# Entrainment of Autonomic Rhythms to Musical Structure: Re-Visiting and Extending Bernardi et al. (2009)

Natalia Cotic[1], Vanessa Pope[1,2], Michele Orini[1], Pier D Lambiase[1,3], Elaine Chew[1,2]

[1]School of Biomedical Engineering & Imaging Sciences, King's College London, UK
[2]Department of Engineering, King's College London, UK
[3]University College London and Barts Heart Centre, UK

## Abstract

*Bernardi et al. [1] saw that autonomic variables can synchronise with the music envelope, revealing the entrainment potential of musical structures. This study aimed to replicate their findings using current music information research and time-frequency analysis (TFC) methods and to extend the analysis to inter-physiological interactions. Continuous blood pressure (BP), electrocardiograms (ECG), and respiration were recorded from 24 participants (13 women, mean age 23.5[95%CI: 22.2–24.8]). The 12 choristers and 12 non-choristers, listened to excerpts from Verdi's La Traviata and Nabucco. Tempo and loudness were extracted from the music's beats and audios. TFC was computed for all signal pairs.*

*No significant group differences were seen in coherence, except for choristers' respiration–BP waveforms during Nabucco ($P<0.02$). Nabucco's musical features and systolic/diastolic BP had strongest coherence against surrogate data ($P<0.0005$). La Traviata showed weaker effects. Coherence between RR–diastolic BP and respiration–BP waveform was also significantly elevated during Nabucco versus silence ($P<0.05$). Visual inspection showed strong alignment between Nabucco's loudness and BP waveform envelopes. These results confirm Bernardi et al.'s findings and show that music entrains autonomic variables, suggesting a mechanism for music's effect on body rhythms.*

## 1. Introduction

Cardiovascular disease (CVD) is the leading global cause of death, accounting for approximately 32% of annual fatalities worldwide [2]. Amid growing interest in non-pharmacological strategies for managing cardiovascular health, music has emerged as a promising intervention. Music listening has been shown to modulate heart rate, respiration, and blood pressure [3–5], with potential therapeutic effects ranging from reduced pain and anxiety to improved cardiovascular fitness. Yet, the underlying mechanisms by which music exerts its physiological influence remain only partially understood, limiting its broader application in personalised or scalable medical interventions.

A seminal study by Bernardi et al. [1] observed that musical structure could elicit immediate and measurable effects on autonomic function. In their work, cardiovascular and respiratory responses were shown to "mirror" the dynamic features of music, with physiological variables such as blood pressure and skin vasomotion synchronising with changes in musical intensity (described as the music envelope). Importantly, this synchronisation—referred to as physiological entrainment—occurred independently of participants' subjective emotional responses or musical background. Particularly compelling was the finding that some of the strongest coherence between music and physiology occurred during vocal music by Giuseppe Verdi that contained phrases near 0.1 Hz (six cycles per minute), aligning with the natural frequency of Mayer waves—an autonomic rhythm associated with baroreflex control. These results suggest that specific temporal structures in music can entrain cardiovascular rhythms at a subconscious level, offering a potential mechanism for therapeutic modulation of autonomic function. However, while Bernardi laid the foundational groundwork, other studies have not replicated or validated these findings.

The present study aims to replicate Bernardi et al.'s with current methods, while expanding the analysis to include inter-physiological coherence (e.g., between respiration and blood pressure) in addition to music–physiology coupling. Participants listened to excerpts from *La Traviata* and *Nabucco*—the same operatic segments shown to induce strong autonomic entrainment in the original study—whilst continuous cardiovascular and respiratory signals were recorded. Coherence was assessed using time-frequency analysis methods, and group comparisons were made between choristers and non-choristers.

By confirming and extending the results of Bernardi et al., this study strengthens the empirical basis for using music for targeted cardiovascular intervention. Understanding

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how specific musical features entrain autonomic rhythms can inform the design of structured music-based therapies, with applications in hypertension, anxiety management, and broader cardiovascular care.

## 2. Methods

**Participants –** 24 participants (13 women, mean age 23.5 [95% CI: 22.2-24.8]) were chosen to match the Bernardi population characteristics, with 12 being choristers and 12 non-choristers. The same music recordings were used as in [1], specifically the two Verdi opera selections which showed strong coherence results, *La Traviata* and *Nabucco*. The participants would first complete a questionnaire with their demographic data and reduced Goldsmiths Music Sophistication Index (MSI) to assess their music knowledge (to be used in future work to assess their influence on physiological responses). A participant's listening session comprised of 5 minutes of initial baseline silence followed by "Libiam nei lieti calici" from *La Traviata* performed at the Royal Opera House (Decca 1995), followed by 2 minutes of silence, then "Va Pensiero" from *Nabucco* performed by Berlin State Opera Chorus (DG 1984) and ended with another 5 minutes of endline silence.

