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Virtual Reality enhances EEG-based neurofeedback for emotional self-regulation

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Abstract. A pilot study to investigate possible differences between a virtual reality-based neurofeedback and a traditional neurofeedback is presented. Neurofeedback training aimed to strengthen the emotional regulation capacity. The neurofeedback task is to down-regulate negative emotions by decreasing the beta band power measured in the midline areas of the scalp (i.e., Fcz-Cpz). Negative International Affective Picture System images were chosen as eliciting stimuli. Three healthy subjects participated in the experimental activities. Each of them underwent three VR-based neurofeedback sessions and three neurofeedback sessions delivered on a traditional 2D screen. The neurofeedback training session was preceded by a calibration phase allowing to record the rest and the baseline values to adapt the neurofeedback system to the user. For the majority of sessions, the average value of the high beta band power during the neurofeedback training remained below the baseline, as expected. In compliance with previous studies, future works should investigate the virtual reality-based neurofeedback efficacy in physiological responses and behavioral performance.

Keywords: brain-computer interface · EEG · extended reality · virtual reality · health 4.0 · emotion regulation · neurofeedback

1 Introduction

Neurofeedback is a form of biofeedback based on signals collected from the brain. Typically, electrical activity from the brain is acquired by using electroencephalography (EEG). Brainwave information is provided in real time to the user so they can learn how to self regulate brain electrical activity [1]. This technique proves effective in the treatment of attention-deficit/hyperactivity disorder [2], sleep disorders [3], and in the self-regulation of emotional behavior [4].

Emotion regulation (ER) is the ability to recognize one's emotions and manage the intensity and duration of emotional experience [5]. Impairment of the ability to regulate affect leads to emotional vulnerability: a high sensitivity to experiencing emotions with high degrees of intensity and for a long time. Various cognitive and behavioral strategies can be employed for ER. Typical cognitive strategies are based on shift of attention, distancing, or cognitive reappraisal. The latter proved to be particularly successful and consists in changing the way the person thinks and evaluates the emotionally critical situation in order to modify his/her emotional impact [6]. A specific kind of reappraisal is the reality checking that is the reappraisal of the meaning of the current situation [7]. Physical exercises such as running can be an effective behavioral strategy for achieving emotional modulation [8].

Thanks to the association between emotions and the diverse brain activation patterns [9] and the relations between cerebral damages and emotion perception and expression [10], neurofeedback can be used for the treatment of emotion regulation disorders. Neurofeedback for ER has been successfully applied to treat schizophrenia [11], stress [12], depression [13], and anxiety [14–16]. In [11], functional Near-Infrared Spectroscopy and EEG were employed for the neurofeedback training of eighteen subjects suffering from schizophrenia. The regulation of frontal delta asymmetry allowed to restore the unbalance between the hemispheres. In [12], frontal alpha power and frontal alpha asymmetry based neurofeedback were successfully exploited for stress mitigation. EEG data from 20 participants were recorded in two neurofeedback sessions. In [17], simultaneous real-time Functional Magnetic Resonance Imaging and EEG-based neurofeedback for ER in 16 subjects with major depressive disorder was carried out. Frontal EEG asymmetries in the alpha band and high-beta band were the exploited EEG-related quantities. Significant upregulation was achieved. In [18], the effectiveness of neurofeedback on brain training of ER was proven. By means of a control group, the study separated the effects of neurofeedback and cognitive strategy. In [15], a neurofeedback training to increase frontal alpha asymmetry was exploited for the reduction of negative affect and anxiety. 32 subjects underwent the experimental activities. As a result, an increment in alpha asymmetry produced a reduction in both negative affect and anxiety. In [19], alpha, beta and alpha-theta bands measured in Pz and Fz locations were regulated by neurofeedback training in two patients diagnosed with anxiety disorder. Anxiety-related symptoms reduced within a three month period. The case study of a subject with anxiety was presented in [16]. A neurofeedback-based protocol was successfully employed to suppress excessive central high beta activity. Neurofeedback training was successfully employed also in healthy subjects. In [20], long-term effects of neurofeedback training based on frontal beta EEG were evaluated on 25 healthy subjects. Resting-state EEG was recorded prior to neurofeedback training and in a 3-year follow-up. Neurofeedback training increased Fz beta activity both in short and long-term. In [21], the impact on mood of frontal alpha-activity based neurofeedback was evaluated. 40 healthy females were involved in the experiments and results demonstrated the feasibility of varying frontal alpha asymmetry just in a single neurofeedback session.

