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The origins of embodiment: Behavioral and cardiovascular responses to music in very preterm newborns

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Abstract

Music perception in newborns is predominantly investigated through brain-based data, while the role of physiological and bodily responses remains underexplored. This study addresses this gap by assessing behavioral and physiological responses to music in clinically stable preterm newborns. Twenty-three very preterm newborns (born before 32 weeks of gestation) were recruited and allocated to either a Music group (n = 12) or a Control group (n = 11). Only infants in the Music group were exposed to a 6-minute musical excerpt composed specifically for the study by Andreas Vollenweider. Combining precise cardiovascular measures with a fine-grained behavioral coding system - the System for Coding Perinatal Behavior (SCPB), we examined the embodied dimensions of musical perception at the beginning of extrauterine life.

During the test phase, infants in the Music group showed reduced distress and fewer eye blinks compared to the pre phase, whereas no comparable changes were observed in the Control group. Hand movement rates were overall lower in the Music group during the pre and test phases, although group differences were no longer present in the post phase. Cardiorespiratory coupling was higher in the Music group during the pre and test phases but did not differ between groups in the post phase. Importantly, parasympathetic indices (HF power and RMSSD) increased specifically in the Music group during the post phase, while remaining stable across phases in the Control group. Overall, the results suggest immediate behavioral modulation during exposure and a subsequent increase in parasympathetic activity following music listening.

These findings provide new insights into the organization of perception in preterm newborns and underscore the importance of integrating bodily and autonomic responses into the study of early music perception. Adopting such

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an embodied perspective may advance our understanding of how music contributes to early perceptual development in fragile neonatal populations.

Keywords: behavioral coding; embodied perception; music perception; parasympathetic activity; preterm newborns

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Introduction

In recent decades, increasing attention has been paid to how newborns perceive complex sounds and music, with most studies relying on brain-based measures such as EEG and fNIRS (Mahmoudzadeh et al., 2017). While these approaches provide valuable insights, they often overlook the contribution of biobehavioural responses. Music perception is inherently multimodal and embodied (Leman & Maes, 2014; Phillips-Silver & Trainor, 2007): beyond the auditory system, it involves autonomic regulation, motor responses, and affective engagement. Investigating these dimensions in early development is essential to understanding how music supports perceptual, emotional, and regulatory processes from the very beginning of life.

Preterm newborns represent a particularly relevant population for this line of inquiry. Born before full maturation of sensory and regulatory systems, they can be described as fetuses developing in an extrauterine environment, where their perceptual experience is shaped both by ongoing neurophysiological maturation trajectories and by the novel sensory inputs encountered outside the womb (Lahav & Skoe, 2014); within this context, they present specific fragilities that make them particularly sensitive to environmental influences. Preterm birth appears to be one of the most pressing global health issues due to its implications for short and long-term morbidity and mortality (Bradley et al., 2025; Perin et al., 2022). Children born prematurely are at higher risk for a range of complications, developmental delays, and long-term neurological impairments (Bell et al., 2022; Marlow et al., 2005; Platt, 2014). In the short term, they frequently exhibit sensory processing difficulties and altered behavioral responses to environmental stimuli (Lahav & Skoe, 2014; Ryckman

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et al., 2017), which have been associated with adverse long-term neurodevelopmental outcomes (Chorna et al., 2014).

In response to these vulnerabilities, and with the aim of tailoring personalized early interventions (Soleimani et al., 2020), increasing efforts have been directed toward understanding how preterm newborns functionally respond to sensory stimulation. This line of research is essential to identify early markers of neurodevelopmental risk, support the development of adaptive regulatory capacities, and inform individualized caregiving strategies in the neonatal intensive care setting (Beltrán et al., 2022).

This growing interest has led to the development of advanced behavioral assessment tools for early monitoring and individualized care. One of the earliest standardized systems, the Brazelton Neonatal Behavioral Assessment Scale, NBAS (Als et al., 1977) conceptualizes the newborn as an active, self-regulating organism. It evaluates motor, autonomic, and interactive capacities through 26 behavioral and 20 reflex items, considering the infant's state as a key modulator of responses.

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The Assessment of Preterm Infants' Behavior, APIB (Als et al., 1982) expands upon the NBAS, targeting preterm, at-risk, and full-term newborns up to one month corrected age. Grounded in ethological-evolutionary theory, it assesses five interrelated behavioral subsystems—autonomic, motor, state organization, attention/interaction, and self-regulation—while also quantifying the environmental support needed for balance and reorganization (Als et al., 2005).

Other notable tools include the Anderson Behavioral State Scale (ABSS), a 12-state classification ranging from quiet sleep to intense crying, often used alongside physiological measures such as heart rate and oxygen saturation

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(Gill et al., 1988). Finally, the Thoman Scoring System (Thoman, 1990) identifies ten primary and six derived behavioral states based on naturalistic observation, capturing motor, vocal, and autonomic cues, and interpreting state regulation as a dynamic reflection of central nervous system development.

Being at the very beginning of extrauterine life, preterm infants have been the focus of numerous sensory-protective interventions, including music-based approaches (Haslbeck et al., 2023; Mohan et al., 2021; Yue et al., 2021). However, most existing studies aiming at assessing the preterm end term newborn's perception of a musical stimulus mainly involve neuroimaging technique (Chorna et al., 2019; Lordier et al., 2019; Loukas et al., 2024; Winkler et al., 2009).