**Physiological Measures –** Physiological signals were recorded whilst the participants listened to the tracks and silences. Synchronised electrocardiographic (ECG) and respiration signals were collected via the heartfm mobile app [6]. ECG data was collected using a Polar H10 heart rate sensor which measures the continuous electrical impulses generated by the heart, sampling at 1000Hz. The RR intervals (time between two adjacent R peaks on the ECG signal) were automatically extracted from the ECG signal using the in-built software of the device, which also downsampled the ECG to 130Hz before identifying the R peaks. The resulting signals were manually corrected by checking them against the ECG recording and removing or adding R peak markers as needed. Respiratory signals were obtained from a BIOPAC respiration belt that captures changes in participants' thoracic circumference. The signal was sampled at a frequency of 13Hz. The respiration data was de-trended through a rolling average, followed by a 4th order Butterworth filter and 1Hz cutoff frequency to remove noise. These steps ensured the data was cleaned without affecting the morphology and natural structure of breathing patterns. Continuous blood pressure (BP) readings were obtained using a CNAP 500 monitor. The data included the BP waveform, separate diastolic and systolic readings, and the heart rate; all were used in the analysis. To synchronise the blood pressure readings which came from a different device, participants were asked to squeeze the hand being monitored, creating a spike in the data. Data prior to the squeeze was removed, synchronising the physiological signals. To segment the data into tracks corresponding to the silence and the music, timestamps from the app which recorded each track's start and end were used to cut the signal into separate files with each track's individual data. The time axis was offset to start from zero for all files following segmentation. For consistency, all signals were placed on a common time axis by track and interpolated to 4Hz, matching the process documented in Bernardi et al. Loudness, in sones, was derived from the audio waveform of the music recordings using the MATLAB MA Toolbox [7]. The tempo was derived from manual beat annotations by members of the team. Music envelopes were extracted by applying the Hilbert transform on the music audio, producing smooth continuous frequency-independent envelopes.

**Analysis –** Following the pre-processing steps, the time-frequency coherence using the smoothed pseudo-Wigner-Ville distribution [8,9] was utilised to compute the correlation between signals in the frequency domain while keeping the tracks' time axes. The parameters for the function were chosen following optimisation and referring to the standard values used for this analysis type. For the silence segments, the coherence was computed between the physiology-to-physiology pairs. For the music tracks, coherence was also computed between the music signal (loudness or tempo) and physiology to observe how the autonomic nervous system was influenced by the external music stimuli. For the statistical testing of the music-physiology analysis, surrogate data was created by concatenating each individual's physiological data for the entire recording excluding the current track. This was done because everyone has a unique reaction pattern and using their own data accounts for this. Following concatenation, segments matching the length of the analysed music signal were chosen from the different surrogate variables. The coherence analysis was run between the music and each surrogate physiology 1000 times for every participant. The real and surrogate results were then compared to calculate the statistical significance. The analysis was done for the entire cohort and separately by the chorister/non-chorister groupings to see if there are identifiable differences.

## 3. Results & Discussion

**Entrainment to Music Profile –** Increased coherence, denoting entrainment, is observed in areas exhibiting large changes in the envelope. This effect is more pronounced in the *Nabucco* selection, seen in Figure 1 compared to the *La Traviata* selection, shown in Figure 2. The same trend can be seen visually on the colour map of the coherence plots between *Nabucco*'s loudness and physiology in Figure 3, where significant coherence occurs around the time of regions with rapid, localised impulses which are shown in the music envelope in Figure 1 (bottom graph).

