Identifying Music-Cardiovascular Change Point Associations for Targeted Micro-Interventions

Mateusz Soliński[1], Vanessa Pope[1], Pier Lambiase[2], Elaine Chew[1]

[1] Department of Engineering and School of Biomedical Engineering Imaging Sciences, King's College London, London, UK
[2] Barts Heart Centre St Bartholomew's Hospital, London, UK

Abstract

Understanding how music shapes cardiovascular and respiratory activity requires identifying the body's reactions to expressive changes in music. This study aims to link acoustic variations in musical expression with those in the corresponding physiological signals to reveal how the body adapts to music's time-varying structures. Synchronised musical and physiological data were collected from 112 participant during a 5-minute baseline and 40-minute listening session covering 9 recorded performances. A total of 755 musical change points were extracted from the audio/MIDI signals and expert annotations. Physiological change points in the respiration, RR interval, and BP time series and the HRV spectra were converted into continuous data streams using Gaussian kernels. Canonical Correlation Analysis (CCA) identified maximally correlated pairs of canonical variates. The first two pairs showed significant correlations, 0.53 and 0.38. High loadings ($> |0.5|$) linked Novel Melodies and tempo changes with increased respiratory frequency, and loudness/energy with reduced RR intervals. Baseline autonomic activity was found to be an important factor in determining listeners' responses to music. These findings indicate that local music events can act as targeted micro-interventions, shaping cardiovascular variables and supporting personalised, music-based theranostic strategies.

1. Introduction

Music-based interventions offer a safe but underexplored complement to cardiovascular therapies; their effectiveness depends on understanding how music shapes the body's responses. Physiological reactions are not uniform across an entire piece of music but are driven by changes in expressive features, ranging from basic elements such as loudness, tempo, and timbre to higher-level constructs like novelty or melodic significance. These expressive changes create identifiable acoustic or interpretable change points that act as "micro-interventions," briefly shifting physiological signals away from their steady state of allostatic regulation [1]. Capturing and analysing these moments offers a systematic way to reveal how music interacts with cardiovascular and respiratory dynamics. The present study applies this change point perspective to link expressive musical events with physiological reactions using canonical correlation analysis (CCA), providing a window into how the body reacts to music.

2. Methods

2.1. Data collection & processing

Data was collected in the HeartFM study, where participants listened to nine expressive versions of eight Western classical pieces rendered on a reproducing piano. Performances included original and altered (louder, faster, or both) versions to test the effects of tempo and loudness. A description of the study can be found in [2]. Physiological monitoring included ECG (Polar H10 sternum strap, Polar Electro Oy, Finland) and respiration (BIOPAC belt, BIOPAC Systems, USA) recorded concurrently and visualised with bespoke HeartFM software [3]. Continuous blood pressure was measured with CNAP (CNSystems, Germany) finger cuffs, yielding systolic, diastolic, and pulse pressure values on a heartbeat-to-heartbeat basis. Musical stimuli were simultaneously captured with a H5 Zoom handy recorder and aligned with MIDI files to allow for precise extraction of acoustic features. From these signals, we derived loudness, tempo, harmonic tension diameter, spectral centroid, and mel-frequency cepstral coefficients (MFCC) as descriptors of timbre. These musical and physiological data streams were synchronised to examine the expressive musical structure and cardiorespiratory dynamics.

All physiological signals were resampled to 5 Hz before analysis. RR intervals were high-pass filtered (Butterworth, 0.03 Hz) and used to compute time-varying HRV spectra via short-time Fourier transform. From these, low- and high-frequency peak values (F_{LF}, F_{HF}) and power (P_{LF}, P_{HF}) were derived, with HF ranges adapted dynamically to respiratory frequency following Orini et al. [4]. Respiratory intervals were extracted from detrended, low-pass filtered belt signals and manually verified. Baseline RR intervals were further analysed in Kubios HRV to compute parasympathetic (PNS) and sympathetic (SNS) indices, based on established HRV parameters. k-means clustering of these indices stratified participants into three autonomic groups: PNS-dominant, balanced, and SNS-dominant. The resulting preprocessed and clustered data streams formed the basis for linking musical features with cardiovascular and respiratory dynamics.

