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The Effect of a Single-Session Biofeedback Intervention on the Regulation of Induced Stress and Working Memory Performance

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Abstract

Background: Acute stress can impair cognitive functioning, particularly working memory. Various methods including biofeedback has received attention for stress management purpose; however, the effectiveness of single-session biofeedback interventions on cognitive performance has been less studied. This study examined whether heart rate variability (HRV) biofeedback can moderate stress levels and improve working memory following stress induction.

Objective: The aim of the present study was to investigate the management of working memory performance after stress induction using a single-session HRV biofeedback intervention in healthy individuals.

Method: This quantitative, quasi experimental study employed a pre-test – post-test design. 29 healthy participants aged 18-40 years from Tehran were recruited after initial screening. In the in-person session, the N-back task was administered twice to obtain baseline measurements. Stress was then induced, and its effect was measured afterward. The N-back task was subsequently performed for the third time, followed by the HRV biofeedback intervention. Immediately after the intervention, participants completed the N-back task again. Data were analysed through within-subject comparisons across different phases and overall group level analyses.

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Findings: The results indicated that the level of stress could influence working memory performance, while the response to a single session of biofeedback may vary depending on the initial stress level.

Conclusion: The effectiveness of biofeedback for stress management and working memory performance may be influenced by the degree of stress induced before the intervention session. Therefore, future studies should examine higher levels of stress induction and different HRV biofeedback intervention protocols.

Keywords*:* Working Memory, Acute Stress, Heart Rate Variability Biofeedback (HRV Biofeedback)

1. Introduction

In the contemporary era that we live in, the management of psychological pressures, including stress, has become one of the essential skills that plays a significant role in individuals' lives. Stress is among the factors that can affect physical health, psychological well-being, and cognitive functioning (Montgomery & Gouveia, 2024). Stress is a complex response that influences various brain regions responsible for cognitive functioning. This condition emerges when an individual's ability to adapt to the surrounding environment exceeds an optimal threshold (Koolhaas et al., 2011; Picciotto & Fabio, 2024). Numerous studies have demonstrated that acute stress affects cognitive abilities such as learning, memory, and decision making (Porcelli & Delgado, 2017; Nietsche et al., 2020; Picciotto & Fabio, 2024). According to previous research, stress is among the factors that may influence executive functions, including working memory performance. However, the role of working memory in response to acute stress has not yet been sufficiently clarified, and inconsistencies in findings still remain. Such inconsistencies concern whether acute stress facilitates working memory performance or interferes with it. It appears that working memory performance possesses its own complexities; consequently, in response to stress, varying levels of stress and individual differences have yielded inconsistent patterns of working memory performance.

Working memory is one of the fundamental cognitive functions involving the ability to mentally store and actively manipulate information over short periods of time. This type of memory plays an important role in regulating and coordinating the functions necessary for decision-making (Baddeley, 2010; Al Marzouqi, 2024). Based on this definition, working memory is an active process that requires retaining and utilizing acquired information in order to achieve a desired outcome. The efficiency of processing in working memory is influenced by factors such as emotional state, environmental conditions, and the individual's specific goals (Al Marzouqi, 2024). Although it is commonly assumed that stress impairs working memory performance, some evidence suggests that stress may not only fail to exert negative effects, but may occasionally lead to relative improvements in working memory. One important moderating factor in the effect of stress on working memory is the temporal interval between stress onset and working memory assessment. A recent meta-analysis examining the effects of cortisol administration on executive functions indicated that cortisol impairs working memory performance when assessed within a short interval (less than one hour) following administration. However, when assessment occurs after a delay of more than one hour, cortisol administration may lead to improvements in working memory performance (Shields et al., 2015, 2016).

Acute stress is short-term and typically occurs in response to a specific event, whereas chronic stress is long-term and persists over an extended period. Both types of stress may negatively affect working memory performance and academic achievement (Al Marzouqi, 2024). One of the cognitive functions believed to be affected by acute stress is working memory (Shields et al., 2016; Gieblar et al., 2023). Based on previous studies, stress may impair working memory, verbal fluency, and cognitive flexibility, with effects being more pronounced under psychologically induced stress, such as the Trier Social Stress Test, than under cognitive stress (Picciotto & Fabio, 2024). Working memory, as one of the primary components of executive functioning, demonstrates high sensitivity to stress, and research has shown that acute stress may reduce the capacity for simultaneous maintenance and processing of information, thereby disrupting cognitive performance (Arnsten, 2009; Schoofs et al., 2009). Given the important role of working memory in attention, decision-making, and goal directed behavior, its impairment under stressful conditions may have significant consequences for individuals daily, academic, and occupational functioning. Considering the importance of stress and its effects on everyday life and its various dimensions, different approaches have been developed for more effective stress management. One of the most well-known approaches is mindfulness-based interventions. These approaches help individuals regulate their responses to stressors by cultivating nonjudgmental awareness of present-moment experiences. Programs such as Mindfulness-Based Stress Reduction (MBSR) have been shown to significantly reduce perceived stress, anxiety, and depressive symptoms (Grossman et al., 2004; Kabat-Zinn, 2003).

