Music-Induced Chills Associated with Musical Reward: A Portable PPG Study 🥶

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Abstract

Many people often experience physical effects as a result of listening to music, dubbed "chills". This study explored these psychophysical manifestations, comparing participant experiences as a result of listening to standardized selections and self-reported selections, in conjunction to exploring how participant historical musical experiences contribute towards these "chills". Psychophysical effects were measured using the NeuroScouting Earbud (PPG) and NeuLog, which measured galvanic skin response (GSR). It was found that psychophysical responses were significant during the window of which the participant reported feeling chills.

Introduction

Music is one of the most important culturally salient facets of human life. Across regions, languages, and time, music remains compelling for many. One common phenomenon when listening to music is the experience of "chills". This can manifest through goosebumps, muscle contractions, shivering, shaking, etc (Grewe, et al. 2009). Overall, with the chills comes a sensation of feeling cold without an apparent cause. Although the chills are not exclusively associated with musical listening, they often accompany a profound, emotional listening experience. As to what musical features exactly cause these sensations is still to be determined.

The rewarding aspects of music listening have been associated with changes in emotional arousal (Salimpoor, 2009). People often report feeling "chills" when listening to music that they find highly pleasurable. Chills involve 2 of 3 emotional components: subjective feeling and physiological response (Grewe, 2009). These physiological responses may include changes in heart rate, blood volume pulse (BVP), galvanic skin response (GSR), and skin conductance level

(SCL) (Salimpoor, 2009; Grewe, 2009). The onset of a chill is typically accompanied by a spike in physiological arousal, such as GSR or heart rate. Respiration rate and skin temperature were previously thought to be included in these responses, but have been found to be unrelated to the physiological arousal of music-induced chills (Salimpoor, 2009).

Music-induced chills are related to the activation of a subdivision of the autonomic nervous system (ANS), the sympathetic nervous system (SNS) (Craig, 2005). When looking at measures of physiological response, it is important to consider the baseline of each participant. A 2009 study found a positive association between subjective ratings of pleasure and ANS activation, as indicated by increases in GSR, heart rate, and BVP amplitude (Salimpoor, 2009). Out of all measures used, GSR is considered to be the most salient predictor of emotional arousal because it is not under the participant's voluntary control, is highly sensitive to changes, and has shown the most significant correlation with increases in pleasure ratings (Salimpoor, 2009). Harrison & Loui (2014) also note that increased heart rate, SCR, and respiratory depth are associated with the onset of frisson (cites Blood & Zatorre, 2001; Craig, 2005; Guhn et al., 2007).

Activation of the sympathetic nervous system (SNS) and withdrawal of the parasympathetic nervous system (PNS) indicate physiological arousal, while the inverse effects are often linked with relaxation (Mori & Iwanaga, 2014). Mori & Iwanaga (2014) hypothesized that baseline physiological arousal may predict intense emotional responses and psychophysiological arousal. Psychophysiological arousal can be experienced during both positive and negative emotional responses (Kreibig, 2010, as cited by Mori & Iwanaga, 2014). Music-induced chills are one indicator of strong positive emotion associated with psychophysiological arousal, as they are known to be a response to strong emotional experiences (Zatorre and Salimpoor, 2013, as cited by Mori & Iwanaga 2014). Previous research implies that individuals who report music-induced chills experience psychophysiological arousal mainly because of an elevated magnitude of skin conductance response (SCR). Additionally, chills were accompanied by intense feelings of pleasure and emotional arousal among individuals who experienced chills while listening to their favorite music (Salimpoor, 2009; Mori, 2014). Mori & Iwanaga (2014) revealed that individuals exhibiting baseline physiological arousal predict the experience of music-induced chills, which elicit intense feelings of pleasure and psychophysiological arousal.