Moreover, behavioral and physiological assessments of preterm newborns' responses to complex auditory stimulation (i.e. music stimuli) often rely on broad categorizations of bodily responses and behavioral state assessments, without capturing the fine-grained dynamics of their responses (Shahbazi et al., 2025).

The aim of this study is to combine precise cardiovascular measures with detailed behavioral coding to provide new insights into the psychophysiological organization of preterm newborns’ perception and responses to music. By applying a fine-grained system for coding perinatal behavior, the SCPB (*System for Coding Perinatal Behavior*, Dondi et al., in preparation), we aim to provide a detailed description of preterm newborn behavior in response to a complex, pre-recorded auditory stimulus.

The SCPB is a recently developed coding scheme specifically designed to identify complex behavioral patterns in fetuses and neonates. It is strictly

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derived from the Baby FACS (Oster, 2015), utilizing its validated Action Units (AUs) and Action Descriptors (ADs) to define aggregate behavioral configurations. While the SCPB itself is in preparation for formal publication, its component units are based on the established gold standard for infant facial coding, and the system has been successfully implemented in previous peer-reviewed studies to confirm theory-based hypotheses regarding neonatal responses (Filippa et al., 2020; Menin, Aureli, et al., 2022; Menin, Ballardini, et al., 2022). For details see Appendix 1_SI.

Adopting an embodied perspective makes it possible to link autonomic indices of regulation with observable behavior, offering a more comprehensive view of how music is processed at the onset of extrauterine life. In particular, examining the interplay between parasympathetic activity and behavior can clarify how music supports self-regulation in vulnerable infants.

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Methods

Population

Twenty-three very preterm newborns (gestational age at birth < 32 weeks) were recruited from the Neonatal Intensive Care Unit (NICU) of the University Hospitals of Geneva, Switzerland, between 2017 and 2020. At the time of testing, all infants were clinically stable, with no major neurological impairments or congenital anomalies reported. Exclusion criteria included major brain lesions detected on MRI, such as high-grade intraventricular hemorrhage, as well as microcephaly, macrocephaly, hydrocephalus, periventricular leukomalacia, and congenital syndromes. Parents provided informed written consent prior to participation. The study was approved by the local ethics committee (GE-BASEC no. 2015-00175) and conducted in accordance with the Declaration of Helsinki.

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Experimental Design and Procedure

The present study was part of a previous study, where newborns were randomly assigned to either the music intervention group (n = 12) or the control group (n = 11), (de Almeida et al., 2023). The Population characteristics are presented in Table 1.

Table 1. Population characteristics

Population Characteristics	*Overall Preterm Newborns n= 23*	*Music Group (n=12)*	*Control Group (n=11)*	*p-value*[1]
Gestational age at birth, weeks, mean (SD)	*28.10 (2.3)*	*28.4 (2.2)*	*27.7 (2.6)*	*0.7*
Gestational age at birth, weeks, range	*24 1/7 – 31 4/7*	*24 3/7 – 31 6/7*	*24 3/7 – 31 4/7*	*0.7*

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Gestational age at test, weeks, mean (SD)[2]	*34.5 (0.8)*	*34.75 (0.97)*	*34.3 (0.5)*	*0.7*
Sex: female (%) / male (%)	*14 (60.9) / 9 (39.1)*	*6 (50) / 6 (50)*	*8 (72.7) / 3 (27.3)*	*0.4*
Birth weight, gram, mean (SD)	*1026.5 (361.9)*	*1061.4 (413.7)*	*988.4 (311.3)*	*0.6*
Birth height, centimeter, mean (SD)	*36.43 (4.0)*	*36.8 (5.0)*	*36.04 (2.8)*	*>0.9*
Birth head circumference (cm), mean (SD)	*25.46 (2.5)*	*25.7 (2.3)*	*25.2 (2.9)*	*0.5*
APGAR score 1 min, mean (SD)	*4.30 (2.3)*	*4.25 (2.5)*	*4.4 (2.3)*	*>0.9*
APGAR score 5 min mean (SD)	*7.17 (2.2)*	*7.7 (1.5)*	*6.6 (2.7)*	*0.5*
Bronchopulmonary dysplasia (moderate to severe), n (%)	*1(4.34)*	*1 (8.33)*	*0*	

[1]Wilcoxon rank sum test; Fisher's exact test; [2]See Appendix B - Tab16_SI for breakdown of age by recording session

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Procedure

Headphones were placed on all 23 preterm newborns. Twelve infants, assigned to the music group, were exposed to a 6-minute musical excerpt in B major, composed by Andreas Vollenweider, with sound levels ranging from 30 dBA (background) to 65 dBA (peaks with bells). The remaining eleven newborns received headphones but were not exposed to the musical stimulus. To capture both immediate and sustained effects, the procedure was structured into three consecutive phases: baseline (6 minutes of silence, hereafter referred to as the pre-condition), test (either music listening or silence) (6 minutes), and post-listening (6 minutes of silence, hereafter referred to as the post condition). Infants were continuously monitored throughout the procedure.

The composition was structured around a harmonic base of human vocal sounds, occasionally enhanced by the addition of harp, punji, and bells. The

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soundscape is presented in stereo, with instruments emerging intermittently. Central to the piece are the harp, which adds a gentle texture and melodic depth; the punji, a traditional Indian wind instrument, which carries the primary melodic line; and bells, which contribute subtle rhythmic accents within the harmonic framework. For additional details on the music stimulus, consult (de Almeida et al., 2023; Loukas et al., 2024).

