Effects of Virtual Reality and Respiratory Biofeedback on Heart Rate Variability and Skin Conductance

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***Abstract*— Virtual Reality (VR) is a versatile tool with broad healthcare applications, including diagnosis, treatment, rehabilitation, and professional training. It has demonstrated effectiveness in managing anxiety disorders, Post-Traumatic Stress Disorder, pain, and specific phobias like social anxiety and acrophobia. Physiological markers, such as Heart Rate Variability (HRV) and Electrodermal Activity (EDA), offer valuable insights into autonomic nervous system activity and stress responses, with HRV reflecting vagal activity and EDA indicating sympathetic activation.**

This study explores the effects of combining VR with respiratory biofeedback on HRV, EDA, and self-reported relaxation across three experimental sessions, with the goal of promoting psychosocial and physiological relaxation. Participants used the "Flowborne" app on the Meta Quest 2 headset, immersing themselves in natural landscapes while receiving real-time respiratory feedback. Data on HRV, EDA, and respiratory dynamics were analyzed to assess both physiological and psychological outcomes. Results revealed a significant increase in high-frequency HRV, indicating enhanced relaxation in sessions following the initial exposure, as well as a decrease in low-frequency HRV. While changes in respiratory dynamics and EDA were not statistically significant, trends suggested improved relaxation, as indicated by an increase in deep breaths. These findings underscore VR's potential to foster emotional well-being and relaxation, with promising future applications in medical and therapeutic settings.

***Keywords*—Heart Rate Variability, Electrodermal Activity, Virtual reality, Respiratory Biofeedback.**

I. INTRODUCTION

The use of Virtual Reality (VR) and biosignals for monitoring and modulating psychophysiological states has gained increasing attention in scientific research and clinical applications [1], [2]. In the clinical field, VR has proven to be a resource for the diagnosis, treatment, and rehabilitation of patients, as well as for the training of medical personnel. Numerous studies have confirmed the effectiveness of VR in the treatment of certain anxiety disorders, mental health [3], pain management [4], social anxiety, fear of flying, spiders, heights. Additionally, VR has been shown to help overcome physical limitations and enhance mindfulness and meditation[5]. A specific application of VR for mitigating anxiety disorders and stress states involves the use of relaxing video experiences , which have been shown to enhance mood and overall well-being [6]. In this context, nature plays a crucial role, as exposure to natural landscapes is widely recognized for its significant psychological benefits [7]. Two key theories, *Stress Recovery Theory* by Roger Ulrich [8] and *Attention Restoration Theory* by Kaplan [9], emphasize the positive effects of nature on mental health, which can be amplified through virtual environments. VR combines nature and mindfulness, enhancing awareness of emotional and physiological states, such as breathing. Biofeedback is a powerful tool for monitoring and regulating physiological states like heart rate (HR), breathing, and muscle tension [5]. When combined with nature-based virtual environments, biofeedback enhances mindfulness by providing real-time feedback on how the body reacts to natural surroundings. This combination not only aids in reducing stress but also fosters a stronger mind-body connection, promoting overall well-being.
Relaxation, crucial for psychological and physical health, impacts physiological parameters like Heart Rate Variability (HRV), which reflects the balance between the sympathetic and parasympathetic systems. HRV spectrum analysis shows low-frequency (LF) linked to baroreceptor-sympathetic activity and high-frequency (HF) associated with respiratory-vagal activity [10]. Watching meditation videos and natural landscapes reduced HR, increased respiratory sinus arrhythmia, and enhanced vagal tone [11], indicating relaxation. A virtual reality game [12], designed to reduce a previously induced stress state, reduced stress, shown by lower HR, decreased low-frequency power, and increased high-frequency power. Another physiological measure used to quantify emotional and stress activity is Electrodermal Activity (EDA), a measure of sympathetic activation. The results of the study [13] showed decreased in response to natural landscapes with fewer and lower-amplitude skin conductance responses (SCR) associated to tonic component of EDA signal.
The aim of this study is to analyse the effects of virtual reality and respiratory biofeedback on HRV and skin conductance during three acquisition sessions. In addition to biosignals measurements, data on the average duration of exhalations and inhalations, as well as the number of deep exhalations, are collected using the "Flowborne" app. Flowborne is a virtual reality application that combines guided meditation and natural landscapes to enhance psychological well-being by

reducing anxiety and mental fatigue [14]. Its key feature, a respiratory biofeedback mechanism, uses a VR controller on the abdomen to detect breathing movements and adapt the virtual environment in real time. This interactive feedback loop helps users practice and regulate diaphragmatic breathing, promoting relaxation and stress management. This study aims to investigate the interplay between VR, natural landscapes, respiratory biofeedback, and physiological responses such as HRV and EDA to promote physiological and psychological relaxation.