Furthermore, the interplay between auditory areas and emotional and reward processing systems serves as a reliable indicator of frisson (Salimpoor et al., 2013). This implies that frisson does not solely rely on isolated reward-processing regions, but rather involves a network of emotional and reward processing regions working together with auditory-motor activity (Harrison & Loui, 2014). These patterns may suggest a reflex akin to "craving," similar to responses elicited by stimuli such as food, sex, and drugs of abuse. The study also found positive correlations between the intensity of frisson responses and the activation of various parts of the brain, including regions associated with autonomic nervous system arousal. The integration of functions across these regions might elucidate listeners' muscular reactions to music, and responses to psychophysiological reactions such as SCR responses and heart rate fluctuation (Blood & Zatorre, 2001, as cited by Harrison & Loui, 2014). Additionally, positive correlations between how individuals evaluated unfamiliar musical stimuli and the connectivity between auditory and reward processing areas were found in Salimpoor et al. (2013) (Harrison & Loui, 2014).

Though it is uncommon, there are a select few individuals for whom music provides no reward. These individuals are otherwise healthy and have normal perceptual ability and reward-related responses towards other stimuli, such as money or food (Martinez-Molina et al., 2016). This phenomenon is known as musical anhedonia, and it cannot be attributed to inhibited perceptual capabilities or general anhedonia. Musical anhedonia has been found to be related to a reduced arousal of the autonomic nervous system (ANS). Musically anhedonic individuals exhibited lower levels of brain activity in the nucleus accumbens (NAcc) in response to music, as well as decreased functional connectivity between the right auditory cortex and the ventral striatum (Martinez-Molina et al., 2016). In contrast, individuals who receive higher than average levels of reward from music showed increased connectivity between these brain structures. Additionally, people with musical anhedonia exhibited lower levels of emotional arousal of the ANS, as indicated by measures of skin conductance and heart rate, compared to those who do receive reward from music (Martinez-Molina et al., 2016).

Familiarity with and liking of a piece are related to the frequency of chill responses as well (Grewe, 2009). A 2005 study reported that 89% of participants reported feeling chills while listening to a familiar piece of music, while 75% reported feeling chills while listening to an unfamiliar piece of music (Craig, 2005). That being said, the level of familiarity appears to play a role as well. A 2009 study found that out of several experimental groups, the group that was most familiar with a piece tended to report the most chills; however, their findings suggest that general familiarity is important to the induction of chills and that intimate knowledge of the stimulus does not increase chill frequency (Grewe, 2009).

Based on the previous literature, the physiological changes of a chill experience may differ from person to person, have different causes or be related to different events within one song. Since music is a highly subjective artform, it is important to account for preference when designing a study assessing this phenomenon. The following study is modeled after Salimpoor, et al. (2009) with our stimuli consisting of self-selected chill-inducing music and chill-neutral music. We also included chill-inducing musical excerpts from a pool of "chills songs". This pool was implemented to observe the physiological responses of music that the participants did not select themselves, but were reported to be chill-inducing stimuli by others. Since the self-selected stimuli were reported in advance of in-person trials, the pool of other selected chill-inducing songs allowed us to screen for effects of priming as well. Additionally, from the Salimpoor, et al. (2009) study, we implement real-time, continuous recordings of physiological pleasure states from sympathetic nervous system activity to measure states of emotional arousal (heart rate and heart rate variability). Overall, higher GSR levels were associated with moments of chills (Salimpoor, et al. 2009; Craig 2005), thus we include this in our physiological recordings as well. Another commonality from the literature incorporated in this study is a measurement of familiarity with the stimuli and its effects on the chills response (Grewe, et al. 2009). This is accounted for in a post-listening survey questionnaire after each excerpt presentation. Prior to in-person trials, each participant completed a preliminary questionnaire that collected each subject's stimuli and assessed for musicality and anhedonic tendencies (Martinez-Molina, et al. 2016). The influence of a distinguishable musical anhedonic subject on a chills experience is extremely insightful for our exploratory analyses.