Note that newborns in the music group were previously exposed to the same musical piece approximately twice per day starting from 33–34 weeks of gestational age until hospital discharge, delivered through headphones (Sennheiser PXC 250-II, Sennheiser electronic GmbH & Co.KG, Wedemark, Germany) adapted to newborns (de Almeida et al., 2023). In contrast, preterm newborns in the control group were not exposed to music either during their NICU stay or during the present experiment, as they received headphones without any music being played.

Newborns were placed supine in a heated crib and recorded with a digital video camera (Sony Handycam Hybrid DCR-DVD150). During the whole protocol newborns' physiological signals were continuously monitored using standard cardiorespiratory equipment (IntelliVue MP40, Philips Medical System, Eindhoven, Netherlands). The electrocardiogram (ECG) and respiratory signals were digitally extracted using IxTrend 2.1 software (Ixellence GmbH, Wildau, Germany). The ECG and respiratory signals were acquired at 500 Hz and 62.5 Hz respectively.

Each newborn was videotaped between one and three times at different gestational ages (M = 35.9 weeks, SD = 1.5, see Supplementary Materials for details on recoding frequency). The rooms were equipped with one or two sliding doors to ensure adequate isolation from external noise. To standardize

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the acoustic environment and minimize the risk of ambient sounds masking the music, sound levels were continuously monitored, and a minimum difference of 10 dB between the music and ambient noise was maintained using a sound level meter.

A total of 59 video recordings were collected. Of these, 6 were excluded from the behavioral analysis due to missing initial and final video triggers, resulting in 53 recordings available for analysis. For the physiological assessment, 3 data tracks were excluded owing to a high frequency of arrhythmic events and 2 due to missing data, resulting in 54 recordings available for analysis.

Behavioral Data Analysis

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The microanalytic (frame by frame) behavioral coding was carried out independently by two coders, with the second reviewing six videorecordings (11.3% of the total sample). Inter-rater reliability between the two coders was assessed using Cohen’s Kappa, adopting a one-second threshold both for the onset and the offset of each event, except for the behavioral patterns for which SCPB only requires the onset to be scored (i.e., Rooting, Startle, Sneezing, Swallow, Drooling, Head movements, Occipito-Frontalis Reflex, Tongue Expulsion). Cohen's Kappa was calculated for all behaviors observed by both coders. This led to the exclusion of low-frequency behaviors (Rooting, Shiver, Sneezing, Hiccup, Swallow, Drooling, Finger-Sucking, Head Retroflexion and Head Anteflexion). As indicated in the SCPB, Hand Movements were coded separately, but, due to the limited number of Hand to Head and Hand to Mouth Movements, the three categories (including the more common Hand to Face, were collapsed into the higher-level category. All behavioral patterns showed good to excellent reliability (with Kappa > .75),

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with the exclusion of Sucking (Kappa = .68) and Rapid Eye Movements (Kappa = .65), that were excluded from further analysis (see Table 1_SI in Supplementary Information for details).

For each of the remaining 11 behavioral categories (Chin Tremble, Distress, Eye Blinking, Eye Opening, Hand Movements, Head Rotation, Non-Rhythmical Mouth Movements, Smile, Startle, Tongue expulsion, Yawning), we fitted one regression at the phase-level . To account for the distributional properties of our dependent variables (count data) and the inherent dependency of observations nested within the three-level hierarchical structure of the dataset (phases nested in video-recordings nested in participants), we employed Multilevel Poisson Regressions. In particular, the dependent variable of each regression was the number of events for one behavioral category observed during one phase (*pre*, *test* or *post*) of an observation, the independent variables included the fixed effects of phase and group (control or music) and their interaction, as well as a random intercept representing the observation nested within participants (as participants had several observations). To account for slightly different phase durations, the offset variable was set to the logarithmic offset of the observation time of that specific phase. When models showed significant interaction effects, additional post hoc comparisons were conducted, adjusted using the Tukey method.

Models were checked for overdispersion using the check_overdispersion command from the R performance package (Lüdecke et al., 2021), adopting the method proposed by Gelman & Hill (Gelman & Hill, 2007). None of the models exhibited over- or underdispersion. All remaining analyses were carried out in the R statistical environment, version 4.5.0, using the packages lmerTest (Kuznetsova et al., 2017) and emmeans (Lenth, 2023).

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Physiological Data Analysis

Physiological series were used to quantify task-diven parasympathetic activation and the level of cardiorespiratory coupling in the infants (Figure 1).

Preprocessing. ECG signals were visually inspected and processed to remove artifacts and extract the interbeat interval (IBI) series using Kubios HRV software version 2.2 (Tarvainen et al., 2014). The resulting IBI series were detrended employing the smoothness prior method (Tarvainen et al., 2002) with a smoothing parameter of $\lambda = 500$ and the detrended IBI series were resampled at 4 Hz via piecewise cubic spline interpolation.

Respiratory signals from newborns were pre-processed following the procedure outlined by Zhang et al. (Zhang et al., 2021). The raw respiratory data were down sampled to 16 Hz and filtered using a fifth-order Butterworth bandpass filter within the 0.05–2 Hz frequency range. Baseline correction was applied through median trend removal over a 1.2-second sliding window. Subsequently, signals were resampled at 4 Hz to synchronize to IBI series and then normalized by z-score.