Another major approach is Cognitive Behavioral Therapy (CBT), which is considered one of the most widely used psychological interventions for reducing stress and anxiety. This approach seeks to identify and modify dysfunctional patterns of thinking that contribute to stress experiences. Research has demonstrated that CBT-based interventions can effectively reduce perceived stress and strengthen individuals coping skills (Hofmann et al., 2012). Other common stress management methods include relaxation techniques such as deep breathing, progressive muscle relaxation, and guided imagery. These techniques help reduce tension and anxiety by activating the parasympathetic nervous system and decreasing physiological arousal. Research reviews have shown that relaxation exercises can reduce stress hormone levels and physiological indicators of arousal (Manzoni et al., 2008). Physical activity and exercise are also considered effective strategies for stress management. Regular aerobic exercise, through increasing endorphin release and improving autonomic nervous system regulation, can reduce stress and anxiety and improve mood (Salmon, 2001). Additionally, some studies have shown that exercise may also enhance cognitive functioning, particularly attention and working memory.

In recent years, biofeedback-based interventions have also attracted attention as innovative approaches to stress management. In biofeedback, information regarding physiological processes such as heart rate or muscular activity is provided to individuals as feedback, enabling them to consciously regulate these processes (Schwartz & Andrasik, 2016). One of the most important branches of this field is Heart Rate Variability Biofeedback (HRV-BF), which aims to improve autonomic nervous system regulation and increase physiological flexibility. Research has shown that HRV biofeedback training can improve emotional regulation, reduce stress, and enhance cognitive efficiency (P. M. Lehrer & Gevirtz, 2014).

Despite the growing body of research on heart rate variability biofeedback interventions, evidence suggests that even a single session of this intervention may affect certain components of cognitive functioning. Studies have demonstrated that HRV-BF, through improving autonomic nervous system regulation and increasing physiological flexibility, may enhance response accuracy and attentional control in cognitive tasks, particularly under conditions involving psychological pressure or high cognitive load (P. M. Lehrer & Gevirtz, 2014; Prinsloo et al., 2013). However, research findings have not been entirely consistent across all dimensions of cognitive performance; while some studies have reported significant improvements in response accuracy, no substantial changes in reaction time have been observed. Such inconsistencies may indicate that the effects of HRV-BF are more strongly associated with regulatory processes and cognitive control than with information processing speed. Nevertheless, the moderating role of heart rate variability biofeedback in reducing the cognitive consequences of acute stress has not yet been sufficiently investigated. Although some studies have confirmed the effectiveness of HRV-BF in improving emotional regulation, reducing perceived stress, and enhancing certain aspects of cognitive functioning (P. Lehrer et al., 2020), limited research has examined the effectiveness of single-session HRV-BF interventions in counteracting stress induced declines in working memory. Accordingly, the present study was designed to address this research gap by examining the effects of induced stress on working memory performance, while also evaluating the role of heart rate variability biofeedback intervention in moderating these cognitive effects.

2. Method

This is a sample text for the Methodology section. If your article is an original research paper, this section is essential and typically includes several key components. Begin by describing the study design, specifying whether it is experimental, observational, or another type, and provide a rationale for your choice. Next, outline the participants involved, detailing the population, inclusion and exclusion criteria, sampling methods, and demographic characteristics. Clearly describe the materials and instruments used in data collection, highlighting their reliability and validity. Provide a step-by-step explanation of the procedure to ensure the study is reproducible. Ethical considerations should also be addressed, including any approvals obtained and measures taken to protect participant confidentiality and secure informed consent. Finally, explain the data analysis methods employed, specifying any software or tools used for statistical or qualitative analysis. This section should be thorough enough to enable replication by other researchers.