Overall, this study aims to measure physiological changes for both chill-inducing and chill-neutral musical stimuli using the NeuLog and BioBud Neuroscouting device and digital application and focus on how these measures vary with trait-level musical reward. Through this study, we were able to pilot test the NeuroScouting digital applications and in-ear device. A comprehensive analysis of the existing literature led us to form this study with the following hypotheses: **(1)** Self-reported and randomly selected chill-inducing stimuli are rated as more engaging, pleasurable, surprising and thrilling over neutral stimuli. **(2)** Chill-inducing over neutral epochs induce a lower interbeat interval and higher skin conductance (galvanic skin response, GSR) as measured with the given portable physiological devices. **(3)** Musical reward and ratings of engagement, pleasure and surprise positively correlate with a stronger chill response (lower interbeat interval and higher skin conductance) in chill-inducing stimuli.

Methods

Participants

We tested a sample size of $n = 46$ participants, 31 of which reported being musically trained (one participant did not report an answer for this question, but did report they play piano). This number excludes 5 additional pilot subjects. Recruitment was conducted using PsyLink, through which undergraduate students enrolled in *Foundations of Psychology* at Northeastern University were given one course credit as compensation. Other participants were recruited via social media or word of mouth by the researchers and compensated with a $15 Amazon gift card for their time. All participants had normal hearing and were at least 18 years of age.

Materials

Four questionnaires were used to assess musical reward, music engageability, musical sophistication, and physical anhedonia. These surveys included the Barcelona Music Reward Questionnaire (BMRQ), the Absorption in Music Scale (AIMS), Goldsmiths Musical Sophistication Index (Gold-MSI), and the Physical Anhedonia Scale (PAS). The second part of the study included an in-ear device and a handheld device.

Physiology Measurement Devices

The in-ear NeuroScouting earbud (PPG) was used to measure heart rate and heart rate variability, and the handheld NeuLog device was used to measure galvanic skin response (GSR).

NeuroScouting Earbud (PPG)

The NeuroScouting device was paired to a tablet with the company's app to provide stimuli, prompt the participant, and record data.

The device rested on the tragus of the ear, using a MAXM6161 sensor with green, red and IR LEDs to penetrate multiple layers of tissue. The device included an accelerometer as well to correct off-line for motion artifacts. Both the sensor and accelerometer sampled at a rate of 100 Hz. Metrics that were extracted included heart rate, heart rate variability (HRV), and respiration rate. Heart rate and heart rate variability were extracted on-line by performing the following on a continuous buffer of data: (1) Forward-backward filtering was used for de-trending with a FIR low pass (corner of 0.5Hz). (2) Smoothing was achieved with a moving average window of 100 samples with a shift of 1 sample. (3) Data was filtered through a final FIR bandpass filter with corners of 0.5Hz and 3Hz, forwards and backwards. Peak-finding was used to determine both heart rate (frequency of peaks) and heart rate variability (time between peaks), with outliers removed. Raw data was also exported for offline analysis.

NeuLog

GSR data in micro Siemens (μS) was acquired with the NeuLog GSR Logger using the corresponding acquisition software at a sample rate of 100 Hz. Two sensors were connected to the index and ring fingers of the non-dominant hand. Participants were instructed to wash their hands and leave a little water on the surface of their non-dominant hand to increase connectivity. Audio was also recorded via the NeuLog acquisition software from the live playback at a sample rate of 100 Hz for time synchronization of physiological measurements.

Stimuli

This was a within-subject study—participants were exposed to self-selected chill-inducing, other-selected chill-inducing and neutral (control) self-selected musical stimuli. Each participant listened to a total of seven 90-second excerpts of musical stimuli. These included 2 of their self-reported "neutral" selections, all 3 of their self-reported chills / highly pleasurable selections, and 2 randomized selections from a pool of chills music, which was compiled from a previous study (Sachs et al., 2016) and additional piloting. The following audio extraction was conducted using a custom preprocessing script with the PyDub and PyTube libraries: Audio files were extracted from self-reported YouTube links, trimmed to 90-second selections such that the designated timestamp or time range occurred randomly within the middle 60 seconds of the excerpt (bounded by the beginning and end of the song). Selections were normalized by applying a gain based on the difference from a target of -23 dB from the audio's original decibels relative to full scale (dBFS). During the in-person experiment, stimuli were presented in pseudo-random order, ensuring that the self-reported chills excerpts were not presented consecutively.

