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Heart Rate and Heart Rate Variability Responses to Cognitive Stress, Physical Stress, and Meditation-Based Recovery Measured Using Wearable Devices

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ABSTRACT

Acute psychological and physical stress can produce measurable changes in physiological signals including heart rate (HR) and heart rate variability (HRV). This descriptive pilot study analyzed the changes in heart rate and HRV during periods of meditation, cognitive stress, and physical exertion. Four participants (n=4; two adolescents aged 16-17 and two adults aged 54-56) completed a sequential protocol consisting of a baseline meditation period, a Stroop test, a recovery meditation period, a standardized three-minute step test, and a second recovery meditation session. Each participant completed the protocol twice: once using non-guided meditation and once using a guided meditation video. Heart rate and HRV data were collected using wearable sensors. Heart rate increased during both cognitive and physical stress, while aggregate RMSSD decreased. During the step test, mean HR increased from 75.82 bpm at baseline to 102.62 bpm during the non-guided meditation condition and from 73.07 bpm to 107.40 bpm during the guided meditation condition, while aggregate RMSSD decreased from 40.19 ms to 7.19 ms and from 53.71 ms to 9.20 ms, respectively. Following the step test, mean HR during guided recovery was 82.61 bpm compared with 89.34 bpm during non-guided recovery, a difference of 6.73 bpm. These findings suggest that wearable physiological monitoring can detect stress-related autonomic responses and may provide a practical method for evaluating recovery following meditation.

INTRODUCTION

Acute psychological and physical stress can produce measurable changes in cardiovascular physiology, including heart rate (HR) and heart rate variability (HRV). These physiological responses provide a way to examine how the body responds to short-term stressors and its post stress recovery. Because these physiological changes reflect activity of the autonomic nervous system, heart rate and HRV have become important biomarkers for studying stress responses and recovery. In particular, increased heart rate is commonly associated with sympathetic nervous system activation and decreased HRV mainly reflects parasympathetic withdrawal, these processes are often described as the body's "fight-or-flight" response.

Recent advances in wearable technology have allowed for continuous at-home monitoring of biomarkers such as heart rate and HRV using affordable external sensors. These devices can collect continuous data during everyday activities, allowing researchers and individuals to observe how the body responds to stressors and returns toward baseline during recovery periods. These tools may be especially useful for studying stress-management strategies such as meditation.

Meditation is commonly used to promote relaxation and may support recovery by increasing parasympathetic nervous system activity. Practices such as mindfulness and controlled breathing have been associated with reduced physiological stress responses, including lower heart rate and improved HRV. However, fewer studies have examined acute physiological responses to both cognitive and physical stressors followed by guided vs. non-guided recovery using accessible wearable sensors. This study addresses this gap by comparing heart rate and HRV responses during a Stroop task and standardized step test with guided and non-guided recovery periods in a descriptive pilot study.

The purpose of this study was to investigate changes in heart rate and heart rate variability during periods of cognitive stress, physical stress, and meditation using wearable sensors. Participants completed a sequence of activities consisting of a baseline meditation period, a Stroop test to induce cognitive stress, a recovery meditation period, a standardized step test to induce physical stress, and a second recovery meditation period. Each participant completed this protocol twice, once with non-guided meditation and no outside influences and once with a guided meditation video that included both box breathing and mindfulness practice. By evaluating and comparing physiological responses across each condition, this study aimed to examine whether meditation supported physiological recovery following stress and to identify indicators of stress and recovery toward each session's baseline. It was hypothesized that both cognitive and physical stress would increase heart rate and decrease HRV, while meditation, particularly guided meditation, would support physiological recovery relative to each session's baseline values.

BACKGROUND

Acute Stress and Physiological Responses

Acute stress can produce measurable physiological changes, including increased heart rate and changes in heart rate variability. These responses are associated with changes in autonomic nervous system activity and can be examined using wearable physiological sensors. Understanding these short-term responses may help researchers evaluate how physiological measures change during stress and recovery.

Autonomic Nervous System

The autonomic nervous system (ANS) regulates involuntary body functions such as heart rate, breathing, and blood pressure. It consists of two branches: the sympathetic nervous system (SNS) and the

parasympathetic nervous system (PNS). The SNS activates the body's "fight or flight" response as a reaction to stress. It increases heart rate, breathing rate, and blood pressure to prepare for action. The parasympathetic nervous system (PNS) activates the "rest and digest" state. It slows the heart rate, encourages relaxation, and helps the body recover after stress (3).

Heart rate and heart rate variability (HRV) are influenced by the activity of the sympathetic and parasympathetic nervous systems. Changes in HRV can provide information about ANS activity, especially changes in PNS activity (4). When encountering stressors, the SNS activity increases and causes heart rate to rise. However, during relaxation, PNS activity increases allowing heart rate to return to resting rate (3, 4).