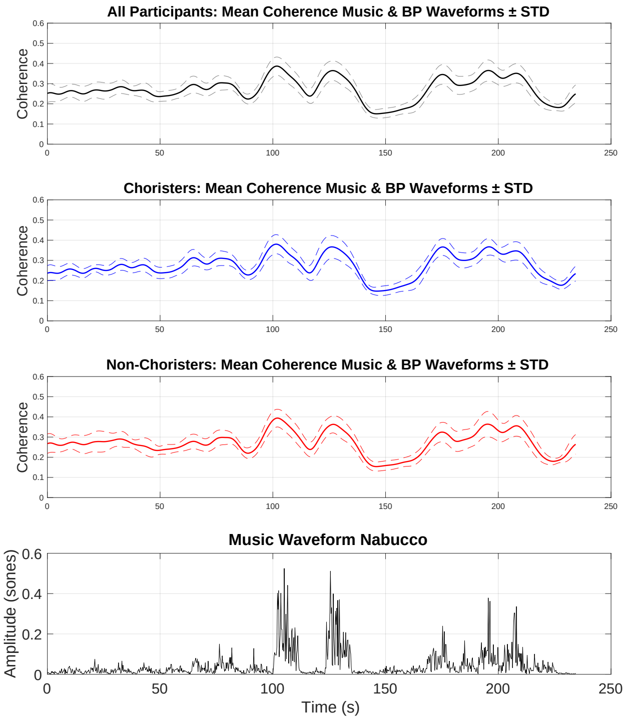


Figure 1: Mean coherence between loudness - BP waveform for all participants, and by chorister/non-chorister groupings for *Nabucco*. Influence of the music envelope can be seen throughout the resulting coherence curve.

Across the entire cohort and the chorister/non-chorister groupings, there are differences between the mean coherence for the silence vs the music tracks for the inter-physiology pairs. This shows that compared to a baseline state, the music influences the way that the body's signals interact one with another. Running paired t-tests between each silent segment and the music tracks show that there is statistical significance between some pairs ($P<0.05$) : RR intervals - diastolic BP (specifically during *Nabucco*). Other pairs approach significance (respiration - BP waveform, RR intervals - systolic BP) during both music tracks.

Bonferroni correction was applied to the data; considering the 6 tests ran per track and music feature, the new significant p-value was 0.008. After 1000 iterations for the surrogate data, comparing the two sets for the loudness/tempo-physiology pairings, it is observed that both music features have significant effect on the BP components (diastolic and systolic) with tempo ($P<0.0005$) leading to higher significance than loudness ($P<0.006$). The tempo has a similar effect on the RR intervals ($P<0.003$). The real data has higher coherence values than the surrogate showing that the response is not due to chance and it is directly influenced by the music track to which the participants were listening.

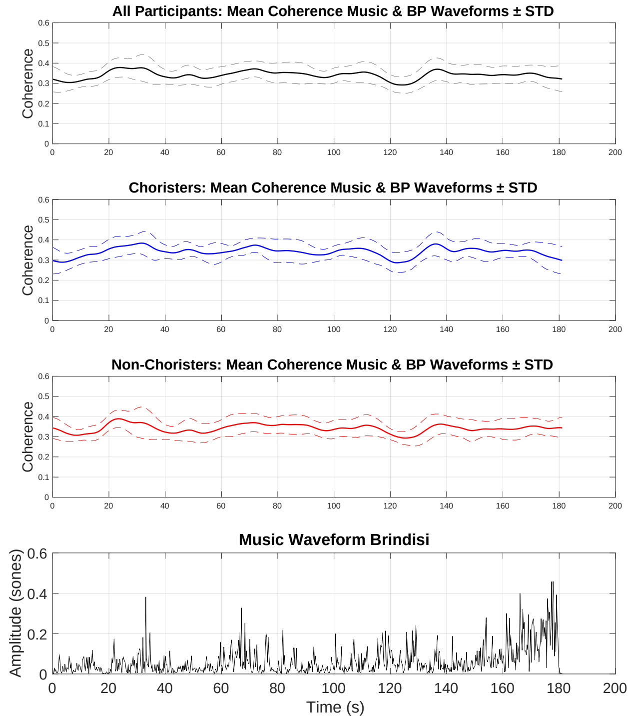


Figure 2: Mean coherence between loudness - BP waveform for all participants, and by chorister/non-chorister groupings for *La Traviata*. Some influence of the music envelope seen in parts of the signal.

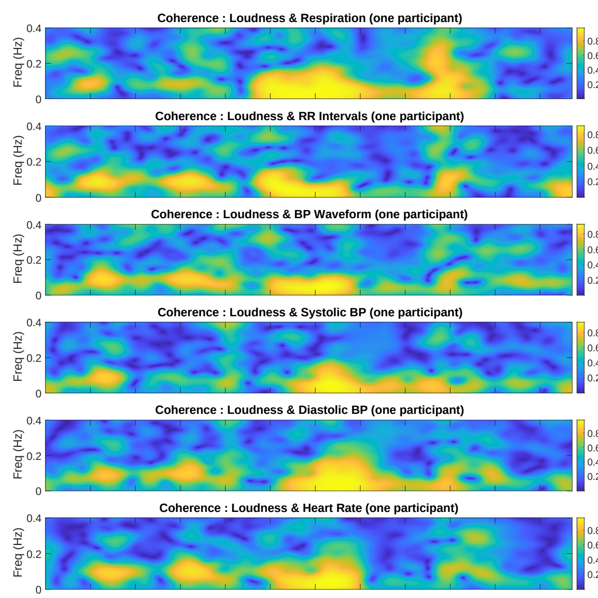


Figure 3: Coherence between loudness-physiology for a participant during *Nabucco*. Increased coherence (light blue to orange) seen around regions with rapid, localised changes (seen in clustered envelope peaks) in bottom subplot of Figure 1, corroborating the hypothesis of music's ability to entrain physiology.

