engineering proceedings

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Proceeding Paper

Investigation of the Impact of Resonant Breathing Frequency on Heart-Rate Rhythm Using an Arduino-Based PPG Sensor System with Real-Time Python Visualization †

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† Presented at the International Conference on Electronics, Engineering Physics and Earth Science (EEPES2026), Bandirma, Turkey, 24–27 June 2026.

Abstract

Mental stress has become a significant health issue because it can disrupt autonomic balance and alter breathing patterns. Breathing techniques, especially when monitored by the HeartMath coherence device, are popular for promoting balanced heart–mind interaction. In this project, we developed an open-source Arduino-based photoplethysmography (PPG) system capable of recording heart pulse signals and displaying them on a specialized Python interface. The heart pulse amplitudes are displayed to allow observation of breathing modulation as an envelope of the PPG amplitude train. Simultaneously, the increase in heart rate during inhalation and the decrease during exhalation are displayed. The Python interface enables real-time monitoring of how 0.1 Hz rhythmic breathing exercises synchronize the heart-rate waveform with the PPG amplitude envelope. The proposed platform can serve as a basis for future studies on breathing techniques to foster a harmonious state, enhancing productivity, creativity, and inner peace.

Keywords: breathing modulation; photoplethysmography (PPG); Arduino; Python interface; heart rate variability (HRV); breathing modulation

1. Introduction

Millions worldwide experience mental stress daily [1], which can disrupt the body's physiological balance [2]. The following harmonizing practices have emerged: controlled positive-thinking biofeedback approaches, meditation, and rhythmic breathing exercises. The impact of 0.1 Hz rhythmic breathing was investigated using the PPG-based HeartMath mobile platform, which has 1.2 million users, and the results confirmed that thankfulness and happiness correlate with elevated states of heart–brain activity coherence and stable heart-rate variability [3]. Rhythmic breathing is commonly studied by observing its effects on the heart activity using photoplethysmography (PPG) signals. By measuring changes in the amplitude of pulse waves from the ear, researchers can track how breathing modulates heart rhythms over time. These variations are then visualized as heart-rate variability (HRV), revealing the synchronization between respiration and cardiac function [4,5]. During sessions of slow rhythmic breathing, for example, at a 10 s pace, a person's HRV begins to oscillate around 0.1 Hz, modulated by the heart-rate increase during inhalation and the subsequent decrease during exhalation. This resonance corresponds to a state of heart–breath synchronization (heart coherence), associated with enhanced emotional regulation

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Academic Editors: Teodor Iliev, Ivaylo Stoyanov, Grigor Mihaylov and Selahattin Kosunalp

Published: 3 September 2026

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and reduced perceived stress [6]. Recent advances in Arduino-based PPG technology enable real-time heart-rate monitoring, providing a practical platform [7] for studying emotions [8], heart-rate variability [9], and respiratory rate [10–13]. The present work aims to develop an Arduino-based PPG measurement system, with real-time Python-based visualization to investigate the influence of 0.1 Hz breathing on the temporal synchronization between pulse-wave amplitude and heart rhythm, as an open-source Arduino-based platform.

2. Materials and Methods

Heart pulse data were recorded using two independent systems. In Figure 1, on the left, a custom-built measurement system based on an Arduino Uno (Arduino S.r.l., Monza, Italy) records PPG signals via an analog PulseSensor (World Famous Electronics LLC, New York, NY, USA) and visualizes them in a custom Python interface. A PPG PulseSensor is attached to the subject's left ear and connected to the Arduino, which optically reads the analog signal corresponding to changes in blood volume. This analog heart-rate PPG sensor is known for its high heart-rate recording accuracy against a predefined raw threshold. In contrast, the manufacturer's sample Arduino code/library reliably provides high-quality, reproducible data readings, as originally verified by two different smart wearable devices. Possible measurement uncertainties are further reduced by placing the pulse sensor on the ear, where the heart rate is much higher than in other parts of the body. The acquired signal is transmitted to a computer. In parallel, a commercial HeartMath device (HeartMath, Inc., Boulder Creek, CA, USA) is used as a reference system. A second ear sensor from the HeartMath system is attached to the same subject, allowing simultaneous measurement under identical physiological conditions. The HeartMath device processes the signal internally and sends data to a smartphone application for visualization and coherence analysis.