Participants

The statistical population consisted of healthy female individuals aged between 18 - 40 years residing in Tehran. The sample size was determined using G*Power software, considering a repeated measures analysis of variance, with a minimum required sample of 25 participants. A total of 34 participants were initially recruited. Five were excluded due to invalid N-back task performance, including failure to follow task instructions or unusually high error rates. The final sample consisted of 29 participants. The sampling method was non-random. In this study, stress induction was carried out using the Trier Social Stress Test (TSST). After the intervention, participants who did not obtain the minimum score on the six-item State Anxiety subscale of the Spielberger State Trait Anxiety Inventory (STAI-6) were excluded from the continuation of the research process. The minimum possible score on this questionnaire is 6 following stress induction were considered for exclusion. No participant met this criterion.

This study was approved by the Research Ethics Committee of Shahid Beheshti University in accordance with ethical code IR.SBU.REC.1404.024 which addresses both research ethics and the rights of participants.

Procedure

To conduct this study within the normal range and among healthy individuals, an online questionnaire was first designed and distributed through various communication networks so that eligible individuals could complete it. After reviewing the responses and conducting the initial screening which included completion of the Depression, Anxiety, and Stress Scale (DASS-21) participants were invited to attend an in-person session at the Brain and Cognitive Sciences Research Laboratory at Shahid Beheshti University.

Upon arrival, in the first stage, participants completed the N-back task after receiving instructions, in order to obtain the initial baseline measurement. Following this, a short interval without intervention was allowed. Participants then completed the N-back task again to obtain the second baseline measurement. After this stage, the stress induction procedure was conducted for 15 minutes. Immediately after the stress induction, participants were asked to complete the six-item Spielberger State Anxiety Inventory (STAI-6) to record their reported levels of anxiety and distress. Subsequently, participants performed the N-back task for the third time. After completing this task, the heart rate variability biofeedback intervention began. The blood volume pulse (BVP) sensor was attached to the index finger of the participants' left hand, and the respiratory sensor was placed around the abdomen, approximately four fingers above the navel. Before the main intervention began, an initial baseline of the participants' breathing rate and speed was recorded. Based on each participant's baseline breathing rate, an appropriate starting point for the intervention was determined. After providing instructions on how the biofeedback system works and training participants in diaphragmatic breathing, the biofeedback intervention was conducted while participants sat comfortably. Immediately after the intervention, participants completed the N-back task once again. In this design, individual differences across the stages were compared within participants (within-subject comparison), and overall comparisons were also conducted across the entire group. This study employed a single-arm, within-subject repeated measures design, in which participants were compared with their own performance across experimental stages to examine intra-individual changes.

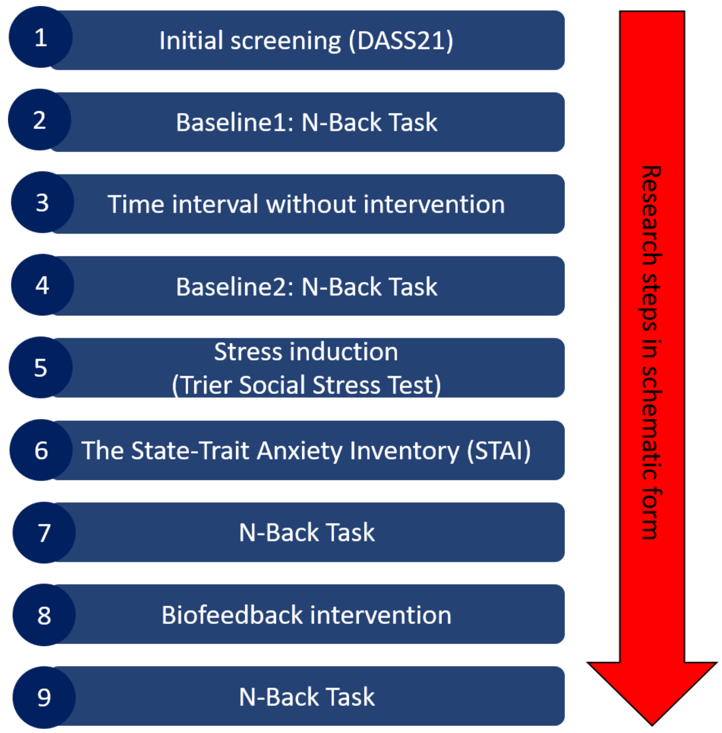

Fig1: Schematic stages of research

Measures

Depression, Anxiety, and Stress Scale (DASS-21): This instrument is the shortened version of the 42 item DASS scale developed by Lovibond and Lovibond (1995) and is used to assess the three components of depression, anxiety, and stress. The questionnaire consists of 21 items divided into three 7 item subscales, which are scored on a four-point Likert scale ranging from 0 (“Did not apply to me at all”) to 3 (“Applied to me very much”), based on the individual’s experiences during the past week. To calculate the score of each subscale, the sum of the item scores is multiplied by 2 in order to make the results comparable with those of the full DASS-42 version. Psychometric studies have also confirmed the satisfactory internal consistency and three-factor structure of this instrument (Antony et al., 1998; Henry & Crawford, 2005).