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Parasympathetic activation . Physiological activity was assessed across the three overmentioned phases (*pre*, *test* and *post*). To ensure comparability, two consecutive windows were cut during the pre- and post-test phases, with the metrics averaged across these two periods.

Parasympathetic modulation of heart activity was quantified by studying the power spectral density within the high-frequency (HF) band, defined as 0.2–1.5 Hz according to previous literature on cardiovascular dynamics assessment in infant age (Filippa et al., 2022). Additionally, the root mean square of successive differences (RMSSD) was calculated as a respective time-domain index of parasympathetic activity (Goto et al., 1997; Järvelin-Pasanen

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et al., 2018; Kleiger et al., 2005). An increase in parasymphatetic activity is reflected by in increase HF power, indicating more defined beat-to-beat oscillations, and higher RMSSD, reflecting greater beat-to-beat variability (Järvelin-Pasanen et al., 2018; Kleiger et al., 2005). In preterm infants, interpretation of these indices must account for atypical autonomic maturation (Longin, Gerstner, Schaible, Lenz, & Koenig, 2006), as they typically exhibit lower baseline vagal activity and relative sympathetic dominance due to incomplete parasympathetic cardiac innervation.

Cardiorespiratory coupling. Cardiorespiratory coupling reflects the dynamic interplay between heart and lungs. Multiple mechanisms contribute to the interplay (Dick et al., 2014), with respiratory sinus arrhythmia (Hayano et al., 1996; Yasuma & Hayano, 2004) being the most well-known, mediated by both mechanical and parasympathetic feedbacks (Bartsch et al., 2014). In preterms infants, autonomic and respiratory systems are still immature, so coupling is reported as variable o absent (Clark et al., 2012; Indic et al., 2011; Joshi et al., 2019; Longin, Gerstner, Schaible, Lenz, & König, 2006). It has been shown that the coupling can be modulated by external influences and interventions (Indic et al., 2011; Van Puyvelde et al., 2014), providing insight into cardiorespiratory regulation in preterm infants within the NICU. To assess the effects of the music stimulus on cardiorespiratory coupling we used the magnitude-squared coherence (MS coherence) analysis (Kay, 1988), which measures the correspondence between interbeat interval and respiration across the frequency spectrum. Welch's periodogram method was used for power spectral density estimation.

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Given two time-series *h* (i.e. heart-related component, in this case the detrended and interpolated RR series) and *r* (i.e. the respiratory signal), the Coherence $C_{hr}$is computed as:

$$C_{hr}(f) = \frac{|P_{hr}(f)|^2}{P_{hh}(f) \cdot P_{hh}(f)}$$

Where $P_{hh}(f)$ corresponds to the power spectral density of the cardiac series *h* as a function of frequency *f*. $P_{hr}(f)$ corresponds to the cross power spectral density of *h* and *r*. Coherence values were averaged over the 0–2 Hz frequency range to characterize the strength of cardiorespiratory interactions during each experimental phase.

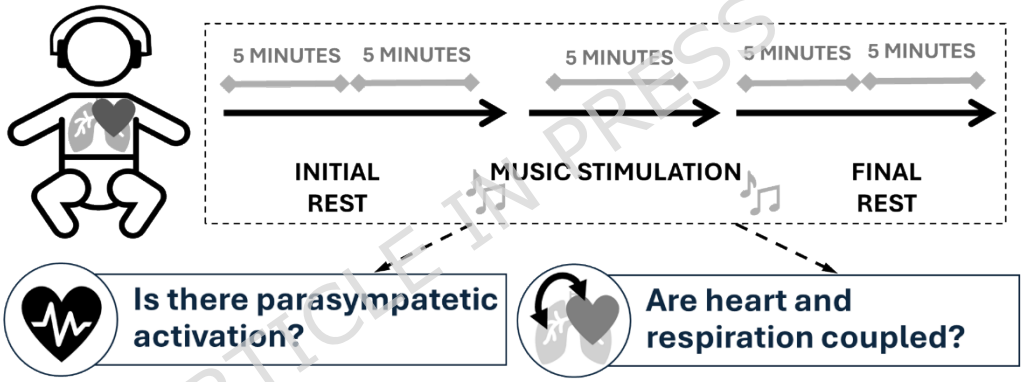


Figure 1. Schematic representation of the protocol phase for the assessment of the newborn's physiological response for the music intervention group, and subsequent research questions.

To examine the overall impact of experimental conditions on physiological scores, we fitted a linear mixed-effects model. The model included fixed effects for phase, group and their interaction. Random intercepts were specified for each subject, with observations nested within subjects to account for repeated measurements and within-subject variability. Post-hoc comparisons were conducted, adjusting using the Tukey method, as described in the previous section.