Emotion induction mechanisms are often grouped into two classes: passive and active [22]. Traditionally, passive elicitation methods place the user as a mere observer, ignoring the importance of personal meaning in the emotional experience. Active mechanisms are characterised by high ecological validity (meaning the ability of experimental results to be generalisable to the real world outside the laboratory [23]), immersiveness and interactivity.

Among active approaches, Virtual Reality (VR) (and, more in general, eXtended Reality) shows great potential for emotional elicitation, offering motivational and empathy mechanisms that make it an ecologically valid paradigm for studying emotions. The sense of presence offered by VR is the result of a technological simulation consistent with the predictive mechanisms of the brain (body matrix) [24, 25]. VR stimulates a wide range of sensory modalities, integrating proprioception, interoception and sensory information [24].

Although the so-called novelty bias may play a controversial role, various researches show that the use of VR leads to even stronger valence and arousal elicitation with respect to passive methods [26]. Nevertheless, there is a lack of reference datasets and databases in the literature that standardise VR content, which is mandatory for performing comparison studies [27]. This represents the greatest limitation in this line of research to date.

Important but less explored (especially with EEG-BCI) in this context is the use of neurofeedback for ER in VR. In this study, and similarly to what has already been covered in the literature [28], International affective picture system (IAPS) images are exploited as visual stimuli also in the VR environment. The aspect of immersivity and engagement is exploited for the environmental neurofeedback rather than the stimulus delivery mechanism.

The goal of the present study is to explore potential differences between a VR-based and a traditional 2D neurofeedback system, aimed to strengthen the ER capacity. Specifically, three subjects carried out three sessions with the 2D neurofeedback system and three sessions with the VR neurofeedback system. In both systems, feedback training exploits standardised stimuli to elicit specific emotions and EEG signals to provide the feedback. Differences between the two proposed systems were assessed through different self-assessment scales that evaluated both emotional states and systems' usability. In Section 2, the overall neurofeedback systems, the experimental campaign for the EEG signal acquisitions, and the statistical and EEG data analysis procedures are presented. The statistical analysis and the EEG data analysis are reported in Section 3. Discussions and conclusions are illustrated in Section 4 and Section 5, respectively.

2 Material and Methods

2.1 VR neurofeedback system

Two different neurofeedback-based systems were developed: a 2D-neurofeedback system and a VR-neurofeedback system. To induce a certain emotional state to the user, IAPS images [29] negatively polarised on the valence axis (and with neutral arousal) were used as eliciting stimuli. Since IAPS images are rated according to the circumplex model of affect, the dimensional model is considered as reference theory. Pictures represented scenes of danger, death, violence, disease etc. Pictures were different and randomly presented to participants in order to prevent habituation and familiarity. In the first system, the application displays sequentially on the screen appropriate visual stimuli. During regulation, the feedback was provided by the colour bar (on the right hand side) and by the frame (placed around the images). Fig. 1-a shows the 2D-neurofeedback application.


(a) 2D feedback (b) VR feedback

Fig. 1: 2D (a) and VR (b) feedbacks


Fig. 2: colour scale

In the VR-neurofeedback system, a visual stimulation mechanism using IAPS images was adopted, so that a one-to-one comparison with the on-screen neurofeedback case was straightforward. Specifically, the application immerses the subject in a virtual room (a minimalist office room in which care was taken not to include distracting elements) in which stimuli are displayed on a room wall. In this case, in addition to the traditional thermometer on the side of the image, feedback is provided by changing the colour of the lights in the room. The colour-changing image frame here becomes the entire virtual environment, which modulates its colours in accordance with the subject's feedback. In Fig. 1-b, the VR environment is shown. In both systems, the colour bar can move from down (blue) to up (yellow) according to the registered cortical activation