Procedure

This experiment consisted of two stages: one remote (pre-screening) and one in-person (music listening).

Remote Pre-Screening: Part 1

The remote stage consisted of an online pre-screening survey, completed prior to attending the in-person portion of the experiment. This survey included: a consent question, the Barcelona Music Reward Questionnaire (BMRQ), the Absorption in Music scale (AIMS) questionnaire, the Goldsmith Musical Sophistication Index (Gold-MSI) questionnaire, the Physical Anhedonia Scale (PAS) questionnaire, and a demographic questionnaire. Additionally, participants completed a self-report form for chills and neutral music. This section asked participants to identify 3 songs with timestamps (mm:ss) or a time range (mm:ss - mm:ss) that gave them the chills. If they did not experience musical chills, they were asked to report 3 songs with timestamps or a time range that they found highly pleasurable. Furthermore, each participant was asked to identify 3 songs with timestamps or a time range that they perceived as neutral. The entire pre-screening survey lasted approximately 20-30 minutes.

In-Person: Part 2

The in-person stage of the experiment took place in the MIND Lab on Northeastern University’s campus. Once they arrived, participants were asked to wash their hands and leave the non-dominant hand slightly damp to increase the accuracy reading of the NeuLog device. The participant then wore the NeuroScouting in-ear device resting on the tragus in the right ear and the NeuLog (GSR) device on the non-dominant hand simultaneously. To input participants into the NeuroScouting app, they were asked to sign up for the study by typing their name and email address in a form presented on the tablet. Participants were previously asked to bring a mobile device to verify their email address. Once their email address was verified, we could begin the experiment. The NeuroScouting app played 7 trials while recording physiological signals with PPG, which include HRV and HR. Before the trials began, a short audio beep track was played to synchronize the NeuLog and NeuroScouting data offline. For each trial, the NeuroScouting app played a 90-second musical excerpt. Before the first excerpt, there was a 30-second rest period for initial readings on the devices. The musical excerpts were taken from the self-report form for chills music of the pre-screening survey. The participant pressed the “chills” button on the app when they experienced chills during the excerpt, which marked a time epoch for the physiological chill-inducing data. After listening to the excerpt, the participant completed a questionnaire, which was assessed on a 7-point Likert scale: engagement, familiarity, pleasure, enjoyment, arousal, valence, thrill, and surprise. The participant also self-reported any musical features of the excerpt that noticeably gave them chills. After repeating the process a total of 7 times with a 30-second period of rest between trials, the participants removed both devices and were thanked for their time. The in-person stage of the experiment lasted about 30 minutes. The entire experiment, both remote and in-person stages, lasted around an hour per participant.

Analysis Plan

Behavioral

Mean scores by question were taken from survey responses acquired after every excerpt. A three-level one factor ANOVA was used to assess significance in behavioral ratings between self-selected chill-inducing, other-selected chill-inducing and neutral stimuli.

Preprocessing Heart Rate, GSR and Heart Rate Variability

Continuous physiological signals were aligned by the onsets of a sync-tone played at the beginning of every participant trial. GSR data (in microsiemens) was de-trended across the trial to reduce the effect of long-term connectivity drifts. Heart rate and variability was acquired through NeuroScouting's online preprocessing pipeline, which included a filtering and peak-finding algorithm (see NeuroScouting materials).

Songs were then marked and segmented from time-locked events collected with the NeuroScouting's custom designed acquisition software. Similarly, data was epoched in 24 second windows beginning 12 seconds before the chill-markers, which corresponded to timestamps at which subjects indicated a music induced chill. For every chill-epoch, a corresponding epoch was randomly selected from the same subject's neutral stimuli as a control comparison.