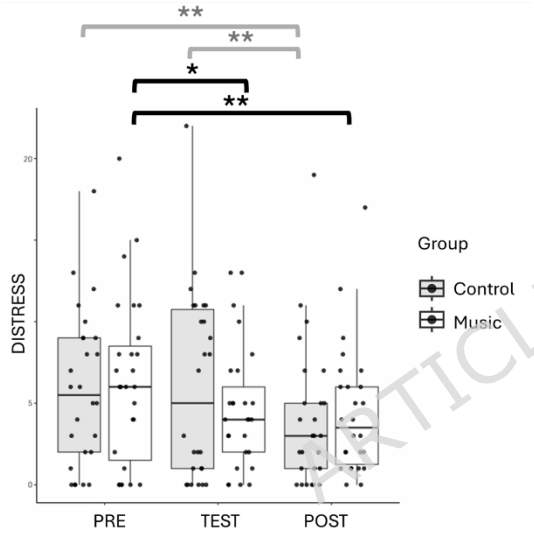
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Results

Behavioral results

Mean rates per minute and standard deviation of the 11 behavioral patterns for the two groups across the three phases of the procedure are reported as supplementary information (see Table 1_SI). Out of the 11 behavioral patterns, five, including Chin Tremble, Head Rotation, Non-Rhythmical Mouth Movements, Startle and Tongue Expulsion, did not highlight effects of group, phase, or their interaction.

Distress



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Figure 2. Distress levels across experimental phases (Pre, Test, Post) for the Control and Music groups. Boxplots represent the distribution of Distress scores in each phase for the Control group (gray) and the Music group (white). Individual data points are overlaid.

Main Model

The main model analysis (AIC = 847.1, BIC = 871.6 ; Table 1_SI) showed a main effect for the pre phase (IRR = 1.353, 95% CI [1.077, 1.700], $p = .009$), with lower Distress rates in the test phase relative to the pre phase. The interaction between the pre phase and the Control group was also significant

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(IRR = 0.719, 95% CI [0.523, 0.989], p = .042), suggesting a different effect of the pre phase on Distress for the groups.

Post-hoc Comparison

Within the Control group, we observed a decrease in Distress rates from the pre phase to the post phase (contrast pre – post; IRR = 1.448, 95% CI [1.131, 1.853], p = .009). Additionally, Distress rates significantly decreased from the test phase to the post phase (contrast test-post; IRR = 1.488, 95% CI [1.164, 1.902], p = .004). No significant difference was found between pre and test phases in this group. Within the Music group, Distress rates decreased from the pre phase to the test phase (contrast test-pre; IRR = 0.739, 95% CI [0.588, 0.929], p = .0255). A decrease in Distress rates was also observed from the pre phase to the post phase (contrast pre – post; IRR = 1.435, 95% CI [1.135, 1.814], p = .007). There was no significant difference between the test and post phases in this group. Inter-group comparisons within each phase did not reveal any significant differences in Distress rates.

These findings suggest that the Control group showed a reduction in distress following the test phase, while the Music group exhibited a decrease in distress during the test phase compared to pre phase, which was maintained into the post phase.

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Hand Movements

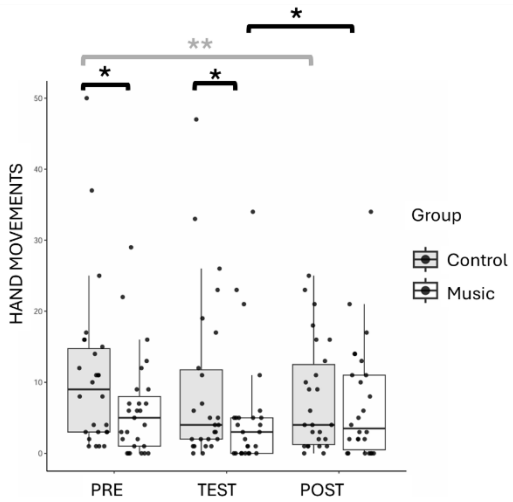


Figure 3. Hand Movements across experimental phases (Pre, Test, Post) for the Control and Music groups.

Main Model

The main model analysis (AIC = 1059.8, BIC = 1084.3; Table 4_SI) showed a main effect of the phase (IRR = 1.349, 95% CI [1.084, 1.680], p = .007). A significant main effect of group was also observed (IRR = 2.03, 95% CI [1.07, 3.84], p = .029), with higher Hand Movement rates in the Control group. Furthermore, the phase × group interaction was significant (IRR = 0.638, 95% CI [0.479, 0.851], p = .002) , suggesting a different effect of the phase for the groups.

Post-hoc Comparisons

Within the Control group, we observed a decrease in Hand Movement rates from the pre phase to the post phase (contrast pre – post; IRR = 1.405, 95% CI [1.176, 1.679], p = .0005). There was no significant difference between the pre and test phases (p = .072) or between the test and post phases (p = .257) in this group.

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Within the Music group, Hand Movement rates increased from the test phase to the post phase (contrast test-post IRR = 0.741, 95% CI [0.595, 0.923], p = .020). No significant differences were found between the pre and test phases (p = .172) or between the pre and post phases (p = .632) in this group. Regarding inter-group comparisons, the Control group showed higher Hand Movement rates compared to the Music group in the pre phase, (contrast Music-Control group; IRR = 0.497, 95% CI [0.264, 0.936], p = .030) and test phase (contrast Music-Control group; IRR = 0.492, 95% CI [0.260, 0.931], p = .029). No significant inter-group difference was observed in the post phase (p = .421). These results interaction effect highlights a notable difference in the pattern of change in Hand Movements between groups: the Control group showed a decrease from pre to post, while the Music group showed an increase from test to post. Overall, Hand Movement rates were lower in the Music group compared to control during the pre and test phases, but differences were no longer present in the post phase.