following the colour scale proposed by [30] (Fig. 2).
The heights of the bars were updated every 1-s according to the level of the EEG feature to regulate. The two proposed applications were developed using Unity [31] (version 2019.4.4f1, Personal 64 bit for Microsoft Windows) as game engine. For the VR system, the HTC Vive Pro 2 [32] was used as VR headset.
FlexEEG™from Neuroconcise [33] was employed for signal recordings. EEG data were acquired from three bipolar channels, namely FC3-Cp3, FCz-Cpz, and Fc4-Cp4 placed according to the International 10-20 Positioning System. Afz is the bias electrode. Electrodes were filled in with conductive gel. The system allows wireless signal transmission via Bluetooth 2.0 and adjustable sampling rate (125 Hz-250 Hz) and ADC resolution (16-24 bits).
EEG signal was acquired, transmitted and real time processed in Matlab environment R2021b version. The EEG system is provided with a Matlab script which allows the parameters setting and a default Simulink model which contains the compiled code to run the FlexEEG. Simulink was employed also for the online processing of the acquired EEG signal. Data were first filtered by using a bandpass filter with cut-off frequencies 20 Hz and 34 Hz, and then 2-s epochs overlapping of 1-s were extracted. Fast Fourier transform (FFT) was then applied to each epoch in order to extract the power values in the considered EEG band. Neurofeedback training focused on the decrease of the high-beta power in midline locations (FCz-Cpz) [34]. For each session, an initial calibration phase was carried out to adapt the neurofeedback session to each participant. 2-min eyes-opened resting state and a task-related baseline were initially recorded [11]. For both phases, the mean high-beta powers of the neurofeedback electrodes were computed and used as the upper and lower limits of the colour scale, respectively. After the calibration phase, the neurofeedback training started. Also in this second phase, EEG data were online processed and the high-beta power computed over the FCz-CPz electrode was used to drive the visual feedback provided to the user. Simulink and Unity communicated via UDP protocol: Unity sent Simulink start and end messages for each task. Simulink returned the values of the reference feature computed in the rest and baseline phases and during the neurofeedback training in order to update the feedback to be provided to the user in real time. In Fig. 3, the overall experimental setup is shown.

2.2 Participants

The present pilot study enrolled three healthy participants (mean age 48.5; two males and one female). All subjects were not familiar with emotion-related BCI experiments and VR systems. All participants gave written informed consent to participate. Ethical approval in accordance with the declaration of Helsinki was obtained from the Ethics Committee of Psychological Research of University of Naples Federico II.

Fig. 3: Experimental setup

2.3 Procedure

The study consisted of six neurofeedback sessions: three sessions via the 2D-neurofeedback system, and three sessions via the VR-neurofeedback system (three days of neurofeedback sessions per week, one session per day). All neurofeedback sessions were carried out at the Arhemlab laboratory of the University of Naples Federico II, in a dark and soundproofed environment to avoid distractions.

Before starting neurofeedback sessions, participants were instructed on the purpose of the experiment and they were given the necessary instructions to conduct the experiment. Subsequently, the participants were asked to sit on a comfortable chair, positioned approximately 70 cm away from a monitor (16” size), and to wear the EEG cap. The researchers filled the electrodes with conductive gel and visually checked the quality of the EEG signal. After EEG configuration, participants were asked to look at the screen and follow the instructions on it, without moving.

Following [35, 36], a specific neurofeedback experimental protocol was elaborated for this study. The task of the experimental activity was to decrease the beta power value registered along the midline sites of the scalp (compared to the baseline) during the exposure to negative stimuli in a chromatic context that informs the subject about the distance from the target.

Each neurofeedback session was divided in two phases: an initial calibration phase and a NF-training phase. The calibration phase was made of 120-s of opened-eyes resting state and of a negative baseline consisting of the projection of 21 images, each lasting 5-s and preceded by 10-s fixation cross. During the calibration phase, the subjects had to relax themselves and after, to passively watch the projected images.

The training phase was made of 22 trials, fourteen of ER in which the participants received a feedback about their performance, seven of passive vision during which the participants had only to see the projected images, and a final transfer run in which the subjects had to regulate their emotion but without the

feedback.
Regulation trials and only vision trials were randomly shown to participants. Each neurofeedback trial was made of 3-s instruction about the following task, 14-s fixation cross and 20-s image projection. In Fig. 4, the overall experimental procedure is reported.