II. Methods

A. Study population

Nineteen healthy subjects took part in the acquisition at the Department of Information and Communication Technologies at the University of Naples "Federico II". The average age was 23.1 ± 3.09, including 9 females and 10 males.

B. Experimental protocol

The study was divided into three phases, as shown below:

Phase	Description	VR condition
Phase1	Acquisition of ECG and EDA Diaphragmatic breathing	NO VR (static scenario)
Phase2	Acquisition of ECG and EDA Diaphragmatic breathing	VR (Flowborne)
Phase3	Acquisition of ECG and EDA Diaphragmatic breathing	NO VR (Relaxing Nature Scenarios)

Figure 1. Experimental protocol

Participants completed a questionnaire before and after each session via Microsoft Forms. The pre-session questionnaire assessed general mood, while the post-session questionnaire gathers feedback on the experience. Throughout each phase, ECG and EDA were recorded in real time using the BITalino (r)evolution Board Kit with a sampling frequency of 1000 Hz, with the same VR scenario applied consistently. The Flowborne app on a MetaQuest 2 headset was used to guide diaphragmatic breathing. The "Endless Ocean" path was selected, and a touch controller placed on the abdomen tracks breathing. In all phases, each lasting approximately 5 minutes (depending on breathing pace), participants were seated in a distraction-free environment. After completion, the app provided three key metrics: average inhalation duration, average exhalation duration, and the number of deep breaths. The average respiratory rate (breaths per minute) was also evaluated and calculated as follows:

$$Respiratory\ Rate = \frac{60}{Inhale + Exhale} \qquad (1)$$

First phase: The participant performed the exercise without wearing the headset, but placed the controller on the abdomen, while the experimenters monitored the session remotely.
Second phase: participants wore the MetaQuest 2 headset directly, to be actively involved in the Flowborne app, giving them greater control over their breathing.
Third phase: In the final session, participants chose a 4K YouTube video, which was projected on a PC in front of them. The VR controller was placed on their abdomen. They could select from various natural landscapes accompanied by relaxing background music. In total, 7 possible options were offered:

1. Italian landscapes.
2. Major Italian lakes (Lake Garda, Lake Como, etc.).
3. Coastal/maritime landscapes.
4. The Dolomites.
5. Main volcanic landscapes.
6. The Grand Canyon in Arizona, USA.
7. Antarctica.

C. Questionnaire

The pre-session questionnaire was composed of four sections, encompassing a total of 62 questions. Each question required a response based on one of two possible scales: Likert (5-point or 7-point) or Visual Analogue Scale (VAS, 10-point) [15].
Section 1 Pre: Mood and General Well-being.
This section includes the PANAS scale, which evaluates the participant's emotional state by assigning a score to each specific mood. A total of 20 different moods are assessed, comprising 10 positive effects and 10 negative effects. Responses are measured using a 5-point Likert scale (1 = Very slightly or not at all, 5 = Extremely) [16].
Section 2 Pre: Breath Awareness.
This section contains 8 questions focused on the degree of control, perception, and awareness of one’s breathing in daily life [14]. Responses are evaluated using a 7-point Likert scale (1 = Never, 7 = Completely).
Section 3 Pre: Stress.
This section includes 24 questions divided into two subgroups. The Perceived Stress Scale (PSS-10) [17], a 10-item questionnaire assessing the ability to manage stress in daily life, and the Copenhagen Burnout Inventory (CBI) [18], a 13-item questionnaire evaluating burnout, with six questions focused on the personal/private domain and seven on the academic/work domain. In both cases, all questions are assessed using a 5-point Likert scale (1 = Never/almost never, 5 = Always) [19].
Section 4 Pre: Self-Efficacy.
This section comprises 10 questions based on the framework developed by Blum et al., aimed at assessing self-confidence and self-efficacy across personal, social, and professional contexts. Responses are recorded on a 10-point Visual Analog Scale (VAS), where 1 represents "Not at all confident" and 10 represents "Completely confident”[14].
The post-session questionnaire consists of eight questions:
Section 1 Post: General Feedback.
The first two questions solicit general feedback regarding the participant's enjoyment or discomfort during the session. Responses are measured using a 5-point Likert scale (1 = Very little, 5 = Very much).
Section 2 Post: Effectiveness of the Session.
The next three questions assess the session's effectiveness in improving breathing and enhancing relaxation. These questions are rated on a 10-point Visual Analogue Scale (VAS) (1 = Completely disagree, 10 = Completely agree).