Physiological Symptoms

Acute stress can be accompanied by physiological changes including increased heart rate, changes in breathing, sweating, and trouble concentrating (1). Heart rate variability (HRV) is the change in time between consecutive heartbeats or heartbeat intervals (4). Research has shown that acute stress can affect HRV, with lower HRV often observed during stressful conditions (4, 5).

Meditation

Meditation is a widely used stress-management technique that has been shown to influence the autonomic nervous system (6). During periods of stress, the sympathetic nervous system activates the body's "fight-or-flight" response, increasing heart rate and reducing heart rate variability. In contrast, meditation promotes activation of the parasympathetic nervous system, which is responsible for the body's "rest-and-digest" functions (6). Increased parasympathetic activity can slow heart rate, enhance relaxation, and improve heart rate variability measures such as RMSSD (7). Previous research has demonstrated that meditation and controlled breathing exercises can reduce physiological markers of stress and support recovery following stressful events (6, 7). As a result, meditation may be an effective strategy for helping biomarkers their pre-stress levels after exposure to stressors.

METHODS AND MATERIALS

Participants

This study includes four participants recruited through convenience sampling from the student researcher’s existing personal and community contacts. Interested individuals were informed of the nature of the study and participated voluntarily. Participants were eligible if they were able to complete the experimental protocol, which included seated meditation, a Stroop test, and a three-minute step test.

Because the protocol involved a physical activity component, participants were asked to confirm that they had no known condition that would prevent them from safely completing the protocol.

Before participation, all participants were informed of expectations and potential risks of this experiment. Complete instructions and additional clarifications were provided before participation. Each adult participant read, understood, and signed consent forms. For adolescent participants, assent was obtained from the participants and consent was obtained from a parent or guardian before data collection. Adolescent participants completed the experimental protocol under the supervision of the student researcher. Participants were free to withdraw from the study at any time and were under no pressure to meet specific performance standards.

The study included four participants: two adolescents (both female aged 16 and 17) and two adults (one female aged 54 and one male aged 56). Based on self-reported activity level, one adolescent and one adult participant were physically active, while the other two were not regularly physically active. None of the participants reported prior meditation experience or use of medications known to affect heart rate, including beta-blockers. Body mass was not collected.

Materials

Data was collected using two wearable sensors: the Polar H10 Heart Rate Sensor and the Polar Verity Sense Optical Heart Rate Sensor. The Polar H10 is a Bluetooth and ANT+ compatible chest sensor which uses electrocardiogram, in other words electrical activity of the heart, measurements to obtain heart rate. Paired with the Elite HRV mobile app, R-R interval data (time between consecutive heartbeats) of a session can be exported and used to calculate heart rate variability. The Polar Verity Sense is an optical heart rate sensor worn on the upper or lower arm. It measures heart rate using optical technology with six LED lights, but it does not record heart rate variability. This sensor has demonstrated acceptable validity and reliability for heart rate measurements, especially during exercise (16). The Polar Verity Sense sensor was paired with the Polar Flow app to record heart rate throughout one session of the experiment, with data later exported through the Polar Flow web app for analysis. Heart rate was recorded using the Polar Verity Sense sensor, while RR-intervals were obtained from the Polar H10 chest strap because of its suitability for RR-interval and HRV measures including RMSSD, supporting its use for HRV assessment (15).

Study Design

This study followed a sequential design in which all participants completed the same series of activities in the same order. The protocol consisted of a baseline meditation period, a Stroop test to induce cognitive stress, a recovery meditation period, a standardized step test to induce physical stress, and a second recovery meditation period. Each participant completed the protocol twice: once with non-guided meditation and once with guided meditation. The study did not include a separate passive-rest control condition, limiting the ability to distinguish between natural post-stress recovery from physiological

changes associated with meditation. Both sessions were completed on the same day during the afternoon. Participants were not given specific instructions about caffeine consumption, food intake, or sleep before testing. No physical activity occurred on the day of testing. Throughout each session, heart rate and heart rate variability were measured using chest and arm sensors paired with mobile apps. The Polar Verity Sense arm sensor was paired with the Polar Flow app to record heart rate and the Polar H10 chest sensor was paired with the Elite HRV app.

Cognitive Stress

The Stroop Color and Word Test (SCWT) was used as the cognitive stress task in this study. The SCWT is a neurophysiological test to assess how cognitive function is affected by conflicting words and ink colors (8). The brain automatically processes words, interfering with naming the ink color by producing cognitive interference when the ink color and word are conflicting. This conflict makes the task more mentally demanding.

