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Raga Bhairavi in virtual reality reduces stress-related psychophysiological markers

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The effects of classical music on psychophysiological parameters are not well understood. This study aimed to investigate the impact of listening to raga Bhairavi, an Indian Classical Music for six days on anxiety, stress, depression, and heart rate variability (HRV) parameters. Forty-four individuals were randomly assigned to either the intervention group (VR-raga), where they listened to raga Bhairavi via 360° video in a virtual reality environment, or the control group, where there was no exposure to raga Bhairavi for six days. Before allocation, the HRV baselines (relax-baseline and stress-baseline) were recorded on the first day. On the first and sixth days of the intervention, HRV was monitored, and the Depression, Anxiety, and Stress Scale (DASS-21) questionnaire was administered before and after the intervention. After six days, all DASS-21 subscales were significantly reduced in the VR-raga group. A similar trend was observed in the seven HRV parameters evaluated in this study, which demonstrated reduced physiological stress and enhanced autonomic balance following the six-day intervention. The findings collectively indicated the efficacy of the VR-based raga Bhairavi intervention in reducing psychological stress markers and highlighted the potential applications of utilizing the VR-based raga intervention for improving mental well-being in the real-world context.

Keywords Indian classical music, Raga Bhairavi, DASS, Heart rate variability, Virtual reality

The current state of mental health and healthcare infrastructure in India necessitates a significant enhancement in the provision of mental healthcare facilities at the grassroots level. As per the National Mental Health Survey conducted by the Government of India in 2016, almost 150 million Indians have some form of mental health issue, such as stress, anxiety, and depression. The prevalence of mental disorders in India is 10.6%, with stress-related disorders constituting a major proportion[1]. As estimated by the World Health Organization (WHO), worldwide 121 million people are affected by depression and is a prevalent mental condition characterized by a persistently poor mood that affects eating, sleep patterns, and general functioning[2].

Considering the growing prevalence of mental illness, it is imperative to explore innovative treatment options. One promising approach is music therapy, which has shown potential benefits in managing mental conditions[3–8]. India, with its diverse array of religions, languages, musical traditions, dances, customs, and landscapes, presents a distinctive backdrop for investigating the impact of music therapy. Historical records demonstrate that Indian classical music has been utilized for therapeutic purposes across a wide span of time, encompassing the Vedic era, up to the 19th century[9]. Raga, which serves as the foundation for melodic structure, is the most fundamental component of Indian classical music. A raga is a framework for creating melodies in Indian classical music, consisting of a specific set of notes and rules on how to use them. It guides musicians to evoke certain emotions and is often associated with particular times of the day or season[10]. Each raga possesses a unique aura, emotional resonance (Rasa), and expressive quality (Bhava)[11]. The raga Bhairavi is considered a complete or “Sampoorn raga” because it includes all seven musical notes. Although traditionally associated with early morning performances, it is often preferred for presentation at the culmination or conclusion of musical events[12]. Ancient Indian music literature, including the Gandharva Veda, Sama Veda, and “Raga Chikitsa” also refer to various ragas believed to have health benefits[13–15]. Recent studies on the theory of ragas, which were also grounded in Ayurvedic (ancient Indian medical system) principles, have reportedly been beneficial for individuals grappling with depression[16].

Despite the extensive range of modes available in the Indian music tradition that can produce relaxation or health benefits, there is a scarcity of scientific literature exploring its potential as an intervention in various musical genres[17–20]. Most studies on Indian music have not incorporated physiological measurements. Although

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in the literature, a lowering of the subscales scores from subjective measures such as the Depression, Anxiety, and Stress Scale (DASS-21) has been used to demonstrate an improvement in mental well-being[21,22], objective measures such as physiological signals have not consistently concur[6,7]. For the purposes of this research, "mental well-being" is defined as a decrease in stress, anxiety, and depression symptoms that supports psychological resilience and emotional balance. To make logical inferences, it is crucial to use both subjective and objective metrics coupled with innovative approaches to prove the efficacy of interventions aimed at mental relaxation[23–25]. This study addresses this issue by employing subjective measures, such as the DASS-21, and objective measures, including HRV.

Moreover, the use of virtual reality in interventions has been shown to be beneficial for promoting overall mental well-being by managing anxiety, promoting relaxation, and reducing feelings of sadness[26]. Although the literature has explored the use of Virtual Reality (VR) to induce relaxation and mindful meditation[27–30], there is a lack of use of virtual reality in creating an immersive experience of Indian classical music. Therefore, our study sought to bridge this gap by evaluating the efficacy of presenting raga Bhairavi in an immersive virtual environment. This study investigated two hypotheses based on the available literature and empirical evidence[4,5,31–34]. The first hypothesis posits that the DASS-21 scores will exhibit a marked improvement following the raga intervention in contrast to the pre- and post-intervention outcomes. The second hypothesis suggests that immersive raga intervention effectively enhances HRV parameters, thereby facilitating physiological relaxation.

