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Rhythmic Entrainment of Heart Rate as a Mechanism for Musical Emotion Induction: A Plausible Hypothesis in Need of Evidence?

Patrik N. Juslin[1], Laszlo Harmat[2], Gonçalo Barradas[3], Gustaf Omstedt[1], and Veronica Redtzer[1]

[1] Department of Psychology, Uppsala University

[2] Department of Psychology, Linnaeus University

[3] School of Health and Society, University of Salford

Author Note

Correspondence concerning the manuscript should be addressed to Dr. Patrik N. Juslin, Division of Emotion Psychology, Department of Psychology, Uppsala University, Box 1225, SE - 751 42 Uppsala, SWEDEN. E-mail: patrik.juslin@psyk.uu.se

Abstract

Several researchers have hypothesized that a musical rhythm can influence a listener's heart rate through a process of entrainment and that this mechanism can influence the emotional feelings of the listener also. However, previous research has yielded mixed results, perhaps due to methodological problems. In this study, we independently manipulated the tempo of pieces of ambient instrumental music with a salient rhythm to influence the heart rate of 36 listeners with varying musical backgrounds, who also reported felt arousal and valence and subjective impressions of various induction mechanisms. Using a 2 × 2 × 2 factorial design, we manipulated direction (up vs. down) and magnitude (±3 % vs. ±30 %) of tempo change and extent of listener movement (finger tapping vs. still listening). For each trial, the tempo was manipulated in reference to the present heart rate of the individual listener. The results showed little evidence of entrainment: In general, listeners' heart rate did not align with the target tempo (i.e., entrainment proper), nor did it change in the direction of the target tempo (i.e., entrainment tendencies). Instead, regardless of direction and size of tempo change, we observed a similar small increase in heart rate and arousal. The results are consistent with a general arousal effect of musical rhythm.

Key words: music listening, emotional arousal, heart rate, rhythmic entrainment, tempo

Rhythm is a fundamental aspect of music (Kotz et al., 2018). Gaston (1968) referred to rhythm as “the organizer and energizer” (p. 17), noting that the favorite music of adolescents almost always contains ‘a driving beat’. Its repetitive structure enables them to synchronize their movements and inner bodily processes with the music. This is an example of a general phenomenon called *rhythmic entrainment* (Thaut, 2008).

Rhythmic Entrainment

The process of entrainment was first discovered by Huygens (1669), who observed that two pendulum clocks with close but unsynchronized periods, mounted on the same wall, will eventually synchronize their strokes. The different amounts of energy transferred between the moving pendulums - due to their initially asynchronous movement periods - cause a negative feedback loop. This feedback drives an adjustment process, in which the difference in energy is gradually reduced to zero, so that the bodies move in synchrony (Thaut et al., 2015).

There are two components required for rhythmic entrainment to occur: First, there must be at least two autonomous *oscillators*. (Oscillators are entities that cycle automatically at more or less regular time intervals.) Second, the oscillators need to be *coupled*, via some physical or chemical process that allows them to influence one another (Clayton et al., 2005).

The resulting process might involve (1) *period* entrainment (i.e., that the oscillators have the same frequency) and (2) *phase* entrainment (i.e., that the focal points occur at the same time). However, it is period entrainment that ‘drives’ the process (Thaut et al., 2015); it is possible to have period entrainment without phase entrainment, but it is not possible to have phase entrainment without period entrainment.

Entrainment is found throughout nature; it seems to be evidenced in some way or other by all animals and plant species. Yet it may be especially salient in humans. Jones and Boltz (1989) argued that human beings are inherently rhythmical creatures, with tunable perceptual rhythms which entrain to a variety of time patterns of the external world. A distinction could be made between the underlying *mechanism* of entrainment (i.e., a gradual mental coupling of oscillators in the brain) and its *manifestation* as 'internal' (e.g., perception, psychophysiology) or 'external' (e.g., motor behavior) synchronization (Juslin, 2019).

Although many types of human behavior (e.g., speech) exhibit rhythmic aspects, none does more so than musical behavior. Hence, it is not surprising that synchronized behavior - as a possible sign of entrainment processes - has been found in a variety of musical contexts in every culture (e.g., Becker, 2004; Keil & Feld, 1994; McNeill, 1995).

Thaut (2008) proposed that all bodily pulses tend to entrain to a musical pulse without conscious effort. Most music listening in everyday life in the modern Western world seems to involve pre-recorded music (Juslin et al., 2008). In such a context, the entrainment can be called 'asymmetrical': Listeners entrain to sounds they cannot themselves influence.

Induction of Emotions

One hypothesized consequence of rhythmic entrainment is that it might influence the emotional *feelings* of the listener. In fact, several scholars have argued that entrainment is a plausible candidate mechanism for musical induction of emotions (cf. Agostino et al., 2008; Becker, 2004; Juslin, 2013, in press; Scherer & Coutinho, 2013; Trost et al., 2017).

Manifestations of entrainment at the *physiological* level might be the most promising route to explain possible rhythmic-entrainment effects on emotions (Juslin, 2019). This is because previous research has already shown that an emotion can be induced not only top-down (central evaluative processes in the brain influencing the body), but also bottom-up (changes in physiological responses influencing brain processes; e.g., Levenson, 2014).

In the present context, then, *rhythmic entrainment* refers to a process where an emotion is induced by a piece of music because a powerful 'external' rhythm in the music is affecting an 'internal' bodily rhythm of the listener (e.g., heart rate), such that the latter rhythm adjusts toward and eventually 'locks in' to a common periodicity (Juslin, 2013, 2019). This adjusted pulse rate then spreads to other emotion components such as feeling (Scherer, 2000), through *proprioceptive feedback* (signals from sensory receptors in muscles, joints, and skin that help to regulate one's movement; Craig, 2016), thus producing a change in the listener's emotions.