Trier Social Stress Test (TSST): The Trier Social Stress Test, first introduced by Kirschbaum et al. (1993) and later extended by Kudielka et al. (2007), is one of the standard paradigms for inducing psychosocial stress in laboratory settings. This test is typically conducted in the form of a mock job interview, in which participants are asked to imagine that they have applied for their “dream job” and have been invited to an interview. The protocol used in the present study consisted of three consecutive stages: (1) a preparation phase (3 minutes), during which the participant had time to prepare for the hypothetical interview; (2) a free speech phase (5 minutes), in which the participant was required to explain why they were the best candidate for the position; and (3) a mental arithmetic phase (5 minutes), which involved serial subtraction of the number 13 from 1021. In the event of an error, the participant was required to restart the calculation from the initial number. The test is administered in front of a “selection committee” consisting of two or three evaluators dressed in formal attire (white laboratory coats) who maintain a neutral demeanor and provide no verbal or nonverbal feedback. In the present study, the evaluation was conducted by a single judge. In addition, participants were informed that their performance would be videotaped and evaluated, including audio analysis, a factor that increases the social-evaluative component and the intensity of the stress response (Frisch et al., 2015).

Six-Item State–Trait Anxiety Inventory (STAI-6): To assess situational anxiety levels, the shortened version of the Spielberger State Anxiety Inventory was used. This 6-item version is an abbreviated form of the original State–Trait Anxiety Inventory and was designed for situations in which response time is limited or rapid assessment of momentary anxiety is required. The questionnaire primarily focuses on immediate feelings of anxiety and is recognized as an efficient instrument for evaluating anxiety in laboratory settings. In this study, this questionnaire was used to assess participants levels of arousal and anxiety following the Trier Social Stress Test. In the present study, raw scores ranged from 6 to 24, with higher scores indicating greater state anxiety.

Heart Rate Variability Biofeedback (HRV-BF): Biofeedback is a method that helps individuals increase their awareness and regulate their biological functioning by receiving signals from their bodies, thereby improving their health and performance. The objectives of biofeedback can be categorized into three domains. The first objective is awareness, which involves increasing awareness of physiological, cognitive, and emotional processes involved in producing change. The second objective is change, which refers to self-regulation and depends on the individual’s ability to create adaptive and beneficial changes. Finally, the third objective of biofeedback is generalization, which refers to long-term improvement and is only possible when the skills learned in the therapist’s office are transferred to everyday life settings (Rahmanian & Asbaghi, 2021, p. 47). The biofeedback intervention was conducted using the ProComp Infinity biofeedback device and Biograph Infinity software. The device was connected to a computer via a USB cable, and the required sensors were attached both to the participant’s body and to the device. In the present study, blood volume pulse (BVP) sensors, respiratory sensors, and Biograph software were utilized. The HRV biofeedback session lasted approximately 15-30 minutes, depending on each participant’s progress. A respiration sensor was placed around the abdomen and a BVP sensor on the index finger to monitor breathing rate and heart rate, respectively. Participants first breathed normally for three minutes to determine their resting breathing rate and then began training from this individual baseline. The researcher instructed participants in diaphragmatic breathing, while a visual display guided inhalation, pause, and exhalation (approximately 4, 1, and 6 seconds, respectively). The breathing rate was gradually reduced toward approximately 6 breaths per minute.

N-back Task: The N-back task, first introduced by Kirchner (1958), is one of the most widely used measures of working memory in cognitive neuroscience. This task is employed to assess working memory capacity and response control, in which participants are required to determine whether the current stimulus matches the stimulus presented n trials earlier (Jaeggi et al., 2010). In the present study, the computerized 2-back version of the task was administered for 5 minutes using Sina Company software, in accordance with the original version of the test.

To evaluate participants performance on the N-back task, two components were examined: response accuracy and response speed. Data related to participants response accuracy and mean response time were categorized separately in Excel. The response accuracy table was calculated based on the proportion of correct and incorrect responses relative to the total number of trials, and the resulting percentages were used for subsequent statistical analyses.

