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Respiration-Driven Closed-Loop Modulation of Binaural Beats

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Abstract:
Binaural beats (BB) have gained attention for their potential to entertain brainwave activity to favor relaxation. Current research on BB typically employs a static frequency difference (Δf), which may limit their adaptability to individual physiological states. Furthermore, existing systems do not incorporate real-time biosignals, thereby missing the opportunity to align auditory stimulation with the body's own dynamic physiological rhythms. This work presents a closed-loop system for real-time modulation of binaural beats based on respiratory activity. Unlike conventional approaches, the proposed method continuously adjusts the Δf according to the user's real-time respiratory biosignal. This design is motivated by the established role of breath control in the sympathovagal balance, relevant for relaxation and meditative practices. The system aims to enhance the effectiveness of BB through physiological alignment. Respiratory activity is acquired via a chest belt sensor and linearly mapped to a Δf range of 4–10 Hz, corresponding to relaxation-related brainwave frequencies in electroencephalography. The system has been implemented on a custom embedded platform, enabling low-latency signal processing and stable audio output. 10-minute functional pre-tests were conducted involving five healthy participants, and the results validated the proposed operational concept.

Keywords: *Binaural Beats, Binaural pulse modulation, Respiration, closed-loop system*

Introduction

Relaxation has been associated with a wide range of health benefits, including improved cardiovascular function, reduced stress levels, and enhanced cognitive performance [1]. In recent years, there has been increasing interest in non-pharmacological techniques to facilitate relaxation through neurophysiological modulation [2]. Among these, auditory stimulation via binaural beats (BB) has gained attention for its potential to entertain brainwave activity in specific frequency bands associated with mental states such as focus, meditation, or relaxation [3, 4].
BB are perceived when two pure tones of slightly different frequencies are presented separately to each ear. The brain detects the frequency difference (Δ*f*) and generates a third, perceived rhythmic beat, which can influence neural oscillations through a process known as auditory driving [3]. The effectiveness of BB in modulating cognitive and affective states has been explored in a range of studies, with particular emphasis on frequency ranges such as theta (4–8 Hz) and alpha (8–12 Hz), which are commonly linked to relaxed wakefulness and meditative states [3, 4, 5].
Despite their potential, most current implementations of BB systems rely on an open-loop principle with static parameters, typically applying a fixed Δ*f* throughout the session, irrespective of the listener's physiological state. This lack of adaptivity may limit their efficacy, especially when used for individualized relaxation or therapeutic purposes. Integrating real-time physiological feedback into auditory stimulation systems may offer a more responsive and effective approach [6].
Respiration presents itself as a particularly suitable biosignal for this purpose, as its depth and period are strongly related to the sympathovagal balance of the autonomic nervous system [7], closely coupled with the mental state. Controlled breathing is a fundamental component of meditative and mindfulness practices, and variations in respiratory amplitude and rhythm are known to influence the autonomic nervous system. Previous work has demonstrated the role of breath regulation in increasing vagal tone, improving heart rate variability, and enhancing subjective relaxation [8]. These characteristics make respiration a strong candidate for driving adaptive modulation in auditory neurostimulation contexts [1, 8].
This paper introduces a closed-loop system that dynamically adjusts the Δ*f* of BB in real-time according to the user's respiratory amplitude. The respiratory signal is mapped to a Δf range of 4–10 Hz. The system is implemented on a custom embedded platform, enabling real-time signal acquisition, processing, and audio synthesis with imperceptible latency. This approach leverages a closed-loop design to enhance the responsiveness of BB applications to the user's physiological state, aiming to induce a measurable relaxation response.

Material and Methods

This section describes the system components and methods for implementing the closed-loop BB prototype, covering the hardware and software architecture, including signal acquisition, processing, and audio output, as well as the functional test.

System Overview

The setup, illustrated as a block diagram in Fig. 1, shows the implementation of a closed-loop approach for modulating BB in real time based on the user's respiratory activity. It is composed of three main functional blocks: (a) a respiratory signal acquisition module, (b) a signal processing and mapping unit, and (c) a stereo signal generator.