Materials and methods

Participants

A total of 44 individuals (13 women and 31 men, average age: 24.43 years, standard deviation: 4.18 years) were recruited for the study at the Indian Institute of Technology Mandi, India. To ascertain the number of participants required for the study, a priori sample size calculations were performed using G*Power ver.3.1.9.7[35] for the difference between two independent means for the t-test, which revealed a maximum and minimum sample size of 27 and 12 participants with medium ($d_z = 0.5$) and large effects ($d_z = 0.8$), respectively, when using standard d values[36, pp. 25–27]. Our earlier pilot study[3] revealed a large effect size with all three DASS subscales and medium to large effect sizes with HRV parameters. Thus, a conservative estimate of $d_z = 0.55$ was chosen which gives a sample size of $N = 42$. Therefore, 44 participants were included in this study to manage the dropout or attrition in the study.

The eligibility criteria for the study participants were as follows: they must have been between the ages of 18 and 35 years, of either sex, and met the medical and surgical health requirements (no history of heart disease or hypertension, no presence of pacemakers or other cardiac implants, no surgeries, particularly those related to the cardiovascular system), which were originally self-reported via an online form and subsequently validated during a visit to the lab. Consumption of alcohol or tobacco products was prohibited, and participants taking any medication were excluded from the study. Institutional Scientific Committee on Human Research and Ethical Review Board (REF: IITM/IEC(H)/2023/VD/P2) approved the study protocol. The standards outlined in the declaration of Helsinki were followed in this study[37] and written informed consent was taken from the participants to be a part of the study and for the publication of specific information/image(s) on an online open-access platform.

Tools, statistical instruments, and measures

A MetaQuest 2 (Meta Stages, California, US)[38] headset was used to view a 360° video of raga Bharavi, which is available online[39]. This headset is a handheld Head-Mounted Display (HMD) that is designed for engaging with immersive media and playing virtual reality games.

To real-time HR/HRV acquisition we have used emWave Pro Plus (HeartMath Institute, California, USA)[40]. It is a Photoplethysmogram (PPG) based device that records heartbeats by attaching it to the earlobe (as shown in Fig. 1). In the literature, similar HRV studies have used Photoplethysmogram (PPG) signal[41–46] and for the PPG sensor, emWave Pro has been used in the with a high degree of accuracy of acquired inter-beat interval (IBI) data when compared with Electrocardiogram (ECG) device[47]. The accompanying software, as shown in Fig. 1, can display and record real-time HR and HRV. After acquisition, the raw RR peaks were exported and post processed in Kubios[48] for the computation of the HRV parameters. The obtained values of HRV parameters were then used for statistical analysis in JASP[49], and RStudio[50].

The data recordings from emWave Pro were susceptible to noise, particularly high frequency motion artifacts. The computed HRV parameters; particularly short term time domain parameters, absolute frequency band powers and SD2/SD1 are highly sensitive to these artifacts[51,52]. Therefore, we tried to control these artifacts during data acquisition and post processing. During data acquisition, participants were asked to make minimal head movements since data was recorded from their ear lobe. During post-processing, the artifact correction available in Kubios[48] was employed before computing the HRV features. The "Automatic noise detection" setting in the Kubios was set to "low". It aimed to identify segments with several consecutive distorted beats that could affect HRV analysis accuracy, excluding these segments from the analysis. Intermittent abnormal beats, such as ectopic beats, are not marked as noise since they can be reliably corrected by the automatic beat correction algorithm[53, p. 11]. The "Beat correction" setting in the Kubios was set to "automatic". It identifies artifacts in the RR interval time series by using a time-varying threshold based on the quartile deviation of the surrounding beats. It detects ectopic, missed, and extra beats through specific patterns in the successive difference of the RR series and compares the current RR intervals to a median value. The detected artifacts were corrected by interpolating or adjusting the RR intervals to preserve HRV data accuracy[53, p. 12,54].

During analysis, the percentage values (mean ± standard deviation) of RR beat correction applied varied during different phases of data recording: Relax (0.79 ± 1.87); Stress (1.73 ± 1.65); Pre-intervention-Day 1