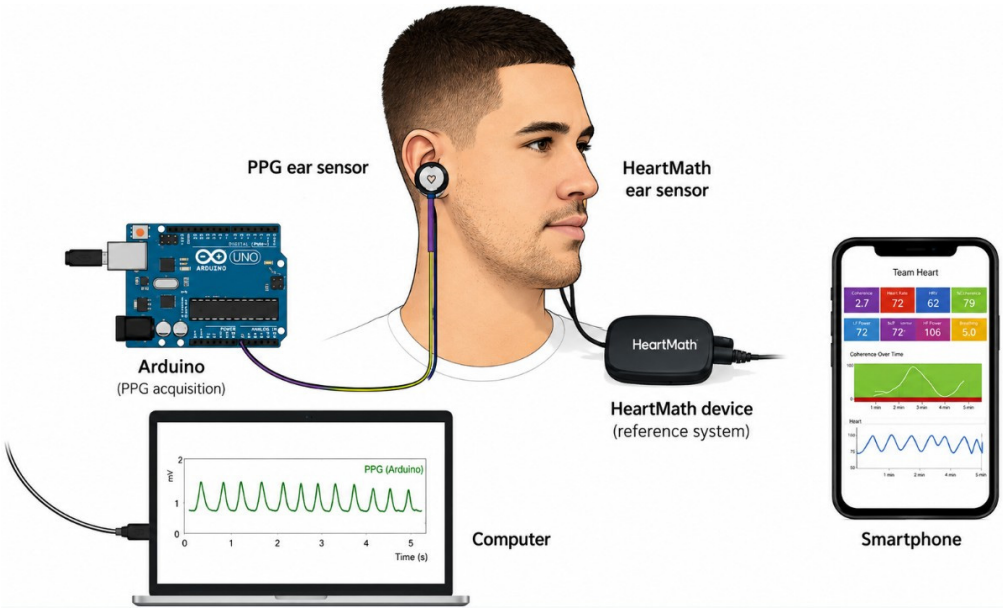


Figure 1. Proposed Arduino-based PPG PulseSensor recording system with Python visualization and a HeartMath device as a reference.

This dual-measurement setup enables direct comparison between the developed Arduino-based system and a validated commercial solution. As a result, the accuracy of the measured heart rate and the synchronization between heart-rate variability and breathing can be evaluated and verified.

https://doi.org/10.3390/engproc2026154031

The code flowchart for the Arduino system of Figure 1 consists of (1) real-time signal acquisition and beat detection on the Arduino (Figure 2, left image) and (2) higher-level processing and visualization in Python 3.12 (right image). On the Arduino (version 2.3.9) side, the process begins with acquiring the analog PPG signal from the pulse sensor. Once a valid beat is confirmed, detected above a certain pre-defined threshold, the system calculates the RR interval or the time between successive heartbeats, and the heart rate in beats per minute (BPM) is computed. The acquired data are transmitted to the host computer via serial connection. On the Python side, incoming serial data are parsed into their constituent components and then displayed as the raw waveform, RR intervals, and BPM. This enables continuous monitoring of heart-rate dynamics during rhythmic breathing. By separating time-critical signal processing on the Arduino from computationally intensive analysis and visualization in Python, the system achieves both efficiency and flexibility. *Plovdiv PPG Python Interface, software version 1* [Software created by the authors]. Available at: https://bit.ly/Plovdiv-PPG-Python-Interface (accessed on 23 August 2026).