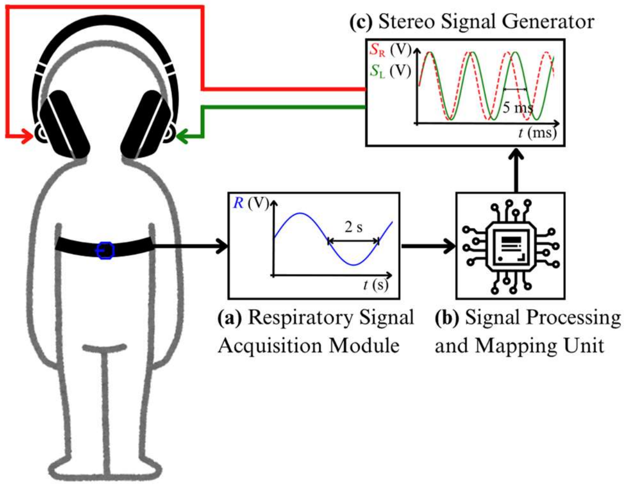

Figure 1: Setup Block Diagram.

Respiratory Signal Acquisition Module

Respiratory effort was measured using a Biopac SS5LB transducer connected to a Biopac MP36 acquisition system (Fig. 1a). The analog signal, proportional to thoracic expansion, was first conditioned by applying a DC offset of 0.75 mV to ensure positivity, and then amplified with a gain of 1000 to match the input range of the single-ended 12-bit Analog-to-Digital Converter (ADC) on the STM32 Nucleo H723ZG board. The resulting signal was well-centered and within a suitable voltage window for digitization, and was subsequently routed to the embedded unit for real-time processing.

Signal Processing and Mapping Unit

Signal acquisition and processing were managed by an STM32 Nucleo H723ZG evaluation module (Fig. 1b). The first operation performed by the processing unit was the sampling of the analog respiratory signal via the board's internal single-ended ADC. The signal was sampled at 80 Hz, a rate selected primarily to satisfy the system's low-latency requirement. Due to the low-frequency content of the respiratory signal, with dominant spectral content below 1 Hz [9], the chosen sampling rate easily meets the Shannon–Nyquist criterion, providing adequate temporal resolution for real-time control of BB without excessive computational load.

Upon system initialization, a 30-second calibration phase was performed to determine the minimum $R_{\min}$ and maximum $R_{\max}$ sample values of the respiratory signal. During the subsequent modulation phase, each new sample, denoted as R (i.e., the current sample representing the instantaneous respiratory effort), was normalized to the [0, 1] interval according to:

$$R_{\text{norm}} = \frac{R - R_{\min}}{R_{\max} - R_{\min}} \tag{1}$$

The normalized amplitude R_{norm} was then linearly mapped to a Δf range of 4–10 Hz, corresponding to the theta and low-alpha brainwave bands commonly associated with relaxation and meditative states, according to:

$$\Delta f = f_{\min} + R_{\text{norm}} * (f_{\max} - f_{\min}) \tag{2}$$

To simplify synthesis and enhance system stability, Δf was quantized with a resolution of 1 Hz, restricting values to discrete steps within the set {4, 5, ..., 10 Hz}. This choice of 1 Hz resolution also contributed to improved system robustness against signal noise.

Audio Signal Generation

The BB signal was generated in real time by producing two sinusoidal waveforms S_L (for left earphone) and S_R (for right earphone) sharing a joint base frequency f_0 of 110 Hz (Fig. 1c), with a variable Δf applied to only one channel as defined by Eq. 2.

These signals were converted to analog form using an external PCM5102 digital-to-analog converter, which provided high-resolution stereo output with low noise and minimal distortion. The analog audio was delivered to the user via over-ear stereo headphones. The sound pressure level was fixed at approximately 65 dB SPL, a value chosen to ensure perceptibility while minimizing auditory fatigue and avoiding amplitude-driven confounds [10]. To maintain a smooth listening experience, phase continuity was preserved during Δf transitions, preventing artifacts or abrupt perceptual shifts. An example of ideal Δf modulation is shown in Fig. 2.

Functional Testing

To evaluate perceptual latency, sound quality, and the continuity of the modulated audio signal, a 10-minute functional test was conducted involving five healthy participants. Each participant listened to the real-time audio output and was asked to report any noticeable delay, discontinuity, or discomfort associated with the auditory feedback. To introduce controlled variability, the test included both spontaneous breathing and guided phases with paced and alternating slow/fast respiratory rhythms.

Results

A fully functional prototype was developed, incorporating both auditory and visual feedback to monitor system behavior and validate real-time signal processing.

Fig. 3 shows a respiratory signal (blue) along with the current resulting value of Δf. User feedback from the functional testing confirmed that the system met real-time requirements under normal operating conditions. Participants consistently reported no noticeable latency and described the auditory output as continuous and free from discomfort. Notably, these results were consistent across different breathing conditions, indicating that the system provides perceptually seamless feedback in terms of responsiveness, signal continuity, and overall user comfort.