In this study, participants completed two Stroop conditions consecutively. In the congruent condition, the written color word matched the ink color. In the incongruent condition, the written word and ink color were different, creating greater cognitive interference. The task was administered using a PDF displayed on a computer screen, obtained from the Stark Science Learning Center at the University of Utah Health (9). Participants were instructed to identify aloud the color of each word as quickly as possible and as accurately as possible, despite conflicting words and ink colors in the incongruent condition. No formal accuracy or completion time measurements were recorded. Because participants responded verbally, speaking may have affected their breathing pattern and consequently influenced heart rate and HRV measurements during the Stroop task.

The SCWT was included as a cognitive task intended to produce cognitive interference . Changes in heart rate and heart rate variability during the task and subsequent recovery period were analyzed to examine physiological responses following cognitive interference.

Physical Stress

A standardized YMCA 3-Minute Step Test was used as a physical stressor for this study (10, 14). Participants stepped up and down from a 12 inch (30.5 cm) bench at a rate of 24 steps per minute for three minutes, paced by a metronome set to 96 beats per minute (10, 14).

Right Up → Left Up → Right Down → Left Down

The step test was included because it increases the body's demand for oxygen, leading to an increase in heart rate and greater sympathetic nervous system activity. During physical exertion, heart rate variability often decreases as parasympathetic activity is reduced. Therefore, the step test served as the physical

stress condition for evaluating changes in heart rate and heart rate variability during exertion and subsequent recovery.

Physiological responses during and after the step test were compared between the non-guided and guided meditation sessions to evaluate differences in heart rate recovery between the non-guided and guided meditation sessions.

Meditation

Meditation was used both as a baseline condition and as a recovery condition after each stress task. During each meditation period, participants completed a 10-minute meditation exercise while seated. In the first session, participants engaged in non-guided meditation without outside influence. They were given no instruction beyond staying seated. In a second session for all three meditation sessions, each participant listened to and watched on a screen a guided meditation video which included both directed box breathing with a 4-4-4-4 second timing and mindfulness practice. The ten-minute "Box Breathing Into Meditation" sourced from Feeling Healing on YouTube aided participants in returning to stable levels as both breathwork and mindfulness meditation has been shown to be associated with reduced biological stress reactivity, meaning it is able to alleviate stress and lower heart rate (11, 12). Therefore, meditation was included in this protocol to examine whether participants' physiological signals returned toward baseline after cognitive and physical stressor

Procedure

Each experimental session lasted approximately 45 minutes to 1 hour and 10 minutes beginning with a ten-minute baseline meditation period, during which participants sat quietly and either practiced non-guided meditation or followed the guided meditation video, depending on the session condition.

After the baseline period, participants completed the Stroop Color-Word Test as the cognitive stress task. This task was included because the Stroop Color-Word Test has been shown to induce physiological stress responses, including increased heart rate associated with sympathetic nervous system activation (13). Participants then completed a ten-minute meditation period while seated and upright to examine changes in heart rate and HRV following the cognitive task.

Next, participants performed aerobic exercise using a three-minute standardized step test to increase sympathetic nervous system activity and consequently heart rate. After the physical stress, participants completed a second 10-minute meditation recovery period while seated and upright.

This sequence of tasks was completed twice by each participant, once with non-guided meditation and no relaxation prompts, and again with a guided meditation video including box breathing and mindfulness practice. Figure 1 outlines the sequence with non-guided meditation and the sequence with guided meditation.

Iteration 1 - non-guided meditation

Baseline (non-guided)	Cognitive Stress (Stroop Test)	Meditation 1 (non-guided)	Physical Stress (Step Test)	Meditation 2 (non-guided)

Iteration 2 - guided meditation with box breathing and mindfulness

Baseline (Guided)	Cognitive Stress (Stroop Test)	Meditation 1 (Guided)	Physical Stress (Step Test)	Meditation 2 (Guided)

Figure 1 summarizes the sequence of activities participants engaged in during the study with iteration 1 representing the sequence with non-guided meditation and iteration 2 representing video guided meditation

Data Processing and Calculations

Raw RR-interval data were exported from the Polar H10 sensor using the Elite HRV export and analyzed in Google Sheets. Phase start and end points were identified based on the sequence and timing of the experimental protocol. No transition periods were removed between phases. The root mean square of successive differences between heartbeats (RMSSD) was calculated for each condition by determining the differences between consecutive RR intervals, squaring the differences, calculating the mean of the squared values, and taking the square root of the mean. RMSSD was used as a measure of short-term heart rate variability. RMSSD was calculated over the available recording period for each activity, consistent with established HRV measurement standards (20). The durations for each activity were one to two minutes for the Stroop task, three minutes for the step test, and ten minutes for each meditation period. RMSSD was calculated for each activity using the available RR-interval data for that experimental condition. Because the RR-interval data were pooled across participants before RMSSD calculation, the resulting RMSSD values are aggregate condition-level measurements rather than averages of individual participant RMSSD values.