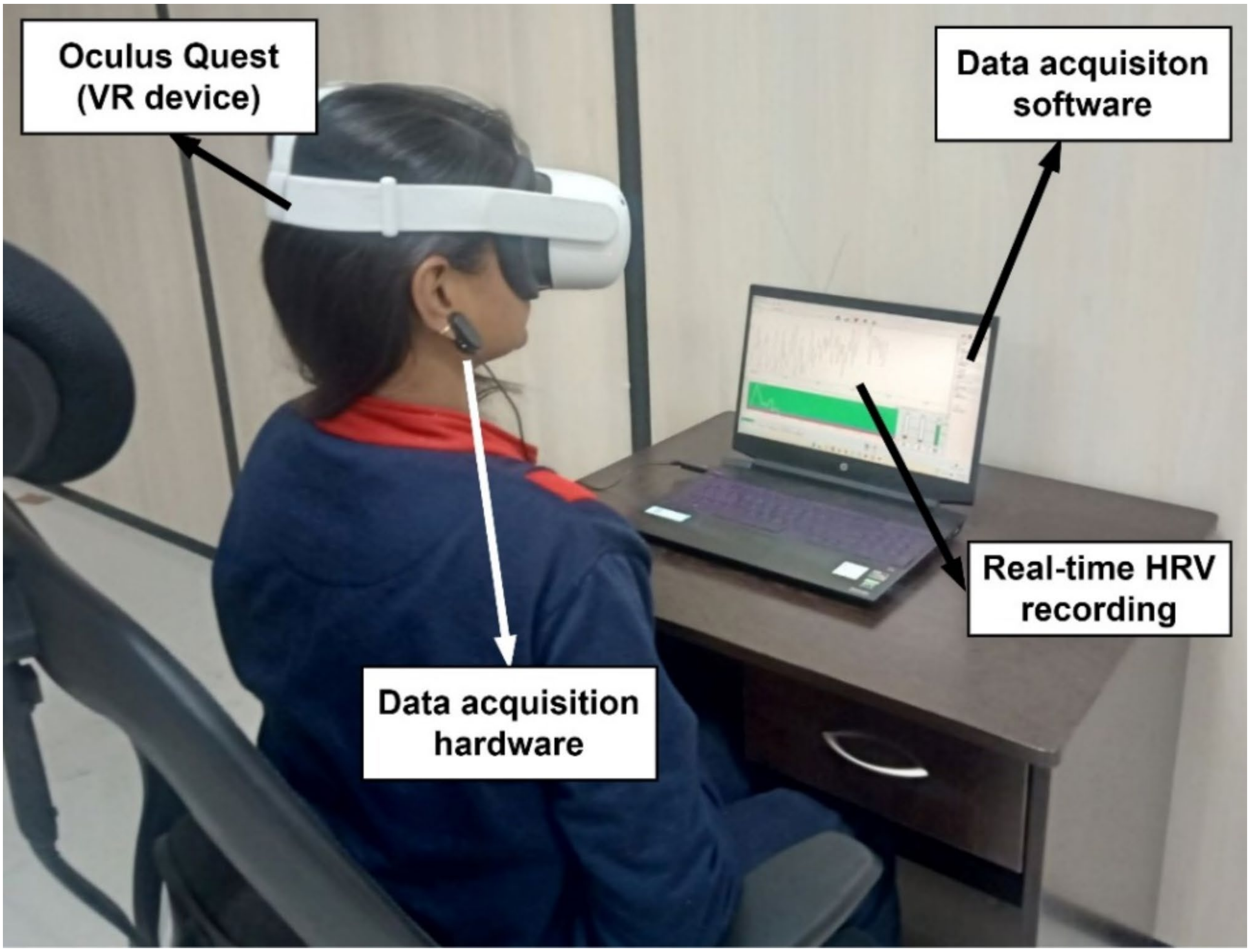

Fig. 1. Participants from the VR-raga group wearing Meta Quest2 during the intervention. The PPG data was taken from the ear lobe, where an ear clip can be seen. The hardware was connected to the left side of the computer's USB port and data acquisition software can be seen running on the computer's screen.

(1.88 ± 1.97); Post-intervention-Day 6 (1.24 ± 1.61). The mean beat correction applied during post-processing was below the tolerance limit (80%) for HRV[55,56].

For the main results and comparison of the HRV parameters, we narrowed down to seven HRV parameters, as per the literature[47,57]: Standard deviation of NN intervals (SDNN), Standard deviation of heart rate (SDHR), HRV triangular index (HTI), Ratio of relative powers in the low frequency and high frequency bands (LF/HF), Respiration rate (RESP), Ratio of Poincaré plot measures (SD2/SD1), and Sample entropy (SampEn). These parameters were chosen because they have an effective history of capturing components of heart rate variability in both the temporal and frequency domains, providing a thorough evaluation of autonomic function. When taken as a whole, these markers likely make it possible to assess vagal tone, sympathovagal balance, and the general complexity of heart rate dynamics. A decrease in parasympathetic (vagal) regulation and an increase in sympathetic activity are linked to changes in these measures, especially reductions in SDNN and SDHR or an increased LF/HF ratio. These changes are frequently indicative of physiological reactions to stress. On the other hand, changes in these markers after the intervention point to an increase in autonomic balance and relaxation, which is a sign of a decrease in physiological stress. Incorporating both linear and non-linear factors guarantees the capture of both long-term trends and short-term variability in autonomic regulation, offering a more comprehensive understanding of the psychophysiological state of the participants. However, for extended analysis (reported in Table B1, B2, and B3 in Appendix B), we analyzed all 37 HRV parameters, as listed in Table A1 in Appendix A.

Of the selected seven HRV parameters, SDNN, SDHR, HTI, LF/HF, and RESP are linear HRV parameters, whereas SD2/SD1 and SampEn are nonlinear HRV parameters. According to the literature, during mental stress there is a significant decrease in the mean values of SDNN[58,59], SDHR[57], and HTI[3,59], whereas there is a significant increase in the mean values of LF/HF[59–61], RESP[58,62–64], SD2/SD1[65,66], and SampEn[67,68]. SDNN correlates with sympathicovagal balance and vagal tone, where a low mean value indicates sympathetic dominance and reduced vagal tone[69]. SDHR represents fluctuations in HR, where the predominant source of variation arises from the parasympathetically mediated RSA[58]. Similarly, HTI is an indicator of sympathetic activation during stress[70]. The

LF/HF ratio is also primarily modulated by sympathicovagal balance[59–61]. RESP can primarily modulate the power in the LF and HF bands via Respiratory Sinus Arrhythmia (RSA) and indicate vagal cardiac outflow[58,62–64,69,71]. SD2/SD1 correlates with LF/HF and is an indicator of sympathetic stimulation[65,66,72]. SampEn relates to signal regularity and complexity and is expected to increase during sympathetic stimulation[67,68].