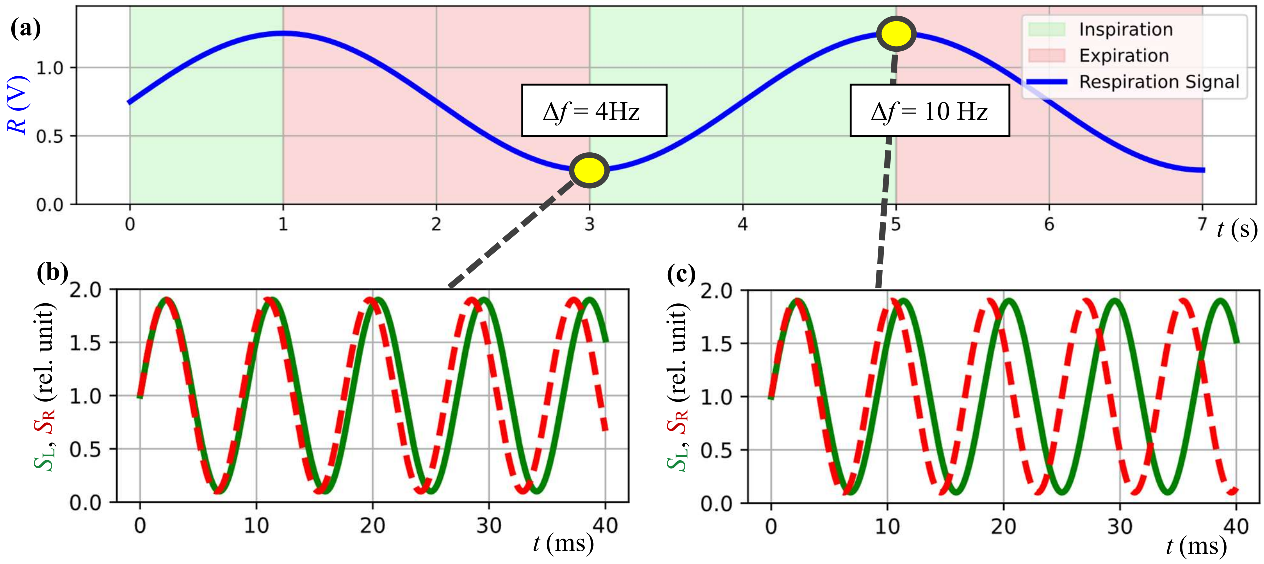

Figure 2: Example of BB modulation driven by respiratory signal amplitude. a) Respiratory waveform with inspiration and expiration phases. Two sample points indicate the smallest and highest amplitudes of the respiration signal R used to modulate the BB. b) BB corresponding to the smallest Δf. c) BB corresponding to the largest Δf.

Discussion

This work presents a closed-loop system for real-time modulation of BB based on respiratory activity. By dynamically adjusting the Δf in response to the user's breathing amplitude, the system aligns auditory stimulation with respiration patterns known to support relaxation.

Latency: To ensure a good user experience in a real-time feedback system, the latency is crucial. The delay between the respiration and the change of Δf is mainly determined by the sampling time of the respiratory signal, which is 12.5 ms according to the 80 Hz sampling frequency. Other factors like conversion and processing times have only a negligible impact (<0.5 ms). Increasing the sampling frequency could lead to a lower latency but also to the acquisition of higher-frequency components, which are more likely related to noise than to meaningful respiratory information. The current latency, as determined by the chosen sampling rate, has proven sufficient to ensure that feedback remains imperceptible to users.

Resolution of Δf: The current Δf resolution was sufficient to ensure robust system behavior and perceptually stable feedback during testing, but it may limit the smoothness of transitions in certain cases. Employing smaller step sizes could provide a finer modulation granularity, leading to more continuous auditory dynamics and potentially enhancing user immersion. However, this must be balanced against the risk of introducing increased sensitivity to noise in the respiratory signal.

Selection of the Biosignal: Respiration was selected due to its strong association with the autonomic nervous system and relaxation, with controlled breathing playing a key role in regulating physiological states. In addition, the respiratory signal is easily accessible, as its absolute value can be processed in real time without extensive preprocessing. This combination makes it a suitable choice for closed-loop biofeedback systems. Alternative biosignals such as electrocardiogram offer richer physiological information [9], but they typically require more advanced processing pipelines and may introduce additional latency and noise.