24 second chills versus neutral epochs were plotted for each of the three physiological measures. In the graphical representation, epochs that deviated in length (due to changes in sampling rate) were excluded. For the linear mixed effects model, analyzing the effect of chill vs. neutral epochs, multiple tests were taken across varying time-windows around the chill event to account

for varying degrees of temporal specificity of the physiological response. All data were included in the statistical analyses.

Exploratory Analyses

Additional analysis will be performed across excerpts (without epoching by chills) to observe differences in large-scale trends between neutral and chill-inducing music.

Results

We hypothesized a negative association between chill-inducing moments and interbeat interval and a positive association with skin conductance. After comparing three physiological measures–heart rate, heart rate variability and skin conductance–between chill-inducing epochs and randomly selected epochs from 'neutral' stimuli, we find a significant increase in heart rate, a significant decrease in heart rate variability (related to interbeat onset) and a prominent peak in skin conductance.

Further, we hypothesized an interaction between musical reward as assessed by the eBMRQ and physiological responses to chills. Our data support this interaction, indicating a significantly higher skin conductance and heart rate response to chills in subjects that fell in the highest tertile of eBMRQ scores. The effect of musical reward is not significant during random neutral epochs, which validates the significance of the differing response to music-induced frissons. The most prominent effect of the chill-reward interaction seems to be in the heart rate and skin conductance measurements. Interestingly, the heightened response of the high-tertile eBMRQ subjects seems to persist across the full 24 second epoch, which suggests that the physiological effect of intense musical moments may be measurable on a large temporal scale.

A linear mixed effects model testing the interaction between eBMRQ tertile and chill vs. neutral epochs while grouping by participant reveals a significant effect of chill epochs ($p<.001$) and a significant interaction between reward tertile and chills ($p<.001$) for heart rate and heart rate variability.

Discussion

We hypothesized that self-selected music would elicit more chills than other-selected or neutral music. We found support for this hypothesis. We further saw that psychophysiological measures, i.e. GSR, BPM, and HRV were sensitive to chills. Results support the idea that chill-inducing music elicits psychophysiological changes and peak experiences in music represent measurable physiological outcomes that may be useful for the design of music-based interventions for health.

Hypothesis 1: Self-reported and randomly selected chill-inducing stimuli are rated as more engaging, pleasurable, surprising and thrilling over neutral stimuli. This hypothesis partially was supported by the behavioral data gathered from the post-listening Likert scale questionnaire. Only self-selected and chill-inducing stimuli were consistently rated as more engaging, pleasurable, surpringing, and thrilling than chill-neutral and other-selected stimuli. The data shows that self-selected chill stimuli were rated as more engaging, pleasurable, and thrilling compared to randomly-selected chill stimuli on average. Randomly-selected chill stimuli were rated as more surprising than self-selected chill stimuli on average. These data support the findings from Salimpoor, 2009 & Mori, 2014 that individuals who experienced chills while listening to their favorite music (self-selected) also experienced intense feelings of pleasure and emotional arousal.

Hypothesis 2: Chill-inducing over neutral epochs induce a lower interbeat interval and higher skin conductance as measured with the given portable physiological devices. Across participants, the results support this hypothesis quite strongly. Lower interbeat interval, inversely correlated with BPM, was found to be higher during chill-inducing epochs compared to neutral epochs (See Figure A). Likewise, HRV was found to be lower during chill epochs than neutral epochs on average across participants. Additionally, skin conductance (GSR) was found to significantly increase during chill epochs compared to neutral epochs (See Figure B). These findings coincide with the literature that these physiological changes accompany chills onset (Salimpoor, 2009; Grewe, 2009). Moreover, these findings parallel those of Salimpoor in that GSR levels are a salient predictor of emotional arousal and chills experience due to their involuntary nature, sensitivity to change, and correlation to pleasure ratings.