Depression, Anxiety, and Stress Scale – 21 Items (DASS-21)[73,74] were used as subjective measures to evaluate participant's overall stress, anxiety, and depression. There were 21 questions equally divided into three subscales. Higher scores indicated an increase in the subscale measure. The participant rated the question based on how much the statement had been applied to them over the past week. This one-week time frame coincides with the duration of six days of intervention and helps us to capture the full effects of the intervention on DASS.

Experiment design

Figure 2 depicts the fundamental phase-wise organization of the experiment. The study followed a between-group (VR-raga and control) repeated-measures (DASS-21 and HRV) randomized control design. The experimental technique was divided into three primary stages, as detailed below.

Phase I (Pre-intervention, Day 0): Upon arrival, the participants were given a brief explanation of the study's objectives before completing a short questionnaire containing background-specific questions about their age and gender as well as a consent form. Next, individual baseline HRV measurements for each participant (relax-baseline and stress-baseline) were calculated. During the relax-baseline, participants performed paced breathing for 5 min by following a visual cue set to oscillate at 0.1 Hz. breathing at 0.1 Hz is known to maximize cardiac coherence and help in relaxation[62,75,76]. The visual cue shown to the participant was a part of the emWave pro software, shown on the computer monitor, and maintained via settings in the software. Next, as a pre-intervention measure, the DASS-21 was administered online on a computer screen. The questionnaire distribution also acted as a washout time between interventions to prevent spillover effects. Then, the stress-baseline was computed, where each participant completed a math exercise on a computer screen using PEBL ver. 2.1 within 5 min[77,78]. The job was divided into three 100-second segments. When time-limited arithmetic questions were posed, the difficulty level increased for each subsequent block. Each participant's response to a question was immediately followed by the results of that question.

Phase II (intervention and control, Days 1–6): During intervention, participants were randomly and equally divided into two groups: VR-raga ($N=22$) and control ($N=22$) using an online service[79]. The groups were matched for age [females: control (25 ± 2.61) vs. VR-raga (22.71 ± 2.93), t(11) = -1.47, $p=.17$; males: control (26.00 ± 4.68) vs. VR-raga (24.00 ± 4.28), t(29) = 1.24, $p=.22$] and gender ratio (females: males) [number of females: control (6) vs. VR-raga (7), $\chi2(1, N=13)=0.08$, $p=.78$; number of males: control (16) vs. VR-raga (15), $\chi2(1, N=31)=0.03$, $p=.86$]. VR-raga intervention was given for six days in a row. In the VR-raga group, participants spent 15 min each day wearing headphones and a VR headset, listening to raga Bhairavi in an immersive environment. A 360° video[39] from Raga Bhairavi was used to demonstrate the intervention. It was played using a Meta Quest 2 headset. One participant in the VR-raga intervention group is shown in Fig. 1. In the control group, participants were allowed to sit for 15 min without VR-raga (no intervention). HRV data was recorded on the first and sixth days of the intervention in both groups.

Phase III (post-intervention and post-control, day 6): In this phase, post-intervention measures were measured from the participants. The participants completed the DASS-21 questionnaire. Then, the HRV recording for 5 min was obtained from the participant in the idle sitting position. Finally, participant's open-ended feedback was taken regarding the intervention and overall study. The total end-to-end session time for a single participant was 37 min.

Statistical analysis

The statistical comparison was conducted on subjective and objective measures as follows: (a) between the mean values of the DASS-21 subscales before and after the intervention, (b) between the baseline corrected mean values of the immediate (day 1) HRV parameters, (c) between the baseline corrected mean values of the long-term (day

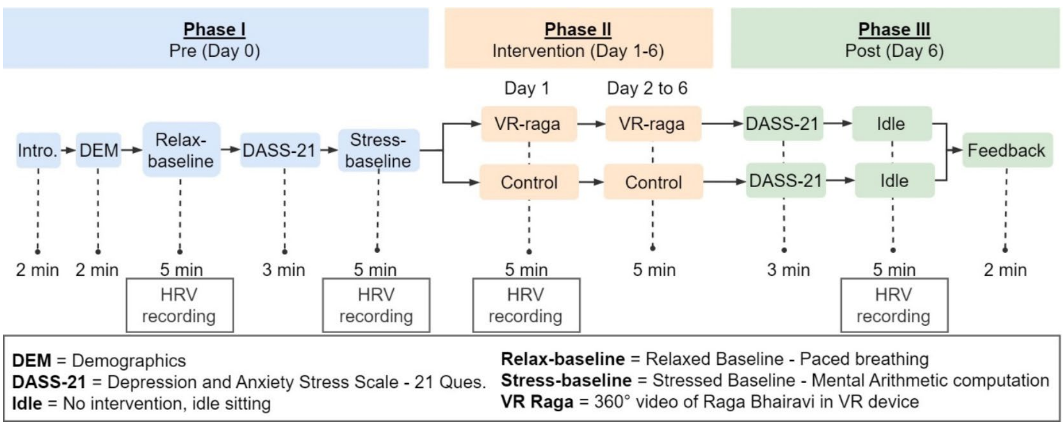

Fig. 2. Phase-wise experimental design for the between-group study.