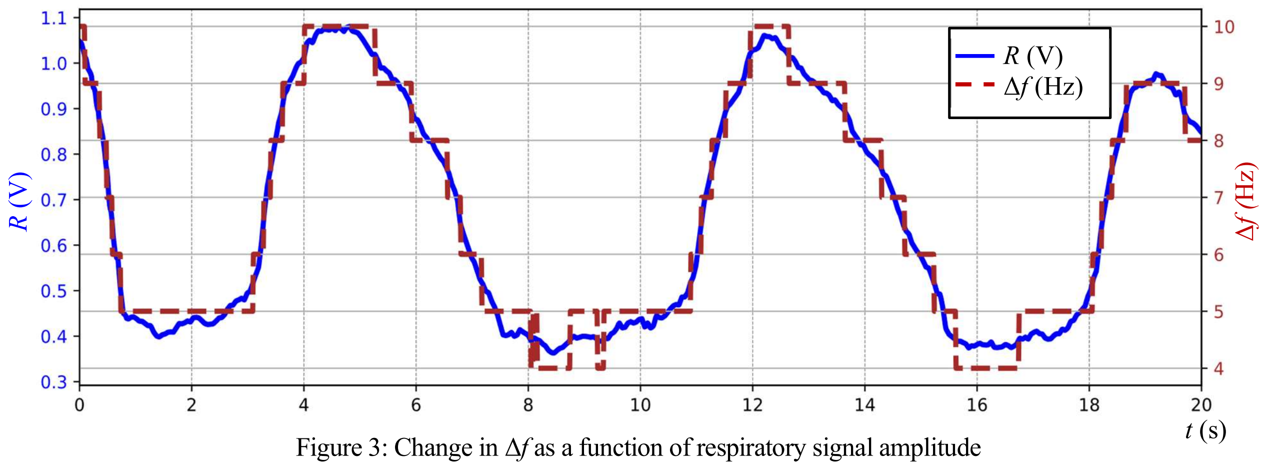

Figure 3: Change in Δf as a function of respiratory signal amplitude

Conclusions

The proposed implementation, based on a custom embedded platform, demonstrated low-latency performance and perceptually seamless feedback, as confirmed by preliminary user testing. Further research will focus on integrating heart rate variability measurements to evaluate the system's impact through statistical analysis. Signal modulation could also be expanded by varying the amplitude of S_L and S_R, as well as the base frequency f_0. Additionally, the system's flexibility opens avenues for incorporating alternative biosignals beyond respiration, potentially broadening its applicability across diverse neurophysiological contexts.

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References

[1] Selye, H. *The stress of life*. McGraw-Hill, 1956.

[2] El-Malahi O, Mohajeri D, Bäuerle A, et al. *The Effect of Stress-Reducing Interventions on Heart Rate Variability in Cardiovascular Disease: A Systematic Review and Meta-Analysis. Life*. 2024

[3] Kasprzak, Cezary. *Influence of Binaural Beats on EEG Signal*, Acta Physica Polonica A. 119. pp. 986-990, 2011

[4] *Foster, Dale S.. "EEG and Subjective Correlates of Alpha-Frequency Binaural-Beat Stimulation Combined with Alpha Biofeedback."* 2011

[5] McConnell, P.A., Froeliger, B., Garland, E. L., Ives, J.C., & Sforzo, G. A. *Auditory driving of the autonomic nervous system: Listening to theta-frequency binaural beats post-exercise increases parasympathetic activation and sympathetic withdrawal*. Frontiers in psychology, 5, 1248., 2014

[6] Merlin Kelly, Tom Carlson, Youngjun Cho. *Diving into Binaural Beat Meditation: An EEG-Based Evaluation of User Experience.* Authorea, 2025

[7] E. Kaniusas, Biomedical Signals and Sensors I, Berlin: Springer, 2012.

[8] Van Diest, I., Verstappen, K., Aubert, A.E. et al. *Inhalation/Exhalation Ratio Modulates the Effect of Slow Breathing on Heart Rate Variability and Relaxation.* Appl Psychophysiol Biofeedback 39, 171–180, 2014

[9] E. Kaniusas, Biomedical Signals and Sensors II, Berlin: Springer, 2015.

[10] M. Chockboondee, T. Jatupornpoonsub, K. Lertsukprasert and Y. Wongsawat, "Long and Short Durations of Binaural Beats Differently Affect Relaxation: A Study of HRV and BRUMS" in IEEE Access, vol. 11, pp. 84842-84851, 2023

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