Hypothesis 3: Musical reward and ratings of engagement, pleasure and surprise positively correlate with a stronger chill response (lower interbeat interval and higher skin conductance) in chill-inducing stimuli. This is partially supported by the data. Participants rated self-selected chill-stimuli to be more engaging, pleasurable, and surprising than the neutral stimuli. The physiological recordings illustrate that chill epochs elicit lower interbeat intervals and higher spikes in GSR than neutral epochs (See Figures A & B). Musical reward was found to influence chills experience as well. Participants in the upper third tertile of the eBMRQ (“high eBMRQ”) consistently saw the largest physiological changes (HR, HRV, and GSR) during chill epochs compared to neutral epochs (See Figure C). Likewise, those in the middle and lower tertiles of the eBMRQ ratings saw less drastic physiological changes compared to those more sensitive to musical reward. Nonetheless, comparing chill epochs to neutral epochs in terms of musical reward, there was a significant difference in variability in physiological changes across all participants (See Figure C). These data support the predicted positive correlation between higher musical reward and stronger chill response. These findings support the current literature that those less sensitive to musical reward exhibit lower levels of emotional arousal indicated by smaller physiological changes of the ANS (heart rate and GSR) compared to those who are more sensitive to musical reward (Martinez-Molina et al., 2016).

While this study provides valuable insights into music-induced chills, it is not without its limitations. This study primarily included participants from Northeastern University's Foundations of Psychology course as well as friends of the researchers from neighboring universities, in the age range of approximately 18-23. Therefore, this sample may limit the ability to generalize findings to a broader population. Exclusion of individuals with hearing and visual impairments also may not fully represent the broader population. This sample did not include musically anhedonic individuals, which could affect our understanding of how music influences responses in this specific group. Participants who scored low on the PAS and BMRQ questionnaires were considered close to being musically anhedonic and categorized as so. This study did not focus on (differences in) specific genres of music, which could affect how participants responded to the pool of other selected chills music. Participants were compensated for their participation, which may have influenced their responses. This could have led to participants not filling out the pre-screening survey accurately or honestly, affecting the validity of the data collected. On the other hand, this could've led to participants trying to induce chills during the in-person experiment due to nervousness.

This study was the first time the NeuroScouting apps and earbud were utilized for music-related data collection. The NeuroScouting apps were in their beginning stages, so we encountered many bugs and delays in running our pilot testing and in-person experiments. Participants' inexperience with the apps may have affected their engagement or understanding of the tasks.

The growing body of research surrounding the potential impacts of music listening on the autonomic nervous system (ANS) may lead to developments in music-based interventions (MBIs). Our results revealed that chill responses to music result in spikes in GSR, BPM, and heart rate, which are physiological responses of the sympathetic nervous system (SNS). In other words, the experience of music-induced chills has been shown to activate the SNS, which is one of two branches of the ANS. Activation of the SNS drives our "fight or flight" response and the release of adrenaline, while activation of the peripheral nervous system (PNS), the other branch of the ANS, drives us to "rest and digest" (Tindle & Tadi, 2022). Stress management is achieved via deactivation of the SNS and activation of the peripheral nervous system (PNS), which work in opposition with one another (Delaney, 2002). Our ability to understand the impacts of different kinds of music listening on our bodies could be salient to the curation of individualized treatments. Further investigation of the interactions between chill-inducing music, psychophysiological responses, and the autonomic nervous system could contribute to the development of effective MBI treatments.

Overall, this study investigated the physiological experience of music-induced chills through the lens of music reward. These results conclude that the effects of chills experiences on our bodies can be measured through physiological changes in nervous system activity (ie. heart rate and GSR). The chills experience is subjective; it is modulated by individual musical reward response levels. Those more sensitive to emotional and physical influences from music are more likely to experience a music-induced chill than those less sensitive to music. Going forward, further research into the determining factors of musical reward sensitivity, musical feature chill triggers, and a predisposition to chills could help paint a clearer picture of how music affects the human body and mind.