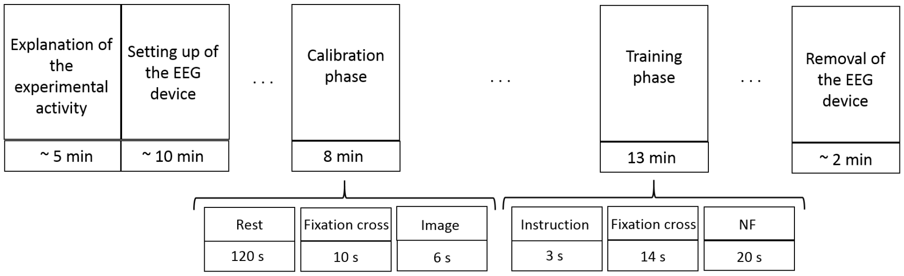


Fig. 4: Experimental protocol

During the training phase, participants had to regulate the felt emotion guided by the provided feedback. In particular, they were instructed to down regulate their target region activity by turning the colour of the frame/room and progress bar to yellow and to hold that level as long as possible. Additional information was not provided to the user. Mental strategy they had to adopt to control the felt emotion was cognitive reappraisal, namely an active cognitive process that allows to change the emotional impact of a situation [37]. Specifically, reality checking was employed. The user was asked to re-evaluate the meaning of the actual situation by thinking: ”this is not real”, ”it is only an image”, or ”it is not really happening”. The subject is required to consider the facts objectively without referring to his opinions, ideas, or beliefs.
The Hospital Anxiety and Depression (HADS) scale [38], the Rosenberg self-esteem (RSE) [39] scale, and the State-Trait Anxiety Inventory (STAI) [40] were employed to assess the levels of anxiety, depression, and self-esteem of the participants before and after the neurofeedback sessions. The Emotion Regulation Questionnaire (ERQ-10) [41, 42] were administered to participants in order to assess their tendency to regulate their emotions. In particular, ERQ-10 was administered at neurofeedback starting, at the end of the three 2D sessions and at the end of the three VR sessions. The usability of two proposed neurofeedback systems was evaluated using the System Usability Scale (SUS) [43], Italian version.

2.4 Statistical Analysis

To evaluate whether there was a change in reported levels of anxiety, depression, and self-esteem following the neurofeedback training, the Wilcoxon signed-rank test was used to analyze the pre- and post- scores of HADS-D, HADS-A, Rosenberg, STAI-S, and STAI-T. Similarly, data of SUS scores (2D versus VR) were analyzed via the Wilcoxon signed-rank test. A Friedman's ANOVA test was computed to compare ERQ-10 scores. Statistical analysis was performed using R Software (version 4.1.1) and a p-value < 0.05 indicated statistically significant differences.

3 Results

3.1 Statistical Results

For each measure, a significant difference was not found; HADS-D, $Z = -1.633$, $p = 0.102$, HADS-A, $Z = -0.365$, $p = 0.715$, Rosenberg, $Z = -1.461$, $p = 0.144$, STAI-S, $Z = -1.826$, $p = 0.068$, STAI-T, $Z = 0 - .365$, $p = 0.715$. The HADS data show that pre-neurofeedback depression scores for all participants were within the borderline range $[8, 10]$ while the anxiety scores for two were in the normal range, one participant was found to have a borderline score for a clinical diagnosis of anxiety. Following neurofeedback training, the depression score reduced for the three participants. A reduction of anxiety was not found. Pre-training scores on the Rosenberg measure of self-esteem were not found to fall below the cut-off for low self-esteem. Althoughugh a significant difference in self-esteem was not found between pre- and post- training scores, two participants had an improved score (with one participant reporting a drop of one point). The pre-training scores on trait anxiety, using the STAI measure, show that all participants had scores suggesting borderline ($n = 2$) to abnormal ($n = 2$) levels of trait anxiety. A reduced score was found for all participants post-training. Notably, the greatest improvement in post-training scores on each questionnaire was found for state anxiety, as measured by the STAI-S.

As regards the usability of the systems, SUS mean score is 56.7 (SD = 26.7) and 59.2 (SD = 29.2) for 2D-neurofeedback and for VR-neurofeedback, respectively. Since SUS scores are above 68, these results indicate a marginally acceptable level of system usability [43]. Moreover, no statistically significant differences between 2D-neurofeedback and VR-neurofeedback in SUS scores were detected by the Wilcoxon signed-rank test ($Z = 0$, p = 0.1736).

While a significant reduction in anxiety and depression was not found post-neurofeedback training according to the HADS measures, prior to training the participants' scores were in the borderline range for a diagnosis of depression, and only one was found to have a borderline score indicative of a diagnosis of anxiety. Furthermore, depression scores were lower post-training for all three. Moreover, all three participants were found to have reduced scores on the STAI measure of state anxiety following training. It is tentatively suggested that neurofeedback training to regulate emotion has the potential to reduce state anxiety, and to ameliorate symptoms for individuals who are predisposed to high levels of trait anxiety. However, to test that hypothesis, further research would be required, involving a larger sample. Concerning the ER capacity, the Friedman's ANOVA test did not detect significant differences in the ERQ-10 scale, both the Cognitive

Reappraisal subscale ($p = 0.0821$) and the Emotional Suppression subscale ($p = 1$), between the means of three evaluations (baseline, at three sessions of 2D-neurofeedback, and at three sessions of VR-Neurofeeback).