Because the study included only four participants, the results were analyzed descriptively rather than using inferential statistical tests. Therefore, the findings should be interpreted as preliminary trends rather than statistically significant conclusions.

RESULTS AND ANALYSIS

Results are presented as descriptive summaries of individual and mean heart rate responses and aggregate RMSSD values. Because the study included only four participants from two different age groups, group mean values were used to summarize overall trends, while individual responses were also examined to describe variation between participants. Table 1 shows the age of the participants. Tables 2 and 3

summarize individual heart rate, mean heart rate, standard deviation of heart rate across participants, and aggregate RMSSD across experimental conditions. Because RMSSD was calculated from pooled RR-interval data, individual participant RMSSD values are not reported. Figures 2 and 3 show individual heart rate responses over time using data from the Polar Verity Sense arm sensor, while Figure 4 shows the heart rate response comparison between the Non-Guided and Guided Meditation Condition Post the Step Test for each participant. This section first presents the non-guided and guided meditation conditions separately, then compares recovery patterns between the two conditions after the step test.

Table 1 - Participant number, age group, age

Participant	**Age Group**	**Age (years)**
P1	Adolescent	17
P2	Adolescent	16
P3	Adult	54
P4	Adult	56

Non-Guided Meditation Conditions

Table 2 summarizes the individual participant HR, mean HR, standard deviation of HR, and aggregate RMSSD across the sequence with non-guided meditation condition. The mean heart rate of the participants demonstrated measurable increases during the stress events. The largest heart rate response occurred during the step test, reaching 102.62 bpm, followed by a decrease to 89.34 bpm during the second meditation recovery period.

Aggregate RMSSD of participants experienced a decrease during stress events and increased during meditation after each stress task. The lowest RMSSD value occurred during the step test, decreasing to 7.19 ms. During the second non-guided meditation recovery period, RMSSD increased to its highest value of 55.90 ms.

Figure 2 shows the individual heart rate responses during the non-guided meditation session. The largest increase in HR generally occurred during the step test, while HR responses during the Stroop task were smaller. However, the magnitude of these increases varied between individuals. Some participants exhibited rapid increases and decreases in heart rate, while others showed more gradual changes throughout the sessions.

Table 2 - Individual participant HR across experimental conditions, mean HR, standard deviation of HR across participants, and aggregate RMSSD during the non-guided meditation condition

	Participant 1 HR (bpm)	Participant 2 HR (bpm)	Participant 3 HR (bpm)	Participant 4 HR (bpm)	Mean HR (bpm)	SD	Aggregate RMSSD (ms)
Baseline	88.47	68.11	82.07	64.64	75.82	9.79	40.19
Stroop Task	82.12	75.44	84.62	61.72	75.97	8.89	38.79
Meditation 1	85.18	59.23	81.20	64.09	72.42	10.99	39.31
Step Test	103.91	89.27	125.19	92.10	102.62	14.14	7.19
Meditation 2	101.28	70.79	91.48	93.82	89.34	11.31	55.90