Table1: Measurements and conditions

	Baseline1	Baseline2	After stress induction	After intervention
N-Back RT	678ms (SD: 160.3)	656 ms (SD:148.6)	569 ms (SD:149.8)	606 ms (SD:127.9)
N-Back AC	%78.6 (SD:8.5)	%86.2 (SD:6.3)	%85.9 (SD:7.2)	%87.8 (SD:4.8)

Statistical Analysis

Data analysis was conducted using R software. In the initial stage, Microsoft Excel was used for data organization and preparation. To assess the normality of the distribution for response accuracy data, the Shapiro-Wilk test was employed. Since the data were found to be non-normally distributed, the Friedman test was used for further analysis. In addition, pairwise comparisons between stages were conducted using the Wilcoxon signed-rank test with Bonferroni correction. For response time data, the Shapiro-Wilk test was also used to examine the normality of the distribution. After confirming the normal distribution of the samples, a one-way repeated measure analysis of variance (ANOVA) was conducted. Finally, pairwise comparisons between stages were performed using the paired-samples t-test.

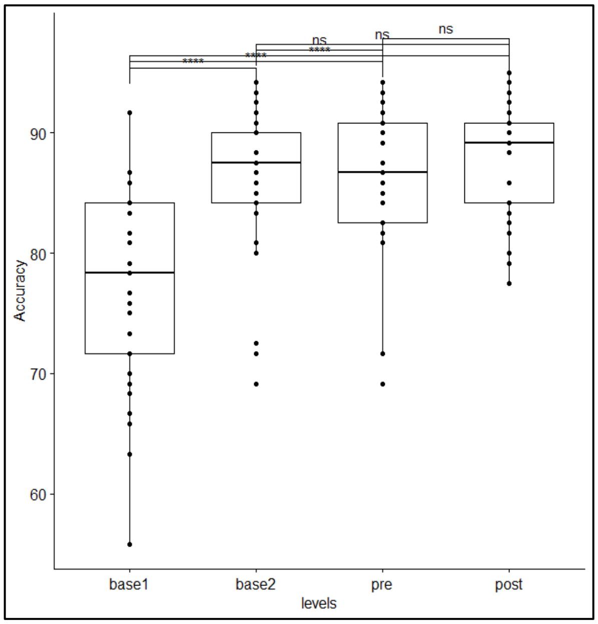

Fig2. Response accuracy levels in boxplot

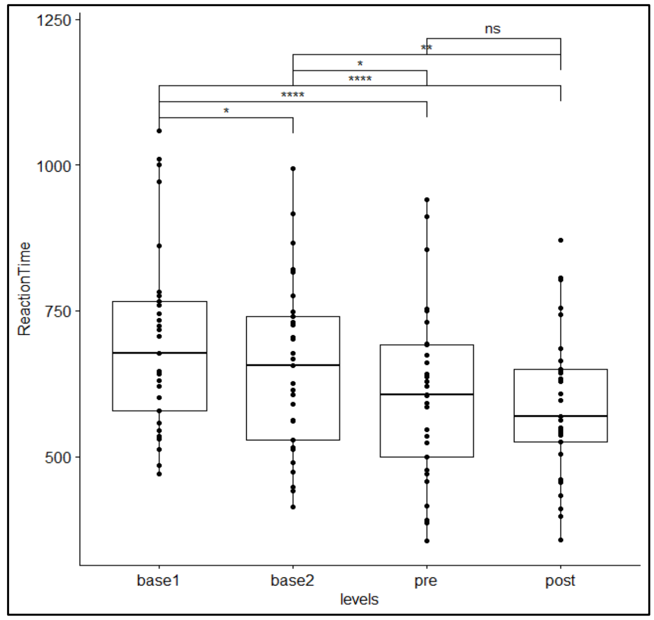

Fig3: Response speed reduction in boxplot

3. Results

STAI-6 Following Stress Induction: Following the TSST, the mean raw STAI-6 score was 14.24 (SD = 3.64), with scores ranging from 8 to 23. No participant obtained the minimum possible score of 6.

Physiological Changes During Biofeedback: Physiological data were available for 28 participants. Mean respiration rate decreased from 13.97 (SD = 2.06) breaths/min at baseline to 10.62 (SD = 1.51) breaths/min during biofeedback ($p < .001$). The latter value represents the average respiration rate across the entire training session; most participants reached or approached the target rate of approximately 6 breaths/min by the end of training. The mean HRV peak frequency during biofeedback was 0.138 Hz (SD = 0.019).