3.2 EEG data results

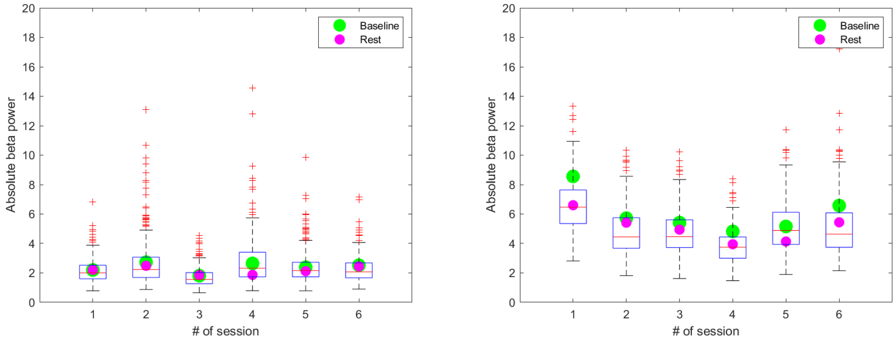
For each participant the high-beta power in midline locations (FCz-Cpz) was elaborated. In particular, the median values of the baseline and resting-state were computed for each session. These two values were adopted to evaluate the trend of high beta power during the training session. In particular, the decrement of beta power appeared linked with the increment of valence level within the subject. For the subjects, in the majority of the session, the median of the training values is below the baseline and often even below the resting-state, as shown in Fig. 5a, 5b, and 5c. However, no statistically significant differences in baseline/resting-state power-gap between traditional and VR-based neurofeedback were detected via Wilcoxon signed-rank test ($Z = 12$, $p < = 0.125$). Finally, relevant differences between traditional and VR-based neurofeedback effects were not observed.

4 Discussion

Findings from the scientific literature suggest that a decrease in the high beta power value registered along the midline sites of the scalp are related to improved ER capacity [16]. In accordance with previous studies [15], the average high beta band power value computed during the neurofeedback training remained below the task-related baseline for most of the sessions. From a qualitative analysis the immersive environment provided by the VR system increased the power gap between baseline and resting-state. Despite this difference was not confirmed by statistical analysis, this is a promising result, by considering also the small sample size.

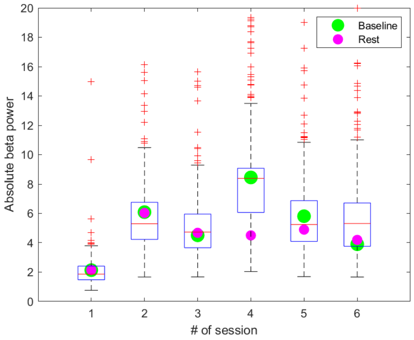
Concerning the ER capacity, significant differences in the results of the ERQ-10 scale at the three end point were not found. The reasons can be manifold: the low number of subjects involved in the experimental activities, the reduced number of sessions (both 2D and VR), and the short time interval between the neurofeedback sessions.

Overall, the participants showed interest in the experimental activity and described it as attractive and innovative. All, except one, stated the possibility to use systems frequently in the future. However, they highlighted the need for more time to use the system autonomously, understand fully neurofeedback dynamics and establish a preference for two proposed neurofeedback-systems. These considerations were supported by the results of the SUS scores. In fact, SUS detected a marginally acceptable level of system usability [43] and it did not detect statistically significant differences between the two neurofeedback systems.



(a) Subject 1

(b) Subject 2



(c) Subject 3

Fig. 5: Boxplot of high-beta power from midline locations (FCz-Cpz) computed during the neurofeedback training for the six sessions (1-3: traditional neurofeedback; 4-6: VR NF). The resting-state and the baseline values are also reported. (a) Subject 1, (b) subject 2, and (3) subject 3.

The results suggest that VR might improve emotion elicitation methods in laboratory environments in the next decade, and impact on affective computing research, transversely in many areas, opening new opportunities for the scientific community. However, more research is needed to increase the understanding of emotion dynamics in immersive VR and, in particular, its validity in performing direct comparisons between simulated and real environments.

5 Conclusions

Possible differences between a VR-based and a 2D-based neurofeedback aimed to strengthen the ER capacity were explored. The task of the neurofeedback was to down-regulate negative emotions by decreasing the midline beta power measured in FCz-Cpz. Negative emotions were induced by using IAPS images as eliciting stimuli. Three healthy subjects underwent the experimental activities completing three VR-based and three 2D-based neurofeedback sessions. Each training session started with a calibration phase for recording the rest and the baseline values of the current subject in order to adapt the neurofeedback system to the user. The average high beta band power value computed during the neurofeedback training remained below the baseline for most of the sessions, as expected. The participants showed interest in the experimental activity and described it as attractive and innovative. No statistically relevant differences were found between VR and 2D neurofeedback. Future developments include: (i) expanding the experimental sample, (ii) increasing the number of neurofeedback sessions, and (iii) increasing the interval between sessions. As stated by previous studies, future works should investigate the effectiveness of the VR-based neurofeedback in physiological responses and behavioural performance.

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