Heart Rate (bpm) vs. Time (min) with non-guided meditation

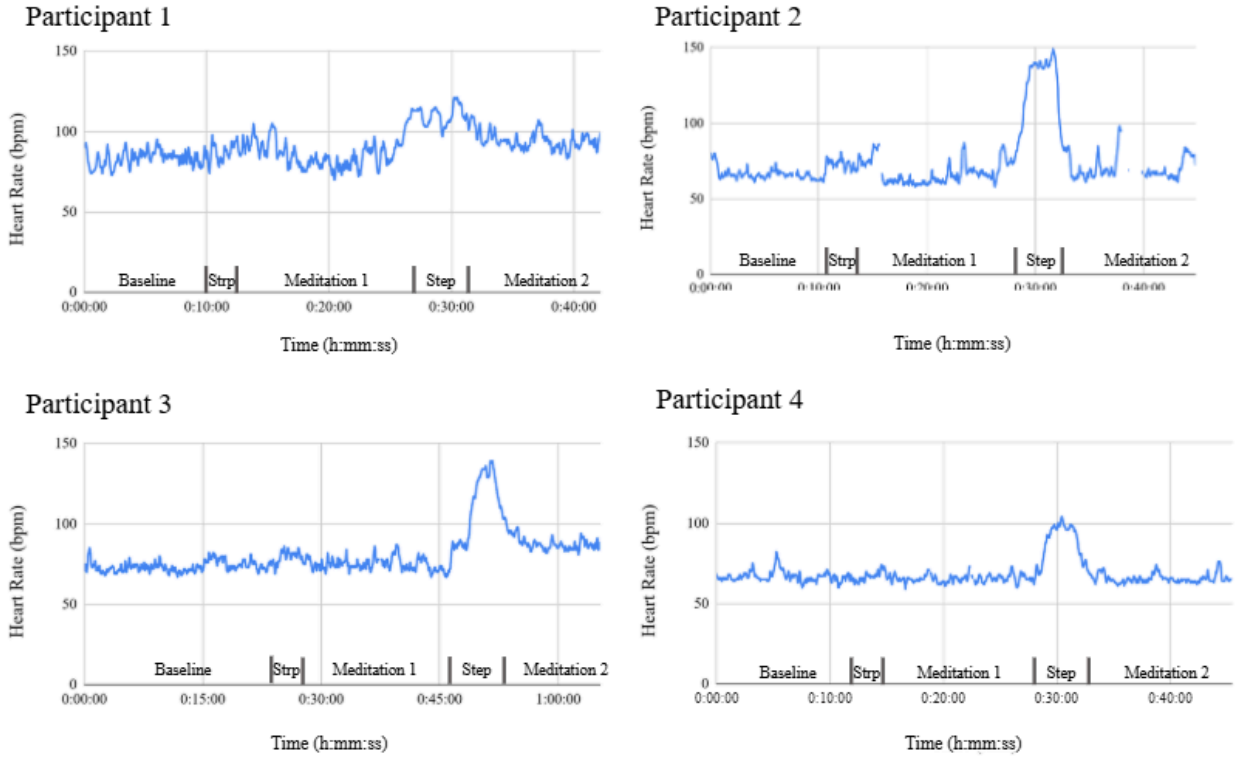


Figure 2 - Individual Heart Rate Response in Non-Guided Meditation Condition

Guided Meditation Condition

Table 3 summarizes individual participant HR, mean HR, standard deviation of HR, and aggregate RMSSD across the experimental sequence with guided meditation conditions. The mean heart rate of the participants demonstrated measurable increases during the stress events. The largest heart rate response

occurred during the step test, reaching 107.40 bpm, followed by a decrease to 82.61 bpm during the second meditation recovery period.

Aggregate RMSSD of participants experienced a decrease during stress events and increased during meditation after each stress task, with the lowest value occurring during the step test of 9.20 ms. RMSSD then increased during both meditation recovery periods, reaching its highest value of 63.26 ms after the Stroop task.

Figure 3 shows the individual HR responses during the sequence with guided meditation conditions. Individual HR responses varied in magnitude across participants, with the largest increases generally occurring during the step test. HR generally decreased during the subsequent meditation periods, although the magnitude of change differed between participants.

Table 3 - Individual participant HR across experimental conditions, mean HR, standard deviation of HR across participants, and aggregate RMSSD during the guided meditation condition

	Participant 1 HR (bpm)	**Participant 2 HR (bpm)**	**Participant 3 HR (bpm)**	**Participant 4 HR (bpm)**	**Mean HR (bpm)**	**SD**	**Aggregate RMSSD (ms)**
Baseline	84.95	67.46	72.81	67.08	73.07	7.22	53.71
Stroop Task	90.50	71.70	78.83	64.93	76.49	9.46	36.87
Meditation 1	83.93	67.39	80.10	65.87	74.32	7.83	63.26
Step Test	107.82	121.04	110.36	90.37	107.40	11.01	9.20
Meditation 2	97.89	77.51	87.12	67.92	82.61	11.13	61.85