The figures below present recordings from the early and later phases of a single-session biofeedback intervention. The changes in respiratory and heart rate patterns can be observed across the session, with a clearer synchronization between respiration and heart rate oscillations emerging toward the later phase of the intervention.

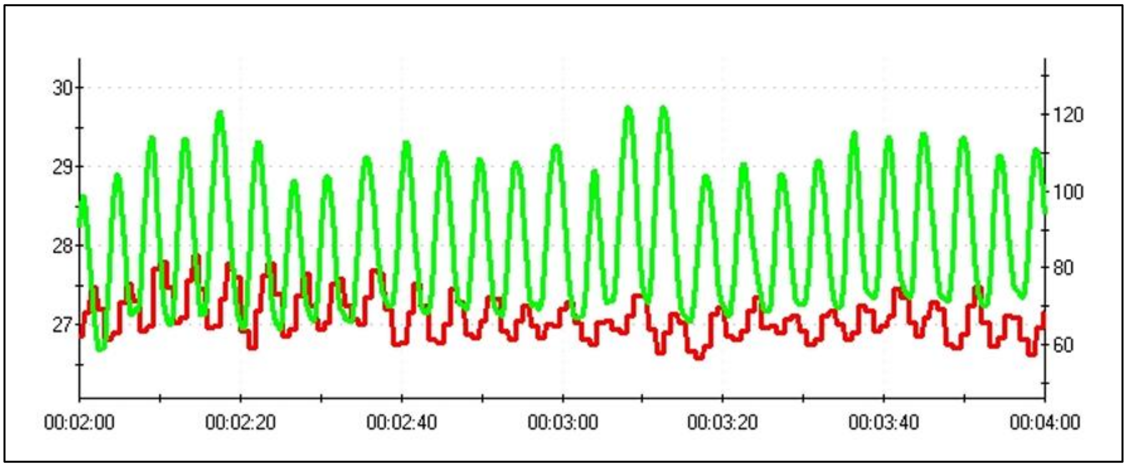

Figure 4. *Representative physiological recordings during HRV biofeedback. The green signal represents respiration and the red signal represents heart rate. A) Early phase of the training session, showing relatively faster and less synchronized respiration and heart-rate oscillations.*

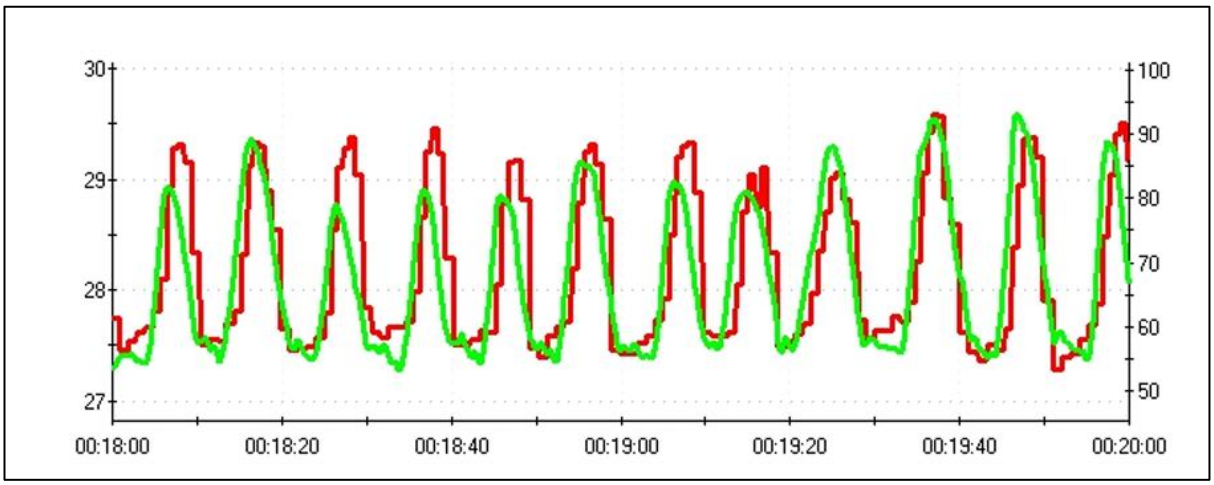

Figure 5. *B) Later phase of the session, showing increased synchronization between respiration and heart rate oscillations as breathing slowed toward approximately 6 breaths/min, reflecting the development of respiratory sinus arrhythmia (RSA).*