D. HRV and EDA data analysis

The data were processed using MATLAB R2022b, and features were extracted from each phase signal. EDA signals were analyzed and decomposed into tonic (skin conductance level, SCL) and phasic (skin conductance response, SCR) components using Continuous Decomposition Analysis (CDA) through Ledalab [20]. The signals were filtered using a low-pass filter with a cutoff frequency of 5 Hz. EDA features were computed on the SCR component. HRV signals were also analyzed using MATLAB with ad hoc script. The computed features are presented in *Table 1*.

Table 1. HRV and EDA features

Signal	Domain	Feature	Description
HRV	Time	SDNN(ms)	Standard deviation of RR intervals
		nSDNN(ms/bpm)	Normalized SNDD dividing the SDNN by the mean HR of each subject.
		meanHR (bpm)	Mean heart rate
	Frequency	pLF(%)	Percentage of power in the LF band (0.04–0.15 Hz) relative to the power in LF + HF
		pHF(%)	Percentage of power in the HF band (0.15–0.4 Hz) relative to the power in LF + HF
		LF/HF	Ratio of the LF to HF
EDA	Time	nSCR	Number of Conductance Responses
		AmpSum (mµS)	Sum of Amplitudes of Significant Skin Conductance Responses
		ISCR (mµS*s)	Integrated Skin Conductance Response (*ISCR*) quantifies the total area of significant skin conductance responses within a time window

E. *Statistical analysis*

Statistical analysis was performed using SPSS v.29.0.1.0. Considering the sample size, the Shapiro-Wilk test was applied to assess data normality. After that, the non-parametric Wilcoxon signed-rank test for paired samples was employed for each of the three group pairs (1-2, 2-3, 1-3).

III. Results

A. *Pre session Questionnaire*

The statistical analysis of pre-session questionnaires showed no significant differences in mood, general well-being, or stress levels before the intervention. Similarly, no significant results were found for self-efficacy and self-control across the acquisition sessions.

B. *Post session Questionnaire*

The responses to the post-session questionnaire were divided into five key sections:

Session satisfaction: The average satisfaction score increased significantly between the first and second sessions (from 5.79 to 7.5). Statistical analysis also revealed a significant difference between the two groups *($p = 0.016$)*, highlighting a strong preference for the second session, which incorporated a *VR* headset and an immersive experience in the app.

Discomfort (e.g., nausea, irritation, etc.): No statistically significant differences were observed. Effectiveness on relaxation: A statistically significant difference was found between the first and second sessions *($p = 0.002$)*.

Effectiveness on breathing: There was an increase in the average score between the first and second sessions, although the results were not statistically significant.

C. *Results of Respiratory BioFeedback (Flowborne App)*

The results of the analysis across the different sessions (1-2, 1-3, 2-3) did not reveal any statistically significant differences *($p > 0.05$)*. However, the respiratory rate slightly decreases between the first and second sessions, while the average number of deep breaths increases significantly from the first session *($n = 10$)* to the final session *($n = 16.5$)*.

D. *EDA results*

As shown in Table 2, EDA analysis found no significant group differences. Except for ISCR, all parameters decreased from session one to two, while session three showed variable trends.

Table 2 Statistical values related to EDA parameters.

	Mean			p-value		
	1	**2**	**3**	**1-2**	**1-3**	**2-3**
nSCR	17.72	15.11	16.00	0.523	0.950	0.820
AmpSum	3.09	2.54	1.53	0.711	0.427	0.140
ISCR	7.81	9.12	13.11	0.836	0.594	0.074

E. *HRV results*

As shown in *Table 3*, the statistical analyses showed significant differences between the first and second sessions for pLF, pHF, and, as expected, LF/HF (*$p<0.001$*). This indicates a strong prevalence of high-frequency components in the HRV spectrum during the second session; this pattern remains consistent in the third session.