2.2. Change point detection

We define change points as abrupt shifts or transitions in the statistical properties of a time series [5] and detect them in continuous musical and physiological signals. To detect them, we developed a framework combining parametric (*cpt.mean()*) and non-parametric (*cpt.np()*) methods from R packages, selecting points that were most consistently identified across parameter settings. In parallel, two experts manually annotated expressive musical events, forming Interpretation Maps with 16 categories (e.g. Novel Melody, Release, Standout Articulation). These annotations captured structural and prosodic features likely to influence listeners' physiology. Musical change points were transformed into a time series by placing Gaussian kernel functions (GKF) at each onset. For physiological signals, the final GKF series was obtained by averaging the individual GKFs over all participants who listened to the piece. These time series served as inputs for the CCA.

2.3. Canonical correlation analysis

CCA was used to identify relationships between musical and physiological change point time series. CCA reduces high-dimensional data by extracting pairs of canonical variates that maximise correlation between linear combinations of musical (X) and physiological (Y) variables. The first canonical correlation (ρ_1) reflects the strongest shared variability, while subsequent pairs are orthogonal and explain additional covariance. This method enables simultaneous testing of multiple relationships while avoiding multiple-comparison pitfalls and highlights the key musical features most strongly linked to cardiovascular and respiratory changes [6]. Interpretation of CCA results focuses on canonical loadings, i.e., correlations between original variables and canonical variates, which indicate the contribution of each variable to the shared response. High positive or negative loadings reveal variables that covary or act in opposition across the two domains. For continuous features like loudness and tempo, loadings indicate directional trends, whereas loadings of manually annotated events like novel melody and climax signify the direction of the physiological response associated with their onset.

3. Results

The study included 112 participants, comprising 63 females and 49 males, with a mean age of 43.9 $\pm$ 16.0 years (21–79). Based on baseline RR-derived PNS/SNS indices, three autonomic clusters were identified: cluster 1 with high baseline PNS/low SNS (n=20), balanced cluster 2 (n=73), and cluster 3 with high baseline SNS/low PNS (n=19). Elevated baseline blood pressure was observed in 25 participants (22%). The total number of change points obtained for analysis, after excluding categories with less than 15 change points over all pieces, was 755. The number of change points found is shown in Table 1.

Surrogate analysis using randomly chosen onsets instead of actual change points showed that the first two canonical variates of the CCA exhibited significant correlations, either considering the whole study group or separate clusters. The values of the canonical correlation are shown in Figure 1. The analysis and interpretation of the loadings obtained are presented in Figure 2. The results for the entire study group show two distinct patterns of association between musical and physiological variables: one related to respiratory dynamics and the other to RR interval modulation. In the first variate, the strongest loadings were observed for respiratory intervals (–0.58) and F_{LF} (–0.73) among physiological measures, paired with novel melody (0.76) and tempo (0.71) among musical features. This pattern suggests that the emergence of a novel melodic idea or an acceleration in tempo was accompanied by shortened respiratory intervals, a shift in respiratory sinus arrhythmia toward higher frequencies, and a reduction in P_{HF} (–0.52), consistent with parasympathetic withdrawal under conditions of novelty or heightened musical intensity. The second variate was characterised by high negative loading for P_{LF} (–0.74) and a positive loading for harmonic tension diameter (0.64).

3.1. Differences between PNS/SNS clusters

The analysis showed that baseline autonomic balance strongly shaped how participants responded to musical structures. Participants with high PNS and low SNS activity (Cluster 1) displayed responses consistent with PNS modulation: the appearance of a Novel Melody (0.76), along with increases in tempo (0.56) and timbral change, MFCC (0.49), was associated with lengthened RR intervals (0.61), reflecting a more adaptive, vagal-driven pattern. In contrast, those with high sympathetic activity (Cluster 3) showed the opposite trend. In this group, increases in loudness (0.75), tempo, MFCC, and spectral