6) HRV parameters, and (d) between the difference in the means of HRV parameters on post-intervention (day 6) and pre-intervention (day 1). The data were checked for normality using the Shapiro-Wilk test and a t-test (t) or Wilcoxon test (W) was applied for normal and non-normal data, respectively. A two-way mixed-model ANOVA was conducted on the DASS subscales to determine the interaction effects between time and group. A significance level (α) of 5% and power (1-β) of 80% were used for the analysis. The post-hoc effect size was compared according to Cohen's standard effect size values[36, pp. 25–27]. Benjamini–Hochberg (BH) method was used to control the False Discovery Rate when applying multiple statistical tests on the seven HRV parameters[80]. Furthermore, for completeness, we also retained our findings of all 37 HRV parameters and included them in Appendices A and B. JASP ver. 0.18.3.0[49], and RStudio ver. 2022.07.1[50] was used for the statistical analysis.

Results

Psychological parameters: DASS analysis

The mean values of the DASS measures among the four groups (pre- and post-DASS measures among the VR-raga and control groups) were compared for any significant differences. The Shapiro-Wilk test indicated that the assumption of normality was violated for some of the measures, as shown in Table 1.

Stress

A two-way mixed-model ANOVA revealed a significant effect of time ($F(1, 42) = 29.60$, $p < .001$, $\eta_p^2 = 0.41$), no significant effect of treatment ($F(1, 42) = 1.87$, $p = .18$, $\eta_p^2 = 0.04$), and a significant interaction between time and treatment ($F(1, 42) = 11.99$, $p = .001$, $\eta_p^2 = 0.22$). A post hoc test with Holm correction showed that the stress levels were significantly lower for individuals within the treatment group after six days of treatment ($t(21) = 6.30$, $p < .001$, $d_z = 1.11$), whereas no significant reduction in stress was achieved by individuals within the stress group ($t(21) = 1.40$, $p = .51$, $d_z = 0.25$). An independent sample t-test between the intervention and control groups on the difference (post-pre) in the mean stress score achieved after six days revealed that the VR-raga group had a significant reduction in the stress score compared to the control group ($t(42) = 3.46$, $p < .001$, $d_z = 1.04$).

Anxiety

A two-way mixed-model ANOVA revealed a significant effect of time ($F(1, 42) = 21.23$, $p < .001$, $\eta_p^2 = 0.34$), no significant effect of treatment ($F(1, 42) = 0.004$, $p = .95$, $\eta_p^2 = 0.00001$), and a significant interaction between time and treatment ($F(1, 42) = 12.63$, $p < .001$, $\eta_p^2 = 0.23$). A post hoc test with Holm correction showed that the anxiety levels were significantly lower for individuals within the treatment group after six days of treatment ($t(21) = 5.77$, $p < .001$, $d_z = 1.04$), whereas no significant reduction in anxiety was achieved by individuals within the stress group ($t(21) = 0.74$, $p = .46$, $d_z = 0.13$). An independent sample t-test between the intervention and control groups on the difference (post-pre) in the mean anxiety score achieved after six days revealed that the VR-raga group had a significant reduction in the anxiety score compared to the control group ($t(42) = 3.55$, $p < .001$, $d_z = 1.07$).

Depression

A two-way mixed-model ANOVA revealed a significant effect of time ($F(1, 42) = 17.26$, $p < .001$, $\eta_p^2 = 0.29$), no significant effect of treatment ($F(1, 42) = 0.14$, $p = .71$, $\eta_p^2 = 0.003$), and a significant interaction between time and treatment ($F(1, 42) = 9.87$, $p = .003$, $\eta_p^2 = 0.19$). Post hoc test with Holm correction showed that depression levels were significantly lower for individuals within the treatment group after six days of treatment ($t(21) = 5.16$, $p < .001$, $d_z = 1.16$), whereas no significant reduction in depression was achieved by individuals within the stress group ($t(21) = 0.72$, $p = .48$, $d_z = 0.16$). An independent sample t-test between the intervention and control groups on the difference (post-pre) in the mean depression score achieved after six days revealed that the VR-raga group had a significant reduction in the depression score compared to the control group ($t(42) = 3.14$, $p = .002$, $d_z = 0.95$).