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Eye Blinking

Main Model

The main model (AIC = 250.8, BIC = 275.3; Table 2_SI) showed a main effect of phase, with higher Eye Blinking rates during the pre phase compared to the test phase (IRR = 2.56, 95% CI [1.19, 5.54], p = .017). In addition an interaction between phase and group (IRR = 0.300, 95% CI [0.097, 0.928], *p* = .037), suggesting a decrease in Eye Blinking rates during the test phase that was unique to the Music group.

Post-hoc Comparisons

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Within the Control group, no significant differences in Eye Blinking rates were found across any of the phase comparisons.

Within the Music group, Eye Blinking rates significantly decreased from the pre phase to the test phase (contrast test-pre; IRR = 0.390, 95% CI [0.181, 0.843], p = .044). A significant decrease was also observed from the pre phase to the post phase (contrast pre-post; IRR = 3.733, 95% CI [1.518, 9.176], p = .011). No significant difference was found between the test and post phases in this group (p = .756).

No inter-group differences in Eye Blinking rates were observed between Music and Control group in any of the phases (pre phase: p = .320; test phase: p = .274; post phase: p = .593).

These findings suggest that while the Control group showed no significant changes in Eye Blinking across phases, the Music group exhibited a significant decrease in Eye Blinking during the test phase compared to the pre phase, which was sustained during the post phase. The significant interaction term highlights that the test phase specifically induced a different pattern of Eye Blinking change in the Music group.

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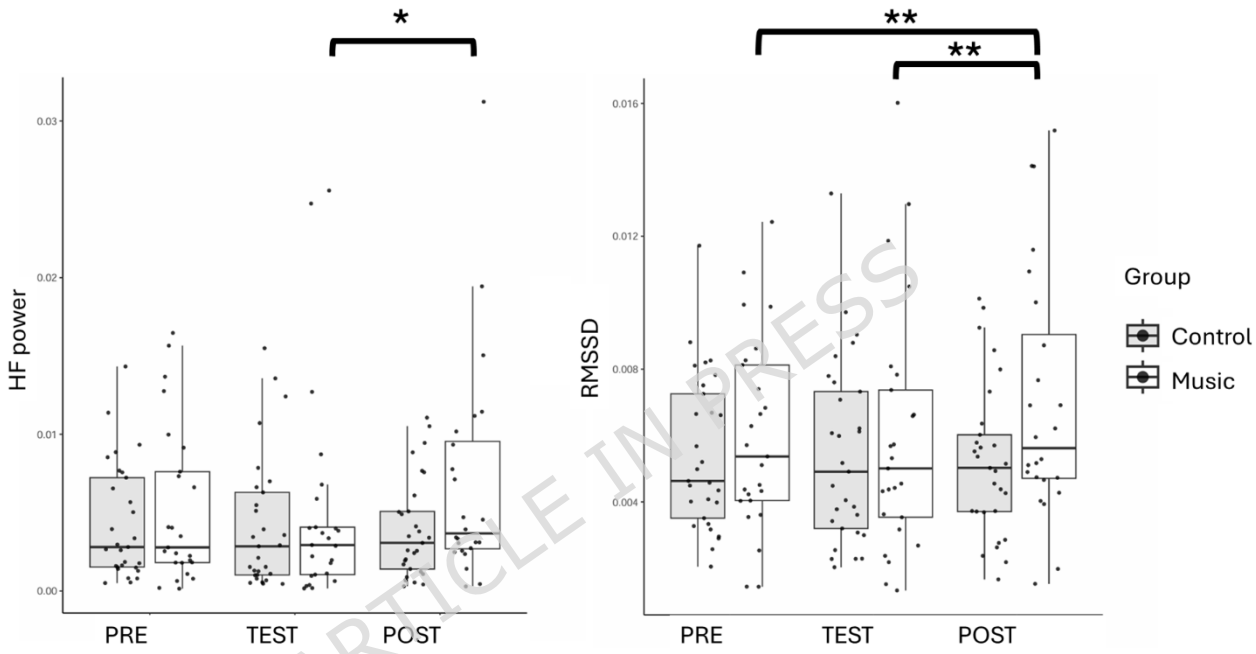
Other Behavioral Patterns

The remaining three behavioral patterns (Smile, Eye Opening, and Yawning) did not show interaction effects between phase and group or differences between groups. Detailed results can be found in the Supplementary Information (Table 1_SI).

Physiological results

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To evaluate the modulation of parasympathetic activity by the test stimulus we analysed the power spectral density within the high-frequency (HF) band, and the root mean square of successive differences (RMSSD) as a respective frequency and time-domain indexes of parasympathetic activity (Goto et al., 1997).



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Figure 4. HF power across experimental phases (Pre, Test, Post) for the Control and Music groups.

HF power, the frequency-domain index of parasympathetic activity

Main Model

The main model analysis revealed a main effect for the phase (b = 0.002, p =. 016), indicating an increase in HF power comparing the test and the resting phase after the test. Additionally, an interaction between phase and group (b = -0.002, p = .042) was present.

Post-hoc Comparisons

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Within the Music group, HF power values were significantly higher in the post phase compared to the test phase (contrast test-post; b = -0.002, p = .041). No significant differences were found between the test and pre phases (p > .05) or between the pre and post phases (p > .05) in this group. Concerning the Control group, no significant differences were observed between any of the phases (all p > .05). These findings suggest that scores increased from the test to the post phase in the Music group, while remaining consistent across phases in the Control group. These results indicate a potential effect of music listening specifically impacting the post phase scores.

