that is chosen by the designer is improving present mood. The designer decides to do this by inducing relaxation, defining the emotional space: valence is positive, arousal low, and dominance high. The desired response intensity is also high. As a consequence, the design space includes the use of positive and calming elements, light bright colors, dim light, nature sounds, and slow movement. The designer also increases presence and immersion, since they may enhance the response intensity, choosing a headset with integrated headphones as a technology to deliver the experience. At the same time, the design elements are integrated into a VR environment. Considering the direction, a narrative is created to explore and interact with the VR environment, modulating the emotional responses using elements and timing.

The same approach can be used for other emotions.

OUR EXPERIENCE

Relying on the simplified design process exposed earlier, we have conceptualized a database of VR environments to elicit frustration (anger-based emotion), disgust, fear, happiness, and sadness.

The chosen direction was to focus on the present, i.e., the purpose of these virtual scenarios was to "improve the present: affecting current moods and activities."

VAD concepts have been adopted to select specific shapes and colors based on the literature available. Finally, semantic elements contributed to creating a narrative and shaping a specific emotional feeling. Standard VR environments to be navigated with a monitor on a PC were chosen and designed as they allow us to monitor user's emotions with a facial expression acquisition system and EEG. Testing the results quickly is indeed fundamental, as we discussed earlier.

An experiment consisting of two steps has been set up to analyze the effectiveness of these VR environments. In the first step, the user was asked to fill in a questionnaire about how he/she felt; in the second, the user's face was acquired with a depth camera with the purpose of subsequently understanding his/her facial expressions with the help of a specifically trained neural network. The users were students participating in the experiments on a voluntary basis.

The outcomes obtained from the experiment suggest that the design methodology is well-conceived

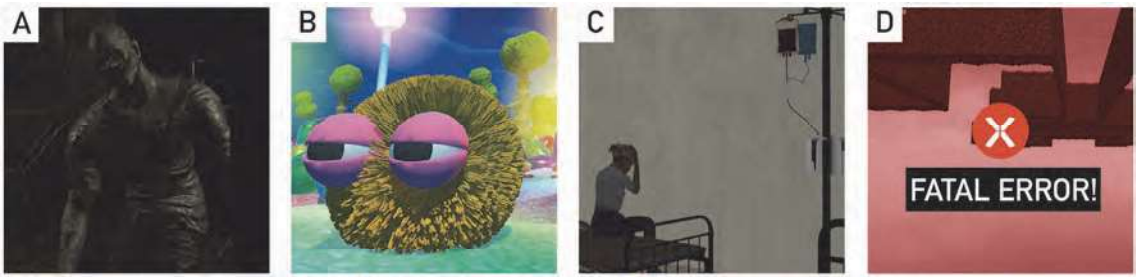

FIGURE 4. Surprising characters raising (A) fear and (B) fun. Real life inspired experiences raising (C) sadness and (D) frustration.

and makes it possible to evoke desired emotions. The majority of the population declared (in the questionnaire) and manifested (via facial expression) to feel the emotion which that specific VR environment was designed for. The obtained valence values (negativity/positivity of emotions) perfectly met the expectations. Though, in most of the cases, the arousal level did not reach very high values (but in acceptable ranges compared with the state of the art), this was probably due to the fact that even if the levels of presence and immersion were high, subjects were not 100% emotionally involved because they realized they were in a fictitious environment.

Another qualitative outcome regards the role of the dominance dimension. Despite the recent downgrade and low consideration of this indicator, the possibility of being in control or, on the contrary, the feeling of being controlled by the elements of the environment resulted to be determinant to evoke the desired emotion. This is particularly true for fear and frustration environments, where the users felt to be powerless and under control of the circumstances.

Best Practices From Our Experience

Valence played a key role for the success of the affective VR environments. For instance, the designer might want to raise fear to improve the experience of playing a horror game. Fear has a negative valence and high arousal that can be elicited using dark colors and sudden movements and sounds, generating an alert state. The desired dominance is low, making the user feel a lack of control over the environment, which is dark, mysterious, and reacts unpredictably to the user's actions. A high sense of presence and immersion is desired to intensify the gaming experience. Therefore, the designer can choose to use spatial sound to locate sounds associated with dangerous characters [see Figure 4(A)] and events in the space.

Unpredictability can also play a central role when raising happiness through fun, in this case using a positive kind of surprise, increasing arousal. Dominance over the environment can be lower compared to the relaxing one described earlier: imagine the sense of slightly losing control due to a euphoric partying experience. Possible elements to be included in the scene would be bright colors, loud music, funny characters [see Figure 4(B)] and sounds, and dynamic colorful lights.

Low arousal emotions, such as relaxation and sadness, should instead avoid unexpected events, providing a smooth experience. A strategy is rather to recall well-known situations in people's lives; an example is proposing a hospital environment, generally associated with death, loss, and suffering [see Figure 4(C)]. Similarly, it is not trivial to raise anger, but designers can inspire with everyday frustrating experiences. An example is complex interfaces and systems, making it hard to accomplish tasks and causing a sense of failure, also presenting warnings and alarms [see Figure 4(D)]. Replicating similar mechanisms and elements in VR can cause stronger negative emotions because of greater user involvement due to immersion and presence.