Cardiovascular parameters: HRV analysis

Table 2 lists the linear and nonlinear HRV parameters that were found to be statistically significant between the VR-raga and control groups. The mean HRV was measured four times during the study procedure. Relax-baseline and stress-baseline measures were derived from relaxation and stress tasks, respectively. The other time periods of HRV parameters were day 1 (immediate measure) and day 6 (long-term measure). Because HRV parameters are highly dependent on individual physiology, the comparison of the measures was preferred after correcting for the baseline. Therefore, we used stress-baseline corrected measures, where the stress-baseline was

Group	DASS subscale	Pre-intervention (Mean ± SD)	Post-intervention (Mean ± SD)	Post-pre difference (Mean ± SD)
VR-raga	Stress	12.36 ± 6.61	5.00 ± 2.74	-7.36 ± 7.02
	Anxiety	9.55 ± 5.62 #	3.91 ± 3.41 #	-5.64 ± 5.88 #
	Depression	9.73 ± 6.88 #	3.18 ± 3.13 #	-6.55 ± 7.26
Control	Stress	12.00 ± 8.42 #	10.36 ± 7.45	-1.64 ± 3.30
	Anxiety	7.00 ± 6.78 #	6.27 ± 5.25 #	-0.73 ± 2.73
	Depression	7.45 ± 6.91 #	6.55 ± 4.83 #	-0.91 ± 4.26 #

Table 1. Descriptive statistics of the DASS subscales. Note: #Shapiro-Wilk test shows deviation from normality.

SN	HRV parameter	VR-raga (Mean ± SD) †	Control (Mean ± SD) †	t or W statistic	*p*-value	Effect size (d_z)
Immediate (day 1)						
1	SDNN ↓	10.83 ± 16.3	9.14 ± 7.68	-0.44 (42)	0.66	-0.13 ○○
2	SDHR ↓	0.89 ± 2.16	0.81 ± 0.96	-0.16 (42)	0.88	-0.05 ○○
3	HTI ↓	2.49 ± 4.65	2.41 ± 2.11	-0.08 (42)	0.94	-0.02 ○○
4	LF/HF ↓#	2.49 ± 5.66	0.34 ± 1.37	-1.73 (23.46)	0.1	-0.52 ●●
5	RESP ↑	-0.08 ± 0.08	-0.03 ± 0.04	2.64 (42)	0.01*	0.8 ●●
6	SD2/SD1 ↓	0.44 ± 0.72	0.25 ± 0.36	-1.1 (42)	0.28	-0.33 ●
7	SampEn ↑	-0.23 ± 0.29	-0.1 ± 0.16	1.83 (42)	0.07	0.55 ●●
Long-term (day 6)						
1	SDNN ↓	16.02 ± 20.95	0.7 ± 11.42	-3.01 (42)	0.0044*	-0.91 ●●
2	SDHR ↓	2.34 ± 3.49	0.11 ± 1.18	-2.84 (42)	0.007*	-0.86 ●●
3	HTI ↓#	3.73 ± 4.46	0.33 ± 2.82	-3.02 (35.51)	0.0047*	-0.91 ●●
4	LF/HF ↓	6 ± 6.76	0.27 ± 1.4	-3.89 (42)	< 0.001*	-1.17 ●●
5	RESP ↑	-0.07 ± 0.13	-0.0059 ± 0.09	2.08 (42)	0.04*	0.63 ●●
6	SD2/SD1 ↓	1.01 ± 0.84	0.19 ± 0.53	-3.86 (42)	< 0.001*	-1.17 ●●
7	SampEn ↑	-0.33 ± 0.35	-0.08 ± 0.16	3.03 (42)	0.0042*	0.91 ●●
Post-pre (day 6 - day 1)						
1	SDNN ↓	5.19 ± 24.09	-8.44 ± 9.86	-2.46 (42)	0.02*	-0.74 ●●
2	SDHR ↓	1.45 ± 3.35	-0.7 ± 1.28	-2.82 (42)	0.0074*	-0.85 ●●
3	HTI ↓	1.24 ± 5.86	-2.08 ± 2.62	-2.42 (42)	0.02*	-0.73 ●●
4	LF/HF ↓	3.5 ± 8.19	-0.08 ± 1.39	-2.02 (42)	0.05*	-0.61 ●●
5	RESP ↑	0.01 ± 0.09	0.03 ± 0.08	0.65 (42)	0.52	0.2 ○○
6	SD2/SD1 ↓	0.57 ± 1.01	-0.06 ± 0.46	-2.66 (42)	0.01*	-0.8 ●●
7	SampEn ↑	-0.1 ± 0.28	0.02 ± 0.14	1.72 (42)	0.09	0.52 ●●

Table 2. Baseline corrected (mean ± SD) values and test statistics of the VR-raga and control groups for HRV parameters. Note: † The values of HRV parameters are stress-baseline corrected (i.e., the stress-baseline value is subtracted from the intervention) and used for reporting and comparison. The values indicate the mean deviation from the stress-baseline. ↓ The mean value was lower in the control group. ↑ The mean value was higher in the control group. # Deviation from the normality (Shapiro-Wilk test, $p < .05$) in one or both groups. t-test (t) for normal and Wilcoxon test (W) test for non-normal data. * The p value is significant after correcting for multiple comparisons using Benjamini–Hochberg (BH) method. ●● Large effect; ● Moderate effect; ○○ Small effect; ○ Trivial effect.

subtracted from the immediate and long-term measures. This eliminates the individual's specific HRV values and normalizes them for comparison purposes. HRV values represent the amount of deviation from the stress HRV values exhibited by the participants. The reason for using the stress-baseline is the low variance found in the stress-baseline values as compared to the relax-baseline. Furthermore, similar studies in the literature have used the stress-baseline for correction[3,47,81,82].