Heart Rate (bpm) vs. Time (min) with guided meditation

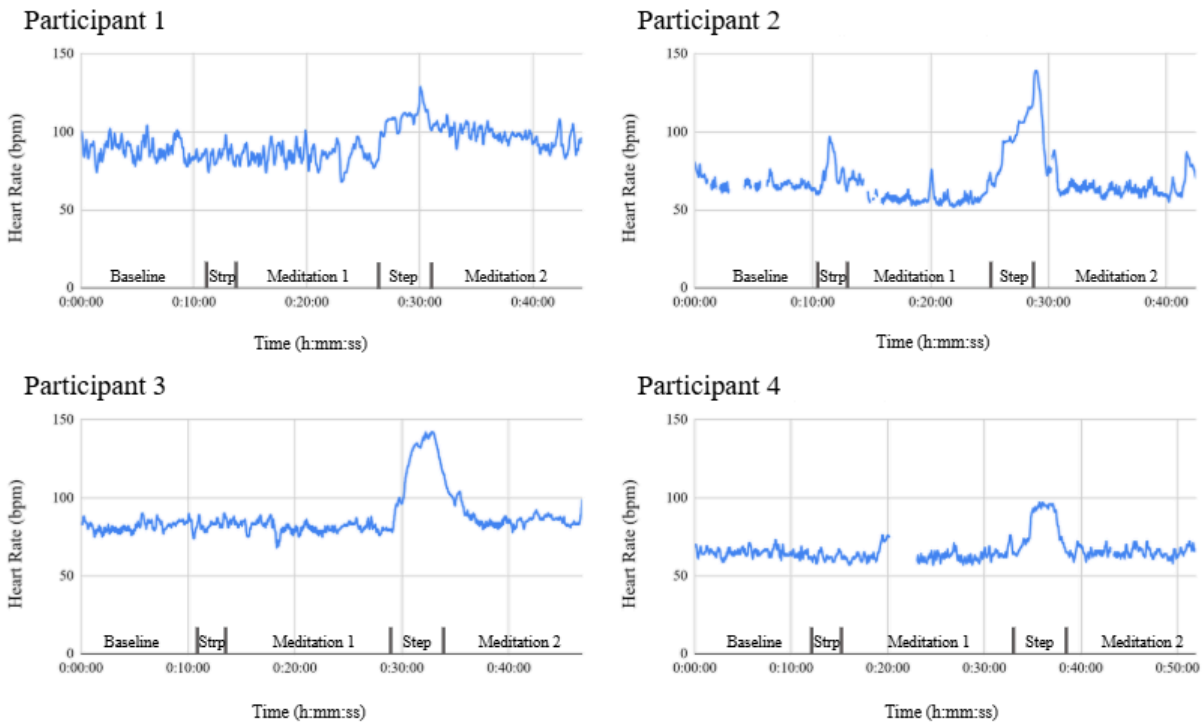


Figure 3 - Individual Heart Rate Response in Guided Meditation Condition

Comparison Between Non-Guided and Guided Recovery Patterns

The effects of the meditation session were most noticeable after the step test, so the step test and post step test data were used to examine differences in heart rate between the two conditions. Compared to the post step test measurements with non-guided meditation, heart rate recovery patterns appeared faster in some participants with the guided meditation. Although the difference was minor, it was more apparent than the changes observed during other conditions. However, because standardized recovery metrics were not calculated, this observation should be considered preliminary and descriptive rather than as definitive evidence.

This trend was generally observed in all participants, suggesting that meditation may have been associated with heart rate following physical activity. The difference between the guided meditation and non-guided meditation post step test results is shown in the following figures, where the change in heart rate can be more clearly seen than in the resting measurements. However, because the guided meditation condition always occurred second, these differences may have been influenced by familiarity with the experimental protocol.

Figure 4 compares heart rate during the guided meditation (blue) and non-guided meditation (red) conditions. For comparison between conditions, heart rate data were aligned according to the start of the step test rather than absolute recording time. Both conditions followed a very similar overall pattern.

Heart rate increased during the step test before gradually decreasing during the recovery period. The guided meditation condition showed a slightly earlier increase in heart rate during the step test and a slightly faster recovery afterward, with heart rate decreasing slightly faster than in the non-guided meditation condition. By the end of the recovery period, heart rates in both conditions had stabilized at similar levels for each participant. Visual comparison between conditions suggests possible differences in post-exercise heart rate patterns between the two sessions. However, standardized recovery measures were not calculated and the fixed session order prevents directly attributing these differences to guided meditation.

Heart Rate (bpm) vs. Relative Position to Step Test: Before, During, and After Step Test: Non-Guided Meditation (Red) and Guided Meditation (Blue)