DISCUSSION

The design and emotional space described in this work reveal and link several elements to build affective VR applications. The design guidelines outlined earlier can be considered during both conceptualizing and development phases of affective environments. The process we illustrated clearly requires extensive knowledge of both VR tools and human emotions. However, even knowledgeable designers should not underestimate this complexity and the possible issues and drawbacks that can emerge from the earliest steps of the process.

One of them concerns the desired emotion. Even if precautions are taken in terms of objectivity of design items to gain as much as possible for making the users feel a specific emotion, the emotional responses come as diverse. This is due to the different life/culture experiences that the users have had. For instance,

high exposure to horror movies will make users more comfortable, and unfortunately less scared, when fearful VR content is presented. This is something inevitable that can only be studied through tests about users' attitudes.

A linked issue regards the higher/lower suitability of some emotions to be simply evoked. Considering the six basic emotions previously mentioned, some emotions might be easier to evoke than others, especially in VR. Among the ones easier to elicit, we can list sadness, disgust, and happiness. This is because they are strictly connected to visual and sound information, which requires less user involvement (thus, less storytelling). On the contrary, anger and surprise could be harder to trigger. In these cases, the user should be very into a narrative to get angered appropriately or surprised. The solution in these cases is to slightly migrate the emotional purpose into other similar emotions in the same sphere, such as frustration for anger.

This just-mentioned migration fosters another issue, which is reflected by several disciplines studying emotions. The six basic emotions have been widely studied and tested. All other emotions that may even be more relevant for applications in human–computer interaction have not received the same attention from the scientific community. Concentration rather than happiness, contempt rather than disgust, and disappointment rather than sadness may be more entitled to be addressed in several fields involving the adoption of VR as an evoking technology tool.

Finally, an open issue when facing emotional elicitation regards their evaluation through testing and measures. It is not trivial to understand the "ground truth" of emotion, i.e., the emotion that the user has felt. Is it the emotion they labeled in the questionnaire fill-in? Is it what the EEG reveals via electric signals? Is it the displayed facial expression? It is possible to compare several types of data to understand if a VR environment effectively evokes the desired emotion. However, the emotional analysis instruments still appear biased (or even drugged) by the elements in the background of the experimental environment, by the expectations and desired outcomes. Although the primary focus of this work was on the design of emotional environments, assessing their effectiveness would require an additional analysis along with process and guidelines.

CONCLUSION

Conceiving VR environments with affective purposes is not a trivial task, and a solid design methodology should be adopted to make the experimentation effective, outlined in such a way to be adjusted after a pilot test. Our experience suggests that each emotion should be taken care of separately to preserve its specific features, such as unpredictability elements for fear, and that the outcomes could be quite diverse depending on life experiences of the testers. The VAD systems turns out to be a valid design tool for framing and assessing emotions, even if the literature seems not univocal in the representation of the emotions based on valence–arousal–dominance indicators. Considering the subjectivity of the emotions in general, this ambition may never be met tangibly.

The main future perspective concerns the study of others rather than the six basic emotions. The human–computer interaction field requires the investigation of more specific and "cutting edge" emotions, and the possibility of detecting also tiny signs of them. As a consequence, referring for instance to deep-learning-based facial expression recognition systems, neural networks should be properly trained to recognize these "shades."

REFERENCES

1. L. Loucks *et al.*, "You can do that?!: Feasibility of virtual reality exposure therapy in the treatment of PTSD due to military sexual trauma," *J. Anxiety Disord.*, vol. 61, pp. 55–63, 2019.
2. E. Brivio, S. Serino, E. N. Cousa, A. Zini, G. Riva, and G. De Leo, "Virtual reality and 360 panorama technology: A media comparison to study changes in sense of presence, anxiety, and positive emotions," *Virtual Reality*, vol. 25, no. 2, pp. 303–311, 2021.
3. G. W. Scurati, M. Bertoni, S. Graziosi, and F. Ferrise, "Exploring the use of virtual reality to support environmentally sustainable behavior: A framework to design experiences," *Sustainability*, vol. 13, no. 2, 2021, Art. no. 943.
4. S. J. Ahn, A. M. T. Le, and J. Bailenson, "The effect of embodied experiences on self-other merging, attitude, and helping behavior," *Media Psychol.*, vol. 16, no. 1, pp. 7–38, 2013.
5. C. Botella, J. Fernández-Álvarez, V. Guillén, A. García-Palacios, and R. Baños, "Recent progress in virtual reality exposure therapy for phobias: A systematic review," *Current Psychiatry Rep.*, vol. 19, no. 7, pp. 1–13, 2017.
6. W. Wei, R. Qi, and L. Zhang, "Effects of virtual reality on theme park visitors' experience and behaviors: A presence perspective," *Tourism Manage.*, vol. 71, pp. 282–293, 2019.
7. K. Kim, M. Z. Rosenthal, D. J. Zielinski, and R. Brady, "Effects of virtual environment platforms on emotional responses," *Comput. Methods Programs Biomed.*, vol. 113, no. 3, pp. 882–893, 2014, doi: 10.1016/j.cmpb.2013.12.024.