Figures

Figure A

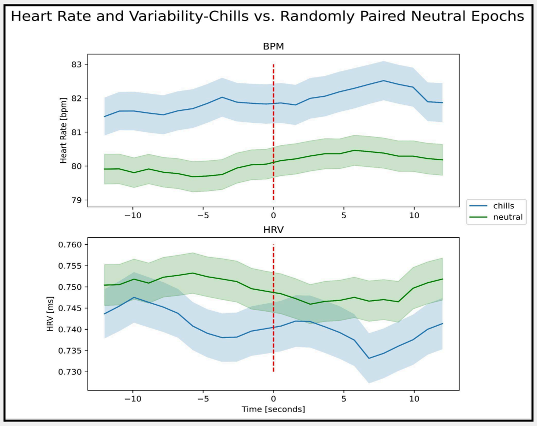


Figure B

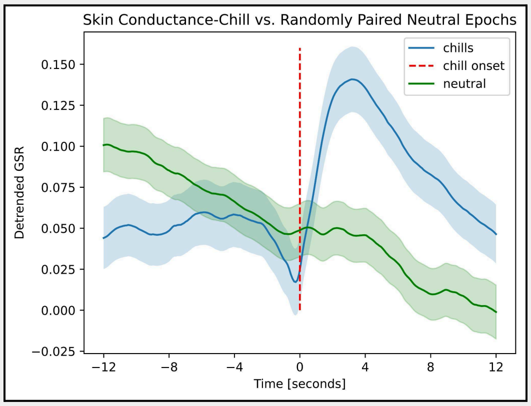


Figure C

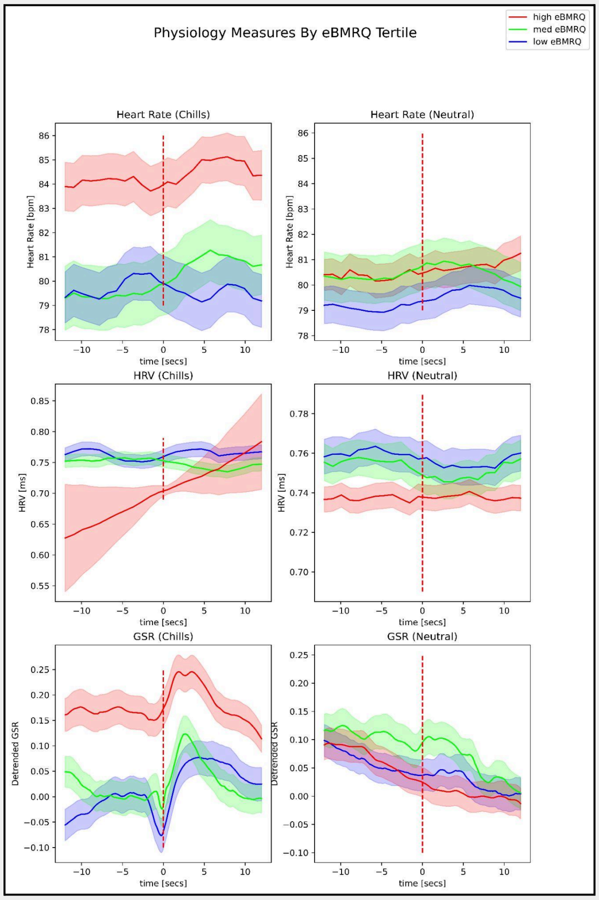
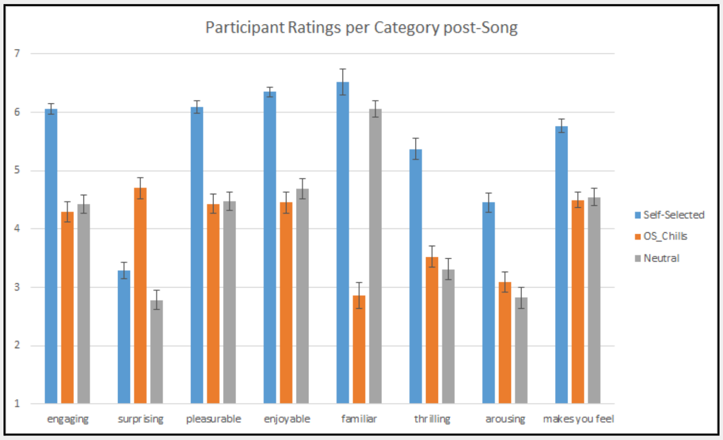