RMSSD, the time-domain index of parasympathetic activity

Main Model

The main model (REML criterion = -1474.0) analysis showed a main effect for the phase (b = 0.001, *p* = . 001), indicating an increase in RMSSD values after the test. Additionally, an interaction between phase and group (b = -0.001, *p* = .004) is present.

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Post-hoc Comparisons

Concerning the post-hoc comparisons, the p-values adjusted using the Tukey method further clarified the observed effects.

Within the Music group, RMSSD values were significantly higher in the post phase compared to the test phase (contrast test-post; b = -0.001, p = .003), and also significantly higher in the post phase compared to the pre phase (contrast pre-post; b = -0.001, p = .007). No significant differences were found between the pre phases and test phase (p > .05) in this group.

These findings indicate that RMSSD significantly increased from both the pre

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and test phases to the post phase in the Music group, whereas no significant changes were observed across phases in the Control group (all $p > .05$).

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MS coherence, the index of cardiorespiratory coupling

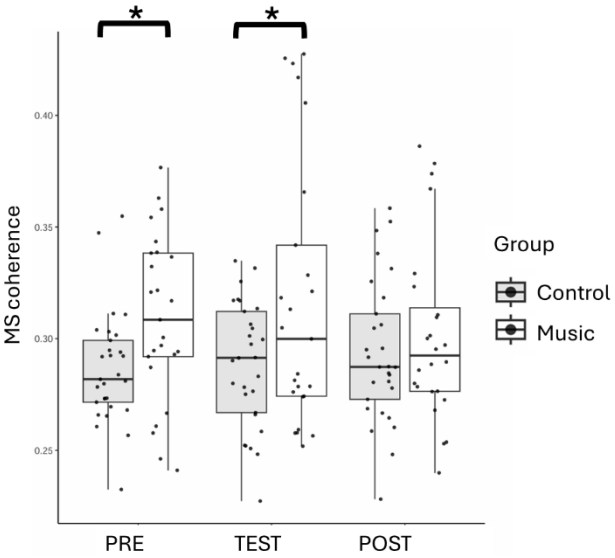


Figure 5. MS coherence across experimental phases (Pre, Test, Post) for the Control and Music groups.

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To assess the cardiorespiratory coupling, a measure of MS coherence has been adopted (see Physiological Data Analysis). The linear mixed-effects model (REML criterion = -603.1) revealed a main effect of both the post phase and the group, as well as an interaction between group and post phase.

The model showed that scores decreased in the post phase compared to test, main effect of phase (b = -0.016, p = .023). The Control group also exhibited overall lower values than the Music group, main effect of group (b = -0.028, p = .014).An interaction between phase and group is also reported (b = 0.022, p = .027).

Post-hoc Comparisons

After Tukey's adjustment, no significant differences were found between phases (all p > .05) in both groups.

Across groups scores were significantly higher in the Music group than the

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Control group during the pre phase (contrast: Music-Control group; b = 0.023, p = .044) and the test phase (contrast: Music-Control group; b = 0.028, p = .014). No significant differences between groups were observed in the post phase (b = 0.007, p = .547).

Discussion

This study offers novel insights into the perceptual and autonomic capacities of preterm newborns by examining how structured musical stimuli modulate fine-grained behavioral and physiological responses, supporting the view that music perception in early life is an embodied process, engaging dynamic interactions.

Across behavioral and physiological measures, newborns in the music group, who had prior exposure to music in the NICU and were re-exposed during the experiment, showed a distinct temporal pattern of responses. Although main effects of phase were observed across groups, potentially reflecting general aspects of the experimental context (e.g., headphone application), significant phase × group interactions indicated that the trajectory of change differed between groups. Specifically, infants in the music group showed reductions in distress and eye blinking from the pre to the test phase, a pattern not observed in the control group. While no between-group differences in distress or eye blinking were detected within individual phases, the music group exhibited an earlier behavioral modulation during exposure, with reduced distress maintained into the post phase. The decrease in distress indicates enhanced emotional stability and aligns with previous findings on the beneficial effects of music exposure in preterm newborns (Loewy et al., 2013)

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and infants (Trehub et al., 2015), while reduced eye blinking may reflect a more sustained state of comfort. In the music group, hand movements, particularly those directed toward the face and mouth, commonly interpreted as self-soothing behaviors (Filippa et al., 2020), were significantly lower than in the control group during both the pre and test phases. Preterm infants are frequently described as exhibiting a “premature behavioral phenotype,” characterized by heightened motor activity, increased emotional reactivity, and reduced inhibitory control compared to their full-term peers (Franz et al., 2018; Lejeune et al., 2015; Treyvaud et al., 2013). In this context, hand movements are widely interpreted as self-soothing behaviors that help regulate arousal and distress (Als et al., 2005; Kochanska et al., 2001). The lower hand movement rates observed in the music group during the pre and test phases may reflect differences associated with prior exposure history; however, because this group difference was already present at baseline, it cannot be interpreted as a direct effect of music exposure during the experimental session. One plausible explanation is that repeated exposure to the same musical stimulus in the NICU may have shaped baseline regulatory patterns in these infants. In this sense, prior familiarity could have contributed to the observed group differences and may have amplified the regulatory responses during the experimental session. While our findings are compatible with this interpretation, the limited sample size did not allow for a direct test of this hypothesis, which should be addressed in future studies. Consistent with this explanation, research shows that preterm newborns can encode and later recognize familiar musical patterns, suggesting early forms of auditory memory and associative learning (Loukas et al., 2022). This would be consistent with previous findings which highlight long-term effects of early