8. R. Lavoie, K. Main, C. King, and D. King, "Virtual experience, real consequences: The potential negative emotional consequences of virtual reality gameplay," *Virtual Reality*, vol. 25, no. 1, pp. 69–81, 2021.
9. M. Slater and S. Wilbur, "A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments," *Presence: Teleoperators Virtual Environ.*, vol. 6, no. *6*, pp. 603–616, 1997.
10. M. J. Schuemie, P. Van Der Straaten, M. Krijn, and C. A. Van DerMast, "Research on presence in virtual reality: A survey," *CyberPsychol. Behav.*, vol. 4, no. 2, pp. 183–201, 2001.
11. R. Skarbez, F. P. Brooks Jr., and M. C. Whitton, "A survey of presence and related concepts," *ACM Comput. Surv.*, vol. 50, no. *6*, pp. 1–39, 2017.
12. R. M. Baños, C. Botella, M. Alcañiz, V. Liaño, B. Guerrero, and B. Rey, "Immersion and emotion: Their impact on the sense of presence," *Cyberpsychol. Behav.*, vol. 7, no. *6*, pp. 734–741, 2004.
13. C. Jeunet, L. Albert, F. Argelaguet, and A. Lécuyer, "'Do you feel in control?': Towards novel approaches to characterise, manipulate and measure the sense of agency in virtual environments," *IEEE Trans. Vis. Comput. Graphics*, vol. 24, no. *4*, pp. 1486–1495, Apr. 2018.
14. G. Makransky and G. B. Petersen, "The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality," *Educ. Psychol. Rev.*, vol. 33, pp. 937–958, 2021.
15. W. Chen, J. Zhang, Y. Qian, and Q. Gao, "How disentangled sense of agency and sense of ownership can interact with different emotional events on stress feelings," *Psicologia: Reflexão e Crítica*, vol. 30, no. 1, pp. 1–11, 2017.
16. A. Gallace, M. K. Ngo, J. Sulaitis, and C. Spence, "Multisensory presence in virtual reality: Possibilities & limitations," in *Multiple Sensorial Media Advances and Applications: New Developments in MulSeMedia*. Hershey, PA, USA: IGI Global, 2012, pp. 1–38.
17. A. Pinilla, J. Garcia, W. Raffe, J.-N. Voigt-Antons, and S. Möller, "Visual representation of emotions in virtual reality," Feb. 12, 2021. [Online]. Available: psyarxiv.com/9jguh
18. P. Ekman and D. Keltner, "Universal facial expressions of emotion," in *Nonverbal Communication: Where Nature Meets Culture*, vol. 27, U. Segerstrale and P. Molnar, Eds. Mahwah, NJ, USA: Lawrence Erlbaum Associates, 1997, p. 46.
19. J. A. Russell and A. Mehrabian, "Evidence for a three-factor theory of emotions," *J. Res. Personality*, vol. 11, no. *3*, pp. 273–294, 1977.
20. G. Riva *et al.*, "Affective interactions using virtual reality: The link between presence and emotions," *CyberPsychol. Behav.*, vol. 10, no. 1, pp. 45–56, 2007.
21. J. Fernandez-Alvarez *et al.*, "Using virtual reality to target positive autobiographical memory in individuals with moderate-to-moderately severe depressive symptoms: A single case experimental design," *Internet Interv.*, vol. 25, 2021, Art. no. 100407.
22. D. Allcoat and A. von Mühlenen, "Learning in virtual reality: Effects on performance, emotion and engagement," *Res. Learn. Technol.*, vol. 26, Nov. 2018.

FEDERICA MARCOLIN is with the Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy. She is the corresponding author of this article. Contact her at federica.marcolin@polito.it.

GIULIA WALLY SCURATI is with the Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy. Contact her at giuliawally.scurati@polimi.it.

LUCA ULRICH is with the Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy. Contact him at luca.ulrich@polito.it.

FRANCESCA NONIS is with the Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy. Contact him at francesca.nonis@polito.it.

ENRICO VEZZETTI is with the Department of Management and Production Engineering, Politecnico di Torino, Torino, Italy. Contact him at enrico.vezzetti@polito.it.

NICOLÒ DOZIO is with the Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy. Contact him at nicolo.dozio@polimi.it.

FRANCESCO FERRISE is with the Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy. Contact him at francesco.ferrise@polimi.it.

Contact department editor Andre Stork at andre.stork@igd.fraunhofer.de or department editor Rahul C. Basole at rahul.basole@accenture.com.