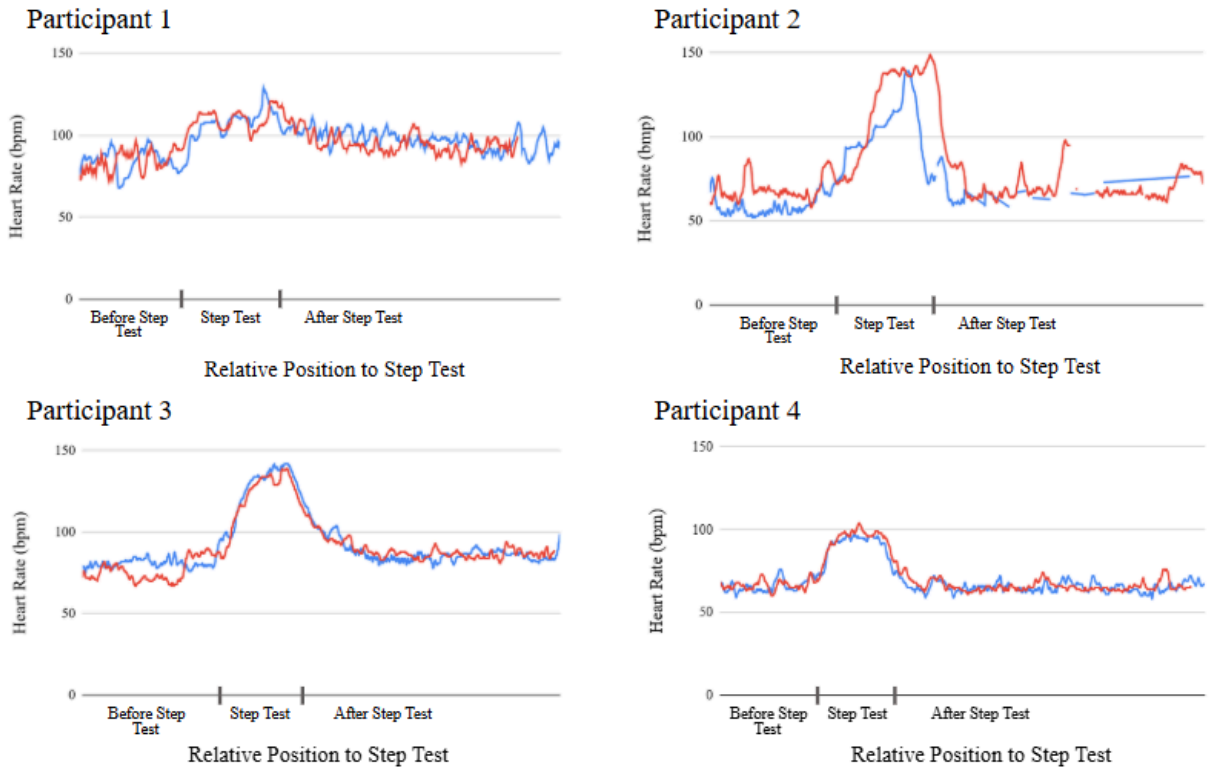


Figure 4 - Individual heart rate response before, during, and after the step test in non-guided and guided meditation conditions. Heart rate data were aligned according to the start of the step test rather than absolute recording time.

DISCUSSION

The results suggest that the physical stressor produced a larger measurable change in cardiovascular activity, while physiological response to the cognitive task was smaller. Heart rate and HRV showed

relatively small changes during the Stroop task, while the step test produced a much larger increase in heart rate and decrease in HRV. This pattern is consistent with previous research showing that the Stroop test can increase heart rate while decreasing RMSSD and other measures of HRV during acute cognitive stress (18). These findings are consistent with increased autonomic activity during periods of acute stress.

The step test generally produced larger increases in heart rate than the Stroop task, suggesting that physical stress placed greater immediate demands on the cardiovascular system of participants than cognitive stress. However, both activities were associated with decreases in HRV. The observed decrease in heart rate and increase in HRV during the post step test recovery are consistent with previous research describing heart rate recovery and autonomic activity following exercise (19). The use of wearable sensors in this study is also supported by previous validation studies showing strong agreement between the Polar H10 and calculated HRV measures from raw RR-intervals and acceptable validity of the Polar Verity Sense for heart rate measurement during exercise (15, 16).

Physiological recovery was observed during the meditation condition recovery periods. During the guided meditation condition, mean HR generally decreased and aggregate RMSSD increased during the recovery meditation periods compared with the preceding stress events, the Stroop task and the step test (Table 3). These changes may reflect increased parasympathetic nervous system activity during recovery. However, because all participants completed the non-guided meditation condition before the guided meditation condition, the observed differences may also reflect familiarity with the experimental protocol, habituation to the Stroop task, or anticipation of the step test. Voluntary slow breathing has been shown to increase vagally mediated HRV, making it difficult to separate the effects of paced breathing from those of meditation in this study (17). Although the small sample size and fixed order of conditions prevent strong conclusions about effectiveness, the findings suggest that guided breathing and mindfulness practices may be associated with physiological recovery after cognitive and physical stress.

LIMITATIONS

This study presents some limitations. First, the sample size was small and heterogeneous, consisting of two adolescents and two adults (Table 1). As heart rate and HRV are known to vary with age, Figures 2 and 3 show differences in resting heart rate fluctuations between participants. However, these visual differences should not be interpreted as differences in HRV. Individual heart rate responses were reported to illustrate variation between participants. However, RMSSD was calculated from pooled RR-interval data and therefore does not provide participant-specific HRV measurements. Individual RMSSD values were not calculated or reported. As a result, the aggregate RMSSD results should not be interpreted as evidence that all participants experienced the same HRV responses and the findings should not be generalized as representative of any specific age group. Furthermore, the sample size was insufficient to perform meaningful age-based comparisons or draw population-level conclusions.