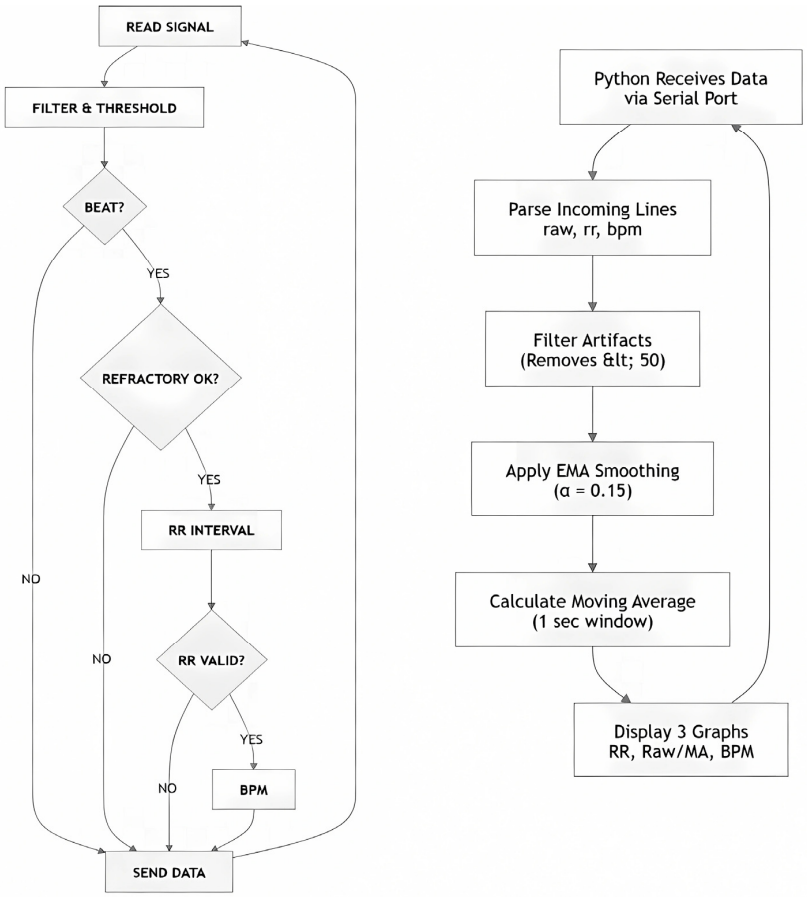


Figure 2. Flowcharts for PPG-Arduino recording system (to the (**left**)) and Python interface (to the (**right**)).

3. Results

As a HeartMath recording device was used at the onset of the project to investigate the impact of rhythmic breathing, the results obtained from five subjects over three minutes of 5s inhale and 5s exhale periods are presented in Figure 3a as follows: a screenshot of the HeartMath recording application, followed by the BMP over time in (b), and a box plot of all BMP values of all five subjects, truncated in three subsessions of one minute duration each. In conclusion, no statistically significant differences were observed among subjects. This result is attributed not to HeartMath purely tracking the time delay between

raw PPG and BMP over time, but to a complex Fast Fourier Transform performed in the background, which is not publicly disclosed. Alternatively, a simplified version of the open-source Python interface output is shown in Figure 3 as follows: the RR interval (the time between consecutive heartbeats), the raw PPG signal, reflecting pulsatile blood volume changes, and BPM, representing heart rate. The red vertical lines mark corresponding cycle events to enhance the optical visualization of time delays. In the next Figure 3e, the upgraded version of the Python application is shown, with added moving average to smooth the raw PPG signal, automatic detection of corresponding pairwise maxima of raw PPG and BMP over time, as well as the time delay between every two corresponding maxima, displayed in real time, as well as calculated average and standard deviation. This latest version of the Python interface, together with its Arduino counterpart, can be downloaded from https://bit.ly/Plovdiv-PPG-Python-Interface (6 June 2026). In image (f), time delays, estimated at the beginning and end of a recording session, are displayed as box plots for each of the five trial participants. Images (e) to (f) demonstrate the practicality of the proposed Python interface, as they reveal time-synchronization patterns in the raw PPG time synchronization of the BMP over time for each subject, which remain hidden in the commercial HeartMath device. The presence of this shared oscillatory pattern across all signals indicates a common underlying physiological rhythm.