**Group Differences –** While some numerical differences were seen between the chorister/non-chorister groupings, they were not statistically significant. The exception was between the respiration-BP waveform pair for the *Nabucco* track (P<0.02), where the choristers showed higher mean coherence across the track compared to the non-choristers. Choristers also showed increased entrainment between respiration-RR intervals during the track versus during the silence for *Nabucco* (P<0.01). Non-choristers showed significance for the coherence between respiration - heart rate (P<0.03) for the *La Traviata* segment. With the current analysis it can be seen that for *Nabucco*-which has more well-defined vocal parts and greater, localised changes in the music envelope, the physiological responses are more synchronised with the music. The *La Traviata* track does not exhibit such structured modulations, resulting in less dynamic responses. Further analysis will be carried out on phase differences between reactions to see if there are differences in response speed to music changes between the two groups.

## 4. Limitations & Future Work

We acknowledge that the current study was limited to only a specific music genre however, this replicated the music tracks selected for use in the paper we are validating. Other tracks were used in [1]; for this analysis, only the two tracks which showed significant results in [1] were used to test the hypotheses. Despite the limited cohort size and demographics, the results closely matched those reported in [1]. The analysis methods are not identical to the ones in the original study, especially the statistical analysis; this is partly due to the use of our own methods for validation. However, the results are consistent across the different approaches.

Future work will aim to incorporate information on musical training and personal taste from the questionnaire that all participants completed to investigate the effect of these potentially confounding variables on observed responses. Phase difference analysis will also be developed to study possible differences in reaction speeds between the chorister/non-chorister groups to the musical stimuli.

## 5. Conclusion

This study confirmed that autonomic responses do synchronise with musical structures, corroborating the observations reported in [1] and supporting the potential for music structures to be used as a tool to shape autonomic variables. Physiological signals, predominantly blood pressure derived measures, closely track the music parameters (loudness and tempo) and follow the music envelope. There are no significant differences observed between the choristers/non-choristers groups. Verdi's *Nabucco* led to the highest coherences between physiology and music (P<0.0005). Using computational tools and coherence analysis we also explored the music induced inter-physiology changes.


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## References


[1] Bernardi L, Porta C, Casucci G, Balsamo R, Bernardi NF, Fogari R, Sleight P. Dynamic interactions between musical, cardiovascular, and cerebral rhythms in humans. Circulation June 2009;119(25):3171–3180. URL `http://dx.doi.org/10.1161/circulationaha.108.806174`.

[2] WHO. Cardiovascular diseases, Jun 2021. URL `https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)`.

[3] Koelsch S, Jäncke L. Music and the heart. European Heart Journal 9 2015;36(44):3043–3049. URL `http://dx.doi.org/10.1093/eurheartj/ehv430`.

[4] Kulinski J, Ofori EK, Visotcky A, Smith A, Sparapani R, Fleg JL. Effects of music on the cardiovascular system. Trends in Cardiovascular Medicine 8 2022; 32(6):390–398. URL `https://doi.org/10.1016/j.tcm.2021.06.004`.

[5] Mandel SE, Hanser SB, Secic M, Davis BA. Effects of music therapy on health-related outcomes in cardiac rehabilitation: A randomized controlled trial. Journal of Music Therapy 9 2007;44(3):176–197. URL `https://doi.org/10.1093/jmt/44.3.176`.

[6] Chew E, Fyfe L, Picasso C, Lambiase P. Seeing music's effect on the heart. European Heart Journal 2024;.

[7] URL `https://www.ofai.at/~elias.pampalk/ma/documentation.html`.

[8] Martin W, Flandrin P. Wigner-ville spectral analysis of nonstationary processes. IEEE Transactions on Acoustics Speech and Signal Processing 1985;33(6):1461–1470.

[9] Flandrin P. Time-frequency/time-scale analysis, volume 10. Academic Press, 1998.



Address for correspondence:

Natalia Cotic
Becket House, 5th Floor, 1 Lambeth Palace Road, London, SE1 7EU, United Kingdom
natalia.cotic@kcl.ac.uk