The order of the meditation conditions was not randomized. All participants completed the non-guided meditation session first and the guided meditation session second. Therefore, results from the guided meditation condition may have been influenced by familiarity with the experimental protocol, habituation to the Stroop task, or anticipation of the step test rather than the guided meditation alone. Additionally, the same Stroop task was used in both sessions, which may have introduced habituation effects and reduced its ability to produce the same level of cognitive interference during the second session. Both sessions occurred on the same day during the afternoon with no physical activity executed on the day of testing. However, caffeine consumption, food intake, and sleep before testing were not controlled and may have contributed to variability in heart rate and HRV. Additionally, because all participants completed the same stepping workload, the relative exercise intensity may have differed across participants due to differences in age and fitness level. Future studies should randomize or counterbalance the order of meditation conditions and standardize these factors to reduce potential order effects and variability.

Another limitation is that breathing rate was not measured during the experimental sessions. The guided meditation included controlled box breathing with a 4-4-4-4 pattern of inhalation, breath-holding, exhalation, and breath-holding phases, resulting in a slower breathing rate. Slow breathing can influence RMSSD through respiratory sinus arrhythmia (17). This means that the higher aggregate RMSSD observed during the guided meditation may have been influenced by the breathing pattern itself in addition to physiological recovery during stress. Because participants responded verbally during the Stroop task, speaking may have altered breathing influenced heart rate and HRV being the cognitive stress condition. Future studies should measure breathing rate alongside heart rate and HRV to better distinguish the effects of controlled breathing and changes in breathing rate from those of meditation.

The baseline period consisted of a ten-minute meditation period rather than a neutral seated rest period, with the meditation matching the condition for each session (non-guided meditation or guided meditation). Therefore, the two sessions had different baseline reference points. For the non-guided meditation condition, baseline heart rate was 75.82 bpm and baseline aggregate RMSSD was 40.19 ms compared to 73.07 bpm and 53.71 ms for the guided meditation condition. Comparisons were interpreted as changes within each session relative to its own baseline rather than as differences from a common physiological baseline for each participant. A neutral seated rest period before the experimental sessions would provide a more suitable baseline for future studies.

Another limitation of this pilot study is that RR-interval correction was not performed before RMSSD was calculated. This is particularly important for the post step test meditation period where the heart rate was still elevated and changing rapidly. The higher aggregate RMSSD values calculated during this period may partly reflect residual measurement artifacts such as missed beats or signal dropouts. These values should as a result be interpreted cautiously and not as direct evidence of increased vagal activity.

Because RMSSD was calculated over recording windows of different durations, direct comparisons across activities should be interpreted cautiously. This is particularly relevant for the step test, during which movement and rapidly changing heart rate may reduce reliability of RMSSD measurements. Future

studies should use matched, stable analysis windows, such as the last five minutes of each meditation period or shorter consecutive intervals during recovery.

Additionally, because heart rate was obtained from an optical sensor, measurements during movement (step test) may have been affected by motion artifacts. Data gaps for Participant 2 and 4 and the noisy data of Participant 1 may reflect temporary sensor contact or signal quality issues rather than physiological changes alone.

Additionally, the study did not include a neutral passive-rest control condition, so the observed recovery cannot be attributed specifically to meditation. Future studies should include a seated-rest control condition to better distinguish the effects of meditation from natural post-stress recovery.

Finally, because the study included only four participants, the results should be viewed as preliminary observation of within-subject physiological responses to stress and meditation rather than evidence of population-level effects. Future studies should include larger and more age-homogeneous cohorts to better evaluate the influence of meditation on stress and recovery responses.

CONCLUSION

This study analyzed physiological responses during meditation after stress by measuring heart rate and heart rate variability during baseline, cognitive stress, physical stress, and recovery meditation conditions, with non-guided meditation and guided meditation. The results showed that heart rate generally increased during stress and decreased during meditation and recovery, while heart rate variability tended to be lower during stress and higher during recovery. These findings suggest that meditation may be associated with activation of the parasympathetic nervous system and help the body recover from stress. Because all participants completed the non-guided meditation condition before the guided meditation condition, differences between the two conditions may have been influenced by familiarity with the experimental protocol, habituation to the Stroop task, or anticipation of the step test. Although individual responses varied and the sample size was small, the overall trends support meditation being associated with post stress recovery and the use of wearable sensors for monitoring physiological stress responses. However, future studies using larger samples and standardized recovery metrics are needed to determine whether guided meditation produced measurably faster recovery.

DATA AVAILABILITY

The data collected and analysed during this study are not publicly available because the study involves a small number of participants and participant privacy concerns.

ETHICS APPROVAL

This is a preliminary student research project conducted independently and no formal Institutional Review Board (IRB) approval was acquired. Informed consent from adult participants and assent from adolescent participants with parent/guardian consent was obtained prior to data collection.

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