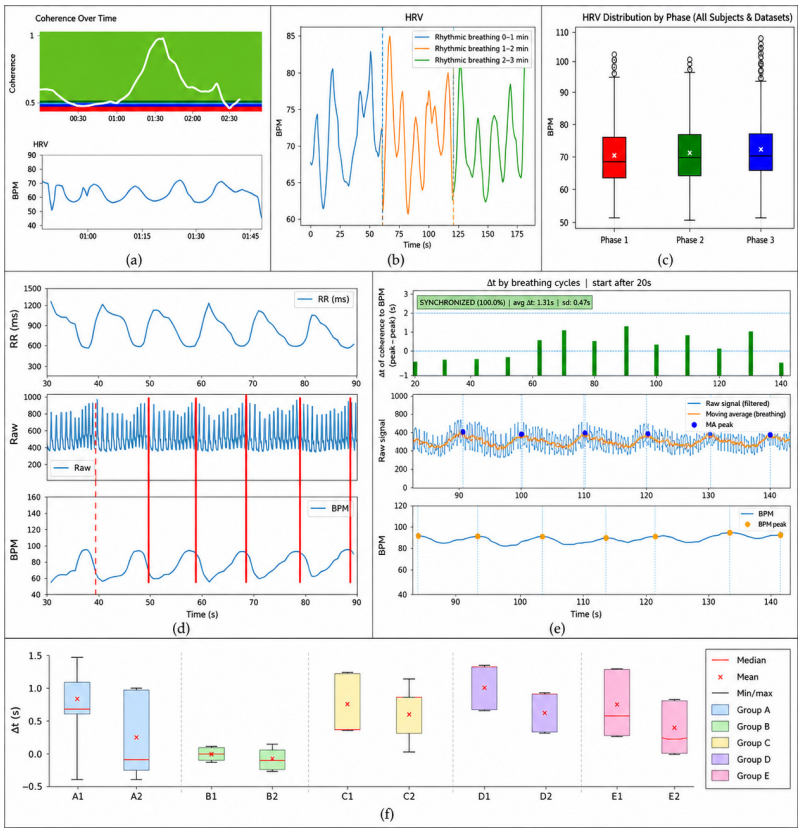


Figure 3. PPG-based HeartMath recordings (used as a reference): (**a**) screenshot of a HeartMath recording; (**b**) extracted HeartMath BMP data over time, divided into three sub-window sessions; (**c**) box plots of the BMP sub-window sessions; (**d**) proposed simplified Python version for tracking of peak synchronization in time between the raw PPG-data and the BMP over time; (**e**) upgraded Python interface version, including a moving average overlaid over the raw PPG values, automatic peak detection of both raw PPG and BPM over time, and a calculation of the time mismatch (temporal delay (Δt)) between raw PPG envelope wave and BPM over time; (**f**) box plots of Δt at the beginning and at the end of the recoding window session are displayed for each trial participant.

https://doi.org/10.3390/engproc2026154031

In summary, at the beginning of the recording, the signals are not perfectly aligned (as indicated by the dashed red line in Figure 3e). There is a noticeable delay between BPM peaks and the corresponding features in the PPG signal, indicating a relatively large temporal lag (Δt) and therefore weaker coupling between the physiological processes. As time progresses, the alignment between signals improves. Peaks in BPM become more closely synchronized with the modulation of the PPG signal, and RR oscillations follow the same rhythm more consistently. This reflects a gradual reduction in temporal delay and improved coordination across systems.