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music exposure on brain maturation (de Almeida et al., 2023; De Almeida et al., 2020; Lordier et al., 2019) and others showing cumulative benefits on HRV from repeated maternal singing interventions (Arnon et al., 2014; Filippa et al., 2024). This interpretation is further supported by the higher levels of cardiorespiratory coupling observed in the music group during both the pre and test phases, potentially reflecting a more organized pattern of autonomic coordination. (Landrot et al., 2007). This interpretation aligns with findings that early music interventions can influence emotional regulation and attention capacities (De Almeida et al., 2020). Loukas et al. (Loukas et al., 2022) further provide a neurobiological basis, showing that early music interventions in the NICU foster cortical maturation in regions such as the orbito-frontal cortex, temporal pole, amygdala, precuneus and posterior cingulate—areas implicated in auditory, emotional, and self-referential processing. This structural and functional development may underpin the more organized behavioral and autonomic regulation observed in the music-exposed group at the baseline.

Finally, at a physiological level, although no significant between-group differences were observed, only the music group demonstrated increased parasympathetic activity, evidenced by elevated HF power and RMSSD, following music exposure. These parameters, widely recognized as markers of vagal tone and autonomic maturity are generally interpreted as markers of vagal tone and autonomic maturation. In contrast, the control group showed minimal or delayed changes across phases. This enhancement of vagal tone is indicative of a more mature autonomic regulation (Lee, 2009) and aligns with the notion that familiar and meaningful auditory stimuli can foster self-regulatory mechanisms.

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Interestingly, a previous study (Lavezzo et al., 2025) showed that preterm newborns with no prior exposure to music responded to a novel musical stimulus with a significant decrease in HF power. This downward shift in parasympathetic activity has been interpreted as a heightened attentional engagement or autonomic adjustment to an unfamiliar auditory environment. In that context, music may have functioned primarily as a novel stimulus requiring increased processing, potentially eliciting a more active or exploratory state rather than immediate regulation.

Taken together with the present findings, these results highlight the potential role of familiarity in shaping the autonomic impact of music. Repeated exposure may facilitate a shift from novelty-driven activation toward a more regulated physiological response in preterm infants.

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Limitations of the study

While this study provides novel insights into the embodied nature of music perception in preterm newborns, several limitations should be acknowledged. A primary limitation concerns the fact that newborns in the music group had already been repeatedly exposed to the same musical piece during their NICU stay, whereas newborns in the control group had not received any prior musical stimulation, either in the NICU or during the experiment (headphones were applied without sound). This design prevents us from disentangling the effects of repeated exposure from the effects of music listening during the experimental session, thereby limiting causal interpretation and generalizability. Furthermore, the present design does not allow us to determine whether the observed effects are specific to music per se, as opposed to repeated exposure to an auditory stimulus more generally. Future

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research should incorporate non-musical auditory control conditions (e.g., matched complex sounds or speech) to clarify stimulus specificity. In addition, studies comparing preterm newborns with and without prior musical exposure, as well as full-term newborns, would help delineate the developmental specificity and plasticity of these responses. Expanding sample sizes and including a broader range of gestational and postnatal ages would further enable characterization of the developmental trajectory of cardiorespiratory coupling and clarify how musical interventions may differentially support autonomic maturation over time.

Second, although our findings suggest sustained regulatory effects beyond the stimulus phase, their temporal stability remains to be determined. Longitudinal studies are needed to assess whether early musical exposure fosters enduring changes in autonomic regulation and behavioral organization.

Finally, while the study supports the use of music as a regulatory stimulus, clinical implementation requires careful adaptation to individual needs and sensory thresholds and developmental needs. Future work should explore how personalized, developmentally tailored sound environments in the NICU can support optimal sensory-affective integration and neurodevelopment in this vulnerable population.

Conclusions

This study provides compelling evidence that music perception in very preterm newborns is not merely an auditory process mediated by cognitive processes, but an embodied one—integrating behavioral cues and autonomic

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physiology. The coordinated modulation of distress, self-regulatory behaviors, and parasympathetic activity in response to familiar musical stimuli suggests that even at the earliest stages of extrauterine life, music can elicit complex, multimodal regulatory responses. The persistence of these effects beyond the stimulus phase underscores the potential of music to shape internal states over time, fostering autonomic stability and behavioral organization. Taken together, these findings suggest that preterm newborns may already begin to form early auditory memories and to integrate them into adaptive physiological responses, providing a potential developmental window into the embodied nature of music perception. By incorporating bodily and affective dimensions, this research advances our understanding of how music contributes to sensory-affective integration in fragile neonatal populations and opens new avenues for using music-based interventions to support early neurodevelopment.

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Author Contributions

GB and LL contributed equally to the methodology design, and data analysis. DM and MD were responsible for data analysis and methodology design. JSA provided clinical suggestions and was responsible for data collection. PH was responsible for project administration, fund raising and conception of the study and contributed to the interpretation of the findings. EPS and MN supported signal processing, statistical analyses, and technical validation. FBM and MF jointly supervised the project and contributed to the final manuscript. All authors reviewed, edited, and approved the submitted version.

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Data availability statement

The datasets generated during the current study are not publicly available due to the sensitive nature of newborn-related data and ethical restrictions, but are available from the corresponding author on reasonable request.

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