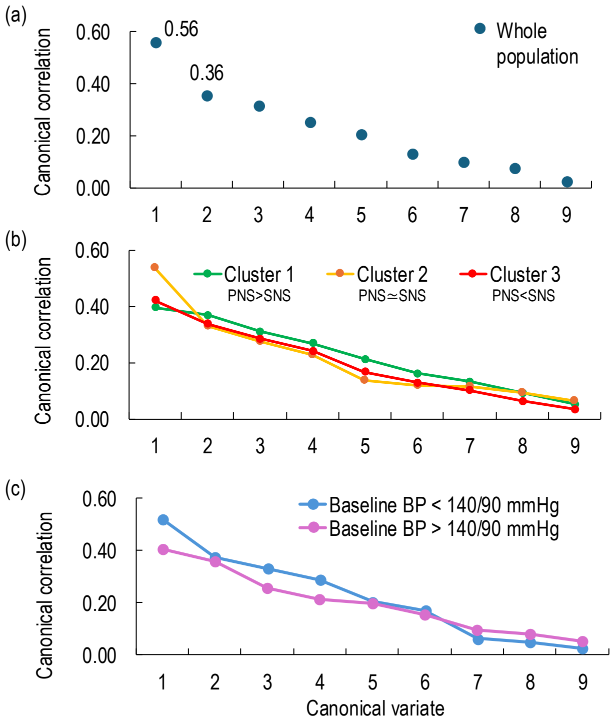

Figure 1. Canonical correlations obtained for each canonical pair (variate) ordered by absolute magnitude for (a) the entire study group, (b) the baseline PNS/SNS clusters, (c) the baseline BP groups.

centroid were coupled with shortened RR intervals (–0.63) and reduced high-frequency HRV power, P_{HF} (–0.66), suggesting sympathetic activation and/or reduced vagal influence. Interestingly, Novel Melody had only a weak effect in this group (0.37), indicating that structural novelty did not override the dominance of intensity-driven responses. The largest group of participants, with balanced autonomic profiles (Cluster 2), exhibited patterns similar to the overall study population.

3.2. Canonical correlations BP-based groups

Both normal and elevated baseline BP groups showed similar interactions between musical features and respiratory patterns. In the first canonical variate, novel melody [0.76, 0.71] and tempo were coupled with reductions in respiratory frequency [F_{LF} –0.65, –0.81], indicating that novelty and intensity consistently influenced breathing regardless of BP. Group differences appeared in the second variate. In the normal BP group, loudness (0.59) was linked with reduced low-frequency HRV power [P_{LF} –0.75], whereas in the elevated BP group, the strongest loadings were for harmonic tension diameter (0.71), return (0.54), and P_{LF} (–0.51). Direct BP measures contributed little in either group (all loadings <0.43).

Table 1. Change point types and number detected, automatically (A) or manually (M), over all music recordings.

Category	N (%)	A or M
Tempo	156 (20.7%)	A
Loudness	152 (20.1%)	A
Spectral centroid	79 (10.5%)	A
MFCC	39 (5.2%)	A
Diameter	94 (12.5%)	A
Significant Melody	71 (9.4%)	M
Novel Melody	44 (5.8%)	M
Return	32 (4.2%)	M
Melodic Interaction	25 (3.3%)	M
Standout Articulation	25 (3.3%)	M
Run/fast Sequence	19 (2.5%)	M
Resolve/Release	19 (2.5%)	M
Total	755	

4. Discussion

This study identified distinct associations between musical and physiological change points during expressive music listening. CCA proved valuable by capturing multivariate patterns of interaction beyond simple mean comparisons, highlighting how specific musical structures, rather than global averages, shape physiological responses. Across the group, the most consistent effect was shorter respiratory intervals and F_{LF} in response to novel melody and increases in tempo or loudness, confirming a close link between novelty, intensity, and breathing dynamics. These results align with earlier work showing synchronisation between musical crescendos and cardiovascular rhythms [7].

A key finding is that responses to music were determined by listeners' baseline autonomic balance. The relative levels of parasympathetic and sympathetic activity shaped how physiological systems adapted to expressive changes, indicating that baseline PNS/SNS indices act as a moderator of music–physiology interactions. In contrast, baseline blood pressure appeared to have only a minor influence. These findings suggest that resting autonomic balance determines both the direction and magnitude of responses to expressive music, with change points acting as micro-interventions eliciting either parasympathetic or sympathetic modulation.

Limitations include reliance on expert annotations, the focus on Western classical music, and the lack of cardiac patient participants. Nevertheless, the use of original and altered performances adds ecological validity. Future research could extend this approach to patient populations, where autonomic state may help predict who benefits most from music-based interventions.