Comparison of immediate baseline corrected measures

Immediate HRV parameters were recorded on Day1 of the intervention and subtracted from the stress-baseline for each participant. The resulting baseline corrected values were statistically compared between the two groups (VR-raga and control). The Shapiro-Wilk test showed evidence of non-normality for LF/HF. An independent sample t-test was applied to normal data and the Wilcoxon test was applied to non-normal data to determine statistical significance. After applying the Benjamini–Hochberg (BH) method to correct for multiple comparisons[80], baseline corrected mean values of only one out of seven HRV parameters deviated significantly between the groups.

Significantly higher baseline corrected mean values were obtained for RESP in the control group than in the VR-raga group, with large effect sizes. Also, the non-baseline corrected mean value of the RESP was higher in the control (0.32 ± 0.05) as compared to VR-raga (0.27 ± 0.07).

No significant differences in the baseline corrected mean values were obtained for SDNN, SDHR, HTI, LF/HF, SD2/SD1, and SampEn.

Comparison of long-term baseline corrected measures

Immediate HRV parameters were recorded on Day1 of the intervention and subtracted from the stress-baseline for each participant. The Shapiro-Wilk test showed evidence of non-normality for the HTI. An independent sample t-test was applied to normal data, and the Wilcoxon test was applied to non-normal data to determine statistical significance. After applying the Benjamini–Hochberg (BH) method to correct for multiple comparisons[80], baseline corrected mean values of all seven HRV parameters deviated significantly between the groups.

Significantly higher baseline corrected mean values were obtained for RESP and SampEN in the control group than in the VR-raga group, with large effect sizes obtained for both RESP and SampEn. Also, the control group had higher non baseline corrected mean values for both RESP (VR-raga: 0.28 ± 0.08; Control: 0.35 ± 0.08) and SampEn (VR-raga: 1.63 ± 0.28; Control: 1.94 ± 0.12).

Similarly, significantly lower baseline corrected mean values were obtained for SDNN, SDHR, HTI, LF/HF, and SD2/SD1 in the control group than in the VR-raga group, with large effect sizes obtained for all these parameters. Also, the control group had lower non baseline corrected mean values for all these parameters namely, SDNN (VR-raga: 55.01 ± 18.42; Control: 35.76 ± 7.44), SDHR (VR-raga: 8.17 ± 3.30; Control: 4.93 ± 1.13), HTI (VR-raga: 14.02 ± 3.92; Control: 9.40 ± 1.26), LF/HF (VR-raga: 8.18 ± 6.19; Control: 1.74 ± 0.79), and SD2/SD1 (VR-raga: 2.65 ± 0.73; Control: 1.67 ± 0.36).

Comparison of post-pre difference of the measures among the groups

Differences in the non-baseline corrected values obtained before and after treatment were statistically compared between the groups. The Shapiro-Wilk test did not show evidence of non-normality in the difference of means for any of the parameters. An independent sample t-test was applied to determine the statistical significance. After applying the Benjamini–Hochberg (BH) method to correct for multiple comparisons[80], the difference in the non-baseline corrected mean values of five out of seven HRV parameters deviated significantly between the groups.

A significantly lower difference in the non-baseline corrected mean values were obtained for SDNN (VR-raga: 5.19 ± 24.09; Control: -8.44 ± 9.86), SDHR (VR-raga: 1.45 ± 3.35; Control: -0.7 ± 1.28), HTI (VR-raga: 1.24 ± 5.86; Control: -2.08 ± 2.62), LF/HF (VR-raga: 3.5 ± 8.19; Control: -0.08 ± 1.39), and SD2/SD1 (VR-raga: 0.57 ± 1.01; Control: -0.06 ± 0.46) in the control group than in the VR-raga group with large effect sizes obtained for all these parameters. In addition, the non-baseline corrected mean values for all these parameters decreased in the control group on day 6 compared to day 1, while for the VR-raga group, the opposite trend was observed.

No significant difference in the non-baseline corrected mean values was obtained for RESP and SampEN in the control group compared to the VR-raga group before and after treatment.

Discussion

This study aimed to evaluate the hypothesis that raga intervention can significantly improve psychological parameters (depression, anxiety, and stress) as well as physiological parameters (HRV) to promote mental well-being. The literature supports a multimodal approach to combining subjective psychological measures with objective physiological measures to draw robust logical inferences regarding the efficacy of raga interventions (listening to raga Bhairavi from Indian classical music) for overall mental well-being. Consequently, in this randomized controlled group study, psychological DASS measures were collectively analyzed in conjunction with physiological HRV parameters.