The key variable examined is the temporal delay (Δt) between the peaks of the raw PPG amplitude envelope and the BPM signal. Across all subjects, a consistent pattern emerges. As subjects begin to breathe rhythmically over a 10 s period, Δt decreases (Figure 3f). In the initial phase, the temporal delay is relatively large (ca. 2 s). Although both signals oscillate at similar frequencies, they are out of phase, indicating weak coupling between physiological systems. As time progresses, Δt gradually decreases, signal peaks shift closer together, temporal delay is substantially reduced, and the signals are nearly aligned. This indicates the emergence of synchronization (entrainment) between heart-rate dynamics and the PPG envelope. Such behavior is consistent with cardiorespiratory coupling, where respiration, blood pressure regulation, and heart rate interact through autonomic control mechanisms. Importantly, while all subjects exhibit a decreasing temporal delay, the extent of synchronization varies, indicating that coupling strength differs across individuals.

4. Discussion

The recorded cardiac data from rhythmic breathing exercises, despite the relatively small number of participants, the short duration of the trials, and the fact that most participants had no prior experience with rhythmic breathing, revealed a distinct temporal synchronization between heart rate and the raw PPG signal envelope representing the breathing sequence. Interestingly, some participants initially reported that the breathing pattern felt unusual or even mildly stressful; nevertheless, in nearly all subjects, a progressive synchronization effect was observed over time. This confirms the natural ability of the cardiovascular system to gradually align BPM oscillations with the breathing rhythm at 0.1 Hz (5 s inhale and 5 s exhale), similarly to the principles employed in the HeartMath approach, and helps explain why rhythmic breathing within this frequency range is widely practiced for stress reduction and emotional regulation within this platform [3]. As for the minimal subject size, HRV-related physiological markers are known to be highly sensitive even in relatively small participant groups [14], and many exploratory HRV studies have similarly been conducted in limited cohorts. Even two-person HRV trials have been published [15] to demonstrate the correlation between phone-based HRV and medical-grade ECG. Therefore, the present work should primarily be viewed as a proof of feasibility and methodological demonstration of the proposed open-source interface for real-time visualization and preliminary investigation of cardiorespiratory synchronization effects. Since these physiological synchronization phenomena are already well-established in the literature, the primary contribution of the present work is methodological: the development of a low-cost, accessible system for teaching, demonstration, and preliminary physiological investigations.

5. Conclusions

This work presents an open-source Arduino–Python platform for studying real-time heart-rate cyclic dynamics during the Hz rhythm. The specialty of the proposed platform's heart-rate feature lies in its ability not only to visualize BPM-over-time heart-rate rhythmic dynamics but also to align them with raw PPG signal and the subject's breathing, capturing

the dynamics' maxima. Although the fact is well-known, it is evident in commercially available heart-coherence systems, such as HeartMath. Furthermore, RR intervals, PPG signals, and BPM exhibit shared oscillatory behavior with increasing temporal alignment. This supports the presence of cardiorespiratory entrainment and highlights the role of autonomic regulation in coordinating cardiovascular dynamics. A progressive reduction in temporal delay (Δt) between PPG envelope and heart-rate peaks is observed across all subjects, indicating increasing phase alignment over time. The results support the proposed platform's applicability as an open-source tool for further research on optimal mental health.

Author Contributions: Conceptualization, E.M. and E.T.; methodology, E.M. and E.T.; software, E.M.; validation, E.M., S.M., A.K. and E.T.; formal analysis, E.M.; investigation, E.M.; resources, E.T.; data curation, E.M.; writing—original draft preparation, E.M.; writing—review and editing, S.M., A.K. and E.T.; visualization, E.M.; supervision, E.T.; project administration, E.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval were waived for this study because it involved non-invasive physiological measurements on healthy adult volunteers, posed minimal risk to participants, and was conducted for educational and research purposes. All participants took part voluntarily and provided informed consent prior to participation.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets generated during the current study are not publicly available because the research is ongoing but are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank the volunteers who participated in the experimental measurements. The authors also express their gratitude to the Faculty of Physics and Technology, University of Plovdiv "Paisii Hilendarski", for providing the facilities necessary for conducting this research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PPG	Photoplethysmography
HRV	Heart-Rate Variability
BPM	Beats Per Minute
RR	R-R Interval
EMA	Exponential Moving Average
Arduino	Arduino Uno Microcontroller Platform

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