Table 3. Statistical values related to HRV parameters.

	Mean			p-value		
	1	**2**	**3**	**1-2**	**1-3**	**2-3**
SDNN	74.46	64.46	58.10	0.248	0.551	0.730
nSDNN	0.98	0.85	0.77	0.586	0.875	0.826
meanHR	83.04	79.70	79.94	0.528	0.064	0.221
pLF	41.77	27.96	30.25	***<0.001***	0.096	0.116
pHF	57.54	71.82	69.41	***<0.001***	0.074	0.090
LF/HF	0.94	0.44	0.51	***<0.001***	0.221	0.074

The descriptive analysis shows that the mean values of SDNN and nSDNN consistently decrease across sessions. The meanHR remains almost constant throughout the sessions. pLF decreases significantly between the first and second sessions, followed by a slight increase in the third session, as shown in *Figure 2* (with an inverse trend observed for pHF).

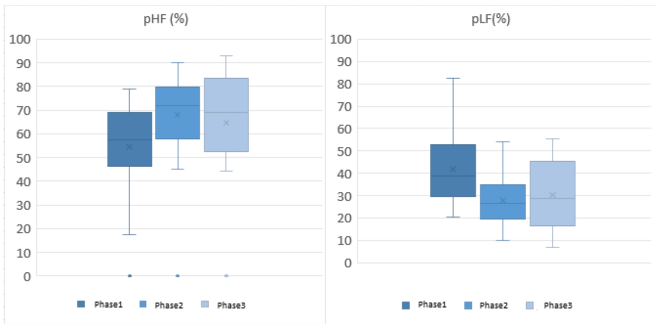

Figure 2. Boxplot for pHF and pLF across experimental phases.

IV. Discussion and Conclusion

From the questionnaire results, mood, general well-being, breathing awareness, and self-efficacy remained largely unchanged across sessions, confirming the stability of the experimental group in terms of stress levels. Significant variations in psycho-emotional parameters could have influenced physiological outcomes. Session satisfaction and relaxation effectiveness significantly increased in the second session compared to the first ($p < 0.05$), confirming the effectiveness of the VR headset in enhancing relaxation. From the physiological analysis for breathing parameters, results indicated slight increases in inhalation/exhalation duration and the number of deep breaths across sessions. These results suggest a gradual trend toward slower, deeper breathing, supported by the post-session questionnaires, which highlighted improved perceived breathing effectiveness. The pLF significantly decreased between the first and second sessions, while pHF increased to a similar extent, indicating a relaxation state compared to the first session. A study by [21] confirmed that deep breathing at approximately 5.5–6 breaths per minute can influence HRV, with extended exhalation increasing HF power and reducing the LF/HF ratio. The rise in pHF and drop in pLF in our study indicate a shift toward parasympathetic dominance, especially during the relaxing video phase, which evokes a consistent vagal response. This supports prior findings on the role of slow breathing and calming stimuli in boosting parasympathetic modulation of HRV. EDA analysis showed a general reduction in SCR responses and Ampsum across sessions. This aligns with findings by [22], which reported reduced nSCR during VR biofeedback tasks. Notably, in five participants who showed significant improvements in respiratory biofeedback parameters, especially between the first and second sessions, the effects of the VR headset were evident. They exhibited deeper breathing, with an increase in deep breaths (from 9 to 26) and a decrease in breaths per minute (from 15.08 to 11.16). Additionally, their EDA metrics significantly decreased: nSCR dropped from 21.6 to 11.8, AmpSum from 4.06 to 1.36, and ISCR from 11.7 to 2.63.

Future studies should address current limitations by increasing the sample size, conducting more controlled sessions, and refining the training protocol, considering the results from this small group. VR has significant potential to enhance mental and physical well-being, offering personalized, non-invasive therapeutic opportunities. Integrating immersive VR experiences with real-time biofeedback, such as *Flowborne*, can promote relaxation, reduce stress, and improve mindfulness. This innovative approach, combining virtual environments with physiological feedback, provides valuable insights into supporting psychological and physiological health.

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