All DASS subscales were significantly improved after the raga intervention compared to the control group. This validates our first hypothesis that the subscales of the DASS-21 scores would be significantly improved by the raga intervention. Our findings corroborate with the literature in which music therapy has been shown to reduce the self-reported measures of the DASS-21 subscales[31,33,34,83,84]. Furthermore, the DASS-21 subscales achieved large effect sizes, which strongly validates the application of Indian classical music as a viable therapy for stress, anxiety, and depression management.

Similarly, during the assessment of the second hypothesis, it was found that the raga intervention had a significant improvement in the HRV parameters. This was determined by comparing the HRV parameters among the different groups. Heart rate variability (HRV) is a measure of cardiac autonomic functioning that has been researched in studies that include the use of music[85,86]. Several studies have reported a reduction in HRV, indicative of physiological relaxation, whereas other researchers have observed either no change or an increase in HRV in response to listening to music, the latter possibly reflecting an arousal effect[3,8,87–91]. In our results, after six days of raga intervention, the various linear and nonlinear HRV parameters were found to significantly deviate from the stress-baseline values.

On day 1 of the intervention, RESP deviated significantly from the stress baseline. The RESP showed higher mean values in the control group than in the VR-raga group, indicating higher parasympathetic activation in the VR-raga group[3,58,62–64]. Although there were no explicit instructions in the VR-raga intervention to breathe slowly, participants still exhibited lower breathing rates. This shows that VR-raga can introduce calming effects on the first day of the intervention.

On the sixth day (day 6) of the intervention, all seven HRV parameters deviated significantly from the stress-baseline. The control group exhibited increased sympathetic activation as indicated by the lower mean values of SDNN[58,59], SDHR[57], HTI[3,59], LF/HF, and SD2/SD1. LF/HF and SD2/SD1 showed contrasting results, primarily because of their dependence on the respiration frequency. The extended discussion in Appendix B highlights the possible cause for the deviation, in which respiratory rates have a strong influence on the frequency-domain HRV parameters[58,62–64]. In contrast, the HRV parameters that showed higher mean values in the control group indicating increased sympathetic activation compared with the VR-raga group were RESP[58,62–64], and SampEn[67,68].

The effects of the intervention on HRV parameters were also analyzed between the groups, where the comparison of the non-baseline corrected values between day 6 and day 1 of the treatment provided insights into the direction of the change in HRV parameters due to the intervention. The results follow the same trend as exhibited by the long-term effects. The RESP and SampEn became non-significant during the post vs. pre comparison possibly due to the lack of baseline correction. Both parameters showed comparatively lower effect sizes when compared to the baseline corrected values on day 6. The effect sizes obtained during non-baseline corrected post vs. pre comparison were slightly lower than those obtained with baseline corrected values, which is due to the difference between the baseline and pre (day 1) HRV parameters values.

One of the limitations of this study is that the effects of virtual reality (VR) were not isolated, which may have contributed to the observed sympathetic arousal[92]. However, literature also shows the beneficial effects of VR in relaxation and meditation studies[27–30], which may have contributed positively to the intervention. Additionally, even if VR had arousal effects, the significant effect size in the HRV parameters indicated that listening to raga music had a relaxation effect, even with the inclusion of an immersive VR component. Future studies with additional control groups are needed to reveal the effects of VR. Another limitation is the putative placebo effect[93], where participants may experience reduced stress because of their belief that the intervention (such as virtual reality) is helping them. Future studies may include a placebo or sham group that receives a non-therapeutic intervention or assess participants' expectations to control for this effect. Future studies may also focus on the long-term use of music therapy over several weeks to regulate the psychophysiological aspects of the human body and to determine the effects of immersive environments versus traditional music therapy. Although the DASS was administered correctly in this research, one aspect is that it covers the entire duration of the intervention (i.e., six days). Future research studies may adapt the DASS questionnaire to focus on specific days or administer DASS daily. Additionally, future studies may investigate the health benefits of other acoustic stimuli, including different musical styles and subgenres, and provide strong support for their use in treating a variety of medical conditions.

Particularly in the realm of mental health, the findings of this study have great potential for the wider use of VR-based music therapy. An efficient, non-invasive way to treat stress, anxiety, and depression may be found with VR-based therapy, as evidenced by the notable improvements seen in both psychological (DASS-21) and physiological (HRV) characteristics. Making immersive, captivating surroundings that can improve the effectiveness of the therapy is one of the main benefits of fusing VR with therapeutic music. Potential uses for this may be found in non-clinical contexts like offices, schools, and even homes, as well as clinical ones like hospitals and mental health facilities. For those living in isolated or underprivileged locations who might not have access to conventional in-person treatments, VR-based music therapy may be quite helpful. Furthermore, telemedicine services, smartphone applications, and virtual consultations may all access this intervention because it is readily linked into digital health systems. Adaptive and customized therapy experiences based on individual reactions might be made possible by the possibility of real-time biofeedback, such as measuring HRV throughout a session, which could further improve the intervention's customization. Subsequent investigations may concentrate on prolonging the length of these treatments, evaluating their effectiveness across other demographics, and investigating the remedial possibilities of alternative musical genres inside virtual settings.

Data availability

The raw data supporting the conclusions of this article will be made available upon request by the corresponding author, K.C., without any undue reservation.

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Declarations

Competing interests
The authors declare no competing interests.

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