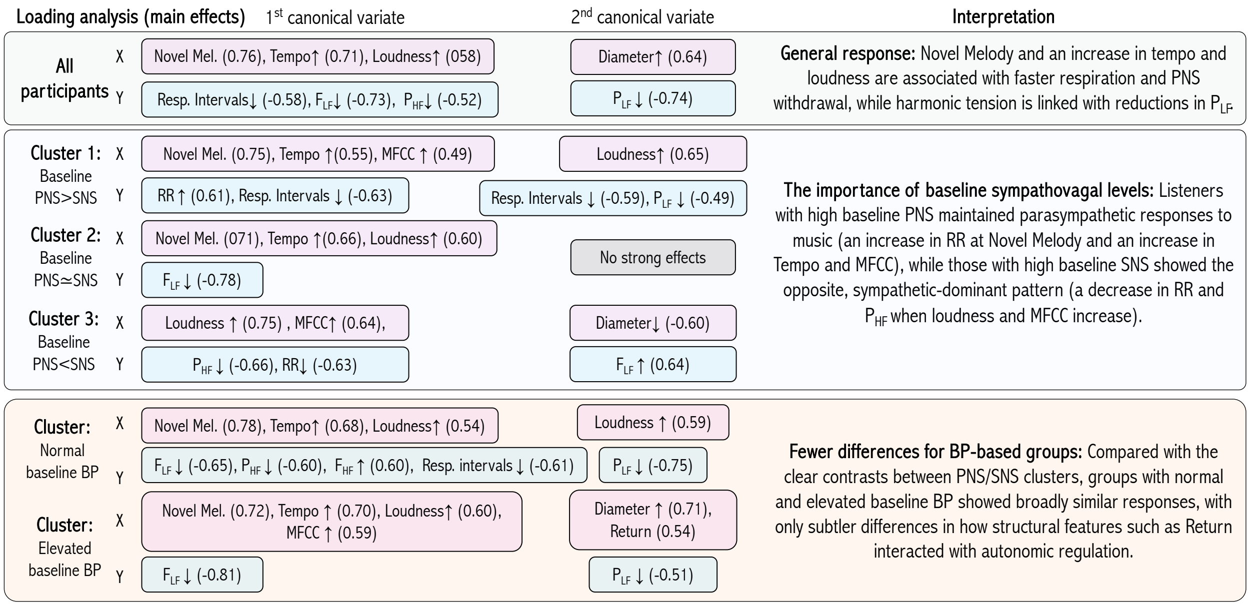

Figure 2. The main effects observed in the Canonical Correlation Analysis based on the canonical loadings for the whole study group and for separate PNS/SNS clusters, together with the key observations for each sub-analysis.

5. Conclusions

The use of the CCA enabled a systematic analysis of music and physiologic data, linking the variables to distinct co-varying or diametrically opposing combinations. This provided insights into the common effects of musical change points between groups, mostly related to respiratory patterns with the expressive categories: Novel Melody, loudness and tempo. Such insights are not only vital for advancing our knowledge of human health but can potentially guide the use of targeted non-invasive therapeutic options. For this, analyses taking into account different clinical patient subgroups are needed as a next step.

Acknowledgments

This result is part of the COSMOS and HEART.FM projects, which have received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement Nos. 788960 and 957532).

Charles A. Picasso developed the heartfm mobile and desktop visualisation applications used for data collection. Poulomi Pal, Courtney Reed and Natalia Cotic also contributed to data collection and segmentation.

References

[1] Reybrouck M, Podlipniak P, Welch D. Music listening and homeostatic regulation: Surviving and flourishing in a sonic world. International Journal of Environmental Research and Public Health December 2021;19(1):278.

[2] Pope VC, Soliński M, Lambiase PD, Chew E. High blood pressure inhibits cardiovascular responsiveness to expressive classical music. Scientific Reports March 2025;15(1).

[3] Chew E, Fyfe L, Picasso C, Lambiase P. Seeing music's effect on the heart. European Heart Journal March 2025; 45(41):4359–4363.

[4] Orini M, Bailón R, Enk R, Koelsch S, Mainardi L, Laguna P. A method for continuously assessing the autonomic response to music-induced emotions through HRV analysis. Medical Biological Engineering Computing March 2010; 48(5):423–433.

[5] Killick R, Fearnhead P, Eckley IA. Optimal detection of changepoints with a linear computational cost. Journal of the American Statistical Association October 2012; 107(500):1590–1598.

[6] Wang HT, Smallwood J, Mourao-Miranda J, Xia CH, Satterthwaite TD, Bassett DS, Bzdok D. Finding the needle in a high-dimensional haystack: Canonical correlation analysis for neuroscientists. NeuroImage August 2020;216:116745.

[7] 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.

Address for correspondence:

Mateusz Soliński
King's College London, Strand, WC2R 2LS, London, UK
mateusz.solinski@kcl.ac.uk