Figure D



References

Colver, M. C., & El-Alayli, A. (2016). Getting aesthetic chills from music: The connection between openness to experience and frisson. Psychology of Music, 44(3), 413–427. https://doi.org/10.1177/0305735615572358.

Craig, D. G. (2005). An Exploratory Study of Physiological Changes during “Chills” Induced by Music. Musicae Scientiae, 9(2), 273–287. https://doi.org/10.1177/102986490500900207.

Grewe, O., Kopiez, R., & Altenmüller, E. (2009). The Chill Parameter: Goose Bumps and Shivers as Promising Measures in Emotion Research. Music Perception, 27(1), 61–74. https://doi.org/10.1525/mp.2009.27.1.61.

Harrison, L., & Loui, P. (2014). Thrills, chills, frissons, and skin orgasms: toward an integrative model of transcendent psychophysiological experiences in music. Frontiers in Psychology, 5, 790–790. https://doi.org/10.3389/fpsyg.2014.00790.

Martínez-Molina, N., Mas-Herrero, E., Rodríguez-Fornells, A., Zatorre, R. J., & Marco-Pallarés, J. (2016). Neural correlates of specific musical anhedonia. Proceedings of the National Academy of Sciences - PNAS, 113(46), E7337–E7345. https://doi.org/10.1073/pnas.1611211113.

Mori, K., & Iwanaga, M. (2014). Resting physiological arousal is associated with the experience of music-induced chills. International Journal of Psychophysiology, 93(2), 220–226. https://doi.org/10.1016/j.ijpsycho.2014.05.001.

Sachs, M. E., Ellis, R. J., Schlaug, G., & Loui, P. (2016). Brain connectivity reflects human aesthetic responses to music. *Social cognitive and affective neuroscience*, *11*(6), 884–891. https://doi.org/10.1093/scan/nsw009

Salimpoor, V. N., Benovoy, M., Longo, G., Cooperstock, J. R., & Zatorre, R. J. (2009). The rewarding aspects of music listening are related to degree of emotional arousal. PloS One, 4(10), e7487–e7487. https://doi.org/10.1371/journal.pone.0007487.

Anttonen, J., Surakka, V. (2007). Music, Heart Rate, and Emotions in the Context of Stimulating Technologies. In: Paiva, A.C.R., Prada, R., Picard, R.W. (eds) Affective Computing and Intelligent Interaction. ACII 2007. Lecture Notes in Computer Science, vol 4738. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-74889-2_26.

Delaney, J. P. (2002). *The Effects of Stress and Relaxation on Heart Rate Variability in Health and Disease* (Order No. 30832278). Available from ProQuest One Academic. (2925388964). https://link.ezproxy.neu.edu/login?url=https://www.proquest.com/dissertations-theses/effects-stress-relaxation-on-heart-rate/docview/2925388964/se-2

Miyata K, Odanaka H, Nitta Y, et al. Music before Dental Surgery Suppresses Sympathetic Activity Derived from Preoperative Anxiety: A Randomized Controlled Trial. JDR Clinical & Translational Research. 2016;1(2):153-162. doi:10.1177/2380084416650613.

Tindle J, Tadi P. Neuroanatomy, Parasympathetic Nervous System. [Updated 2022 Oct 31]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK553141/