Response Accuracy in the N-back Task

To dermine the appropriate statistical test for response accuracy, the normality of the data at each assessment stage was examined using the Shapiro-Wilk test. The results supported the use of nonparametric analyses, as p-values were below .05 at two of the four stages (Base2: $p = .005$; Pre: $p = .002$). Therefore, the Friedman test, as the nonparametric equivalent of a one-way repeated-measures analysis, was used to compare N-back accuracy across the four stages. The results showed a significant overall difference between the stages, $\chi^2(3) = 48.70$, $p = 1.55 \times 10^{-10}$, Kendall's $W = 0.56$. Post hoc pairwise comparisons were then performed using Wilcoxon signed rank tests with Bonferroni correction. Significant differences were found between Base1 and the subsequent assessment stages, as shown in Table 2. However, no significant differences were observed between Base2 and Pre (adjusted p = 1.000), Base2 and Post (adjusted p = .936), or Pre and Post (adjusted p = .427). The corresponding effect sizes and 95% confidence intervals are also reported in Table 2.

Table2. *Pairwise Wilcoxon signed rank test results with Bonferroni correction for N-back accuracy*

	Group 1	Group2	CI 95%	Effect size (r)	Wilcoxon statistic	p	p.adj
Accuracy	Base1	Base2	[0.870, 0.880]	0.874	0	0.00000267	0.000016
Accuracy	Base1	Pre	[0.740, 0.880]	0.834	10	0.00000746	0.0000448
Accuracy	Base1	Post	[0.810, 0.880]	0.860	3.5	0.00000385	0.0000231
Accuracy	Base2	Pre	[0.006, 0.420]	0.008	143	0.852	1
Accuracy	Base2	Post	[0.010, 0.580]	0.265	152	0.156	0.936
Accuracy	Post	Pre	[0.020, 0.640] [0.020, 0.640]	0.344	230	0.071	0.427

Response Time in the N-back Task

Initially, the mean response times across the four stages were calculated and their distributions were examined. Descriptively, participants response times became shorter as the stages progressed. Before conducting the main analysis, the data were screened for extreme and missing values, and no problematic cases were identified. The normality of response time at each stage was then assessed using the Shapiro-Wilk test. Since the p-values were above .05 at all four stages, the assumption of normality was considered to be satisfied. A one-way repeated-measures analysis of variance (ANOVA) was subsequently conducted to examine differences in response time across the four stages. Mauchly's test indicated that the assumption of sphericity was not satisfied (W = 0.488, p = .002); therefore, the Greenhouse-Geisser correction was applied. The corrected results showed a significant difference in reaction time across the assessment stages, $F(2.21, 61.87) = 18.45$, $p = 2.19 \times 10^{-7}$, with a generalized eta-squared effect size of 0.079. The results of the repeated-measures ANOVA are presented in Table 3.

Table3: *Results of the one-way repeated-measures ANOVA for N-back reaction time*

Correction	Effect size (Generalized η^2)	P-value	F	df error	df hypothesis
Greenhouse-Geisser	0.079	2.19×10^{-7}	18.449	61.87	2.21

Table 3. Note. Greenhouse-Geisser correction was applied because Mauchly's test indicated a violation of the

sphericity assumption (W = 0.488, p = .002; ε = .737).

To further examine the differences between the study stages, post hoc pairwise comparisons were performed using paired samples t-tests with Bonferroni correction. Significant differences involving the first baseline were observed, as reported in Table 4. More importantly, reaction time also differed significantly between the second baseline and the pre-intervention stage (adjusted $p = .002$), as well as between the second baseline and the post-intervention stage (adjusted $p = .014$). However, no significant difference was found between the pre- and post-intervention stages (adjusted $p = 1.000$). The mean differences, 95% confidence intervals, and corresponding effect sizes for all pairwise comparisons are presented in Table 4.

Table 4. Pairwise t-test results with Bonferroni correction for N-back reaction time

	Group1	Group2	Mean difference (ms)	CI 95%	t statistic	p	p.adj	Cohen's dz
Reaction Time	Base1	Base2	47.0	[15.8, 78.3]	3.08	0.005	0.028	0.572
Reaction Time	Base1	Pre	91.6	[58.2, 125.0]	5.62	0.00000517	0.000031	1.040
Reaction Time	Base1	Post	109.0	[67.3, 151.0]	5.33	0.0000113	0.0000678	0.990
Reaction Time	Base2	Pre	44.6	[22.0, 67.2]	4.04	0.000378	0.002	0.750
Reaction Time	Base2	Post	62.2	[24.2, 100.0]	3.35	0.002	0.014	0.622
Reaction Time	Post	Pre	−17.7	[−44.4, 9.04]	-1.35	0.186	1	−0.252

4. Discussion

This study was conducted to examine the possibility of re-regulating working memory performance following stress induction through a heart rate regulation biofeedback intervention using heart rate and respiration sensors in a single session among healthy individuals. For this purpose, changes in N-back task scores were evaluated and compared across three stages: before stress induction, after stress induction, and after the implementation of the HRV biofeedback intervention. The results of the data analysis indicated that no significant differences were observed in the changes in N-back task scores between the pre- and post-intervention stages.

In other words, stress induction did not lead to a significant decline in working memory performance among participants and, consequently, the biofeedback intervention did not produce a meaningful improvement in their performance. However, the findings related to response accuracy in the N-back task indicated that the pattern of cognitive performance was more complex. A comparison of the first and second baseline measurements showed a significant improvement in response accuracy, which was likely driven more by practice effects and gradual familiarity with the task than by the intervention itself. Although a significant difference was observed between the first baseline and the post-intervention stage, no significant differences emerged between the second baseline and the post-intervention stage, nor between the post-stress induction and post-biofeedback stages. These results suggest that the short-term heart rate variability biofeedback intervention did not, contrary to initial expectations, have a substantial impact on enhancing working memory accuracy. One possible explanation for this finding concerns the participants initial stress levels. Research has shown that the effects of stress on cognitive performance are not uniform and can either facilitate or impair functioning depending on the intensity of the stress and individual conditions (Shields et al., 2016). Moreover, previous studies have indicated that the effectiveness of heart rate variability biofeedback is more pronounced under conditions of higher stress, as the intervention helps restore physiological balance (Prinsloo et al., 2011; Lehrer & Gevirtz, 2014). Therefore, under moderate stress levels, biofeedback may function primarily as a relaxation technique rather than as a means of enhancing cognitive performance.

Regarding response speed, the results also showed that participants reaction time decreased after the intervention compared with the first baseline stage; however, the absence of a significant difference between the post-stress induction stage and the post-intervention stage indicates that these changes were most likely attributable to the practice and repeated exposure to the task rather than to the intervention itself. This interpretation is consistent with prior findings suggesting that improvements observed across repeated administration of cognitive tasks are largely driven by learning and increased familiarity with the task (Prinsloo et al., 2011). On the other hand, the findings demonstrated that acute stress does not necessarily lead to a decline in performance and may even increase response speed. This pattern can be explained in terms of the role of physiological arousal and the activation of the sympathetic system in accelerating stimulus processing (Hermans et al., 2014). This account is also consistent with the Yerkes Dodson law, according to which moderate levels of stress can facilitate certain aspects of cognitive performance particularly speed and attentional processes. Overall, the present findings suggest that initial stress intensity may be an important factor in the effectiveness of heart rate variability biofeedback and that the effect of stress on cognitive performance may be dual in nature and context dependent.

5. Limitation and future work

This study has several limitations that should be considered when interpreting the findings. First, the absence of a separate control condition makes it difficult to determine whether the observed changes were specifically related to biofeedback, since practice effects, the passage of time, and other nonspecific factors cannot be completely ruled out.

Second, the stress induction procedure did not fully follow the standard TSST protocol. In the original protocol, the task is usually conducted in the presence of three unfamiliar evaluators to strengthen the social-evaluative component and increase the stress response. However, due to practical limitations in the present study, the researcher also acted as one of the evaluators. This may have reduced the intensity of the stress experienced by participants and, consequently, the effectiveness of the stress induction.

Third, although the final sample size was larger than the minimum estimated by the a priori power analysis, the relatively small sample may still have limited the detection of smaller effects. While no significant changes were found at the group level after stress induction or biofeedback, the individual results showed considerable variability. Eleven participants showed decreased or unchanged performance after stress induction but improved after biofeedback. In addition, six participants improved after biofeedback despite showing no decline after stress induction. Overall, 17 participants showed improved N-back performance following the biofeedback session. These differences may reflect individual variability in stress sensitivity and response to biofeedback.

Finally, only female participants were included in the study. This helped to reduce sex-related variability within the sample, but it also limits the generalizability of the findings to males. Future studies should include both sexes to examine whether similar patterns are observed across sex.

Future studies with larger and more diverse samples, appropriate control conditions, and more standardized stress induction procedures may provide a clearer understanding of the effects of single-session biofeedback.

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