It has been suggested that rhythmic entrainment primarily regulates the *arousal* level in listeners - depending on whether the bodily process is entraining to a faster or slower musical rhythm (e.g., an increase in arousal to a faster piece of techno music vs. a decrease in arousal to a slower lullaby).

It has also been proposed that entrainment may contribute to certain positively valenced states, such as a sense of intimacy (Juslin, 2019), social bonding (Stupacher et al., 2020), feeling connected (Juslin, 2013), and joyful activation – including "an action tendency to dance" (Zentner, 2010, p. 108). Thus, Clayton et al. (2020) concluded that music is a context in which the potential for entrainment to induce affect and reinforce social bonds is exploited to the fullest degree.

Previous Studies

The notion of rhythmic entrainment as an induction mechanism seems compelling, but actual evidence that entrainment may induce emotions during music listening has been slow to emerge. Early studies focused mostly on whether musical rhythms could influence bodily rhythms *per se*. For instance, Harrer and Harrer (1977) reported that (some) listeners tended to synchronize either their heart rate or their respiratory rhythm to the music, and that it was possible to drive their pulse with appropriate music.

Bason and Cellar (1972) and Saperston (1993) both reported successful manipulation of a listener's heart rate, provided that the tempo of the stimulus was close to the listener's heart rate. However, both studies featured a special procedure, during which the frequency of the stimulus was coupled to the heart rate of the listener in real-time in a constant feedback loop. Even *if* entrainment could be demonstrated using this type of control, its ecological relevance seems limited; Music does not usually adapt its tempo to a listener's heart rate in a continuous loop.

More recent studies of entrainment have reported primarily negative results. Thus, for instance, van Dyck et al. (2017) played non-vocal ambient music to listeners at a tempo that corresponded to their current heart rates. Then, the same excerpt was played again, with the tempo increased or decreased by 15%, 30%, or 45%. The researchers did not find any heart rate-to-music alignment, suggesting that "human heart rates do not entrain to musical beats" (p. 400). Rather they observed a "general arousal effect" (p. 391) of the music.

Similarly, Labbé Rodriguez (2015) failed to obtain (strict) entrainment of heart rate or respiration to musical rhythms in two experiments which featured either chord sequences or piano pieces. The author conceded that period and phase synchronization "would have been unlikely" (p. 166) with the tempi used (e.g., 128 bpm), which were presumably far from the heart rates of most listeners in these experiments.

Mütze et al. (2020) also made an attempt to influence heart rate using rhythmic stimuli. They programmed a regulatory 'feedback loop' to continuously measure the heart rate of the listener. A simple Djembé-beat was used as the stimulus and coupled to the current heart rate in real-time (replicating, as far as possible, the procedure that was used in Saperston's (1993) study). The authors found little evidence of adaptation of the heart rate to the stimulus tempo.

Because of the reported difficulties in obtaining strict entrainment of the heart rate to a musical rhythm in several studies, some researchers have suggested that we should relax the requirements and adopt a soft definition, according to which it is sufficient to show that the physiological response moves in the right direction – for example, that the heart rate of the listener accelerates *towards* a faster musical rhythm (i.e., without adopting a similar period); so called 'synchronization tendencies' (Labbé Rodríguez, 2015, p. 18). For examples of such tendencies, see Etzel et al. (2006), Khalfa et al. (2008), and Nyklicek et al. (1997).

However, it is debatable whether these studies have actually measured entrainment. The problem with the 'soft' definition of entrainment is that if we do not demand the same period, how can we distinguish entrainment from just *any* change in autonomic arousal? Any emotion that is high in activation will involve a high autonomic arousal, which may be mistaken for an 'entrainment tendency', even if the emotion was not caused by the process of entrainment.

Note further that several studies actually failed to obtain evidence of any adaptation of the heart rate even *toward* the musical tempo (see Dousty et al., 2011; van Dyck et al., 2017; Koelsch & Jäncke, 2015; Krabs et al., 2015; Mütze et al., 2020), thus calling into question if musical tempo per se affects heart rate *at all*.

Possible Limitations

How can the mixed findings in previous studies be explained? One possibility is that the studies have in some way failed to create the ideal conditions for entrainment to occur. First, some of the experiments have used a fairly short stimulus duration (e.g., 60 s; van Dyck et al., 2017), which may be problematic since the entrainment process is likely to take time (Clayton et al., 2005).

Second, some studies have used a target tempo that could be too far from the current heart rate of the listener (e.g., 128 bpm; Labbé Rodriguez, 2015, p. 166). For two oscillators to entrain, their periodicities need to be relatively close (Aschoff, 1979). Moreover, because there are such large individual differences in (resting) heart rate, the only way to ensure that the periodicities are close is to adjust the target tempo *individually* in each trial, according to the current heart rate of the listener.

Third, as noted by van Dyck et al. (2017), many of the studies that reported effects of tempo on heart rate did not actually *isolate* the effects of tempo from other possible factors, such as timbre (Bernardi et al., 2009). There is a whole range of musical features that could influence the heart rate and subjectively felt arousal of listeners. Moreover, such changes in heart rate and arousal might be mediated by a number of different mechanisms - apart from entrainment (see Juslin et al., 2014, 2015).

Fourth, some studies only tested entrainment to faster tempi (Mütze et al., 2020). This type of design makes it hard to distinguish mere 'arousal effects' of the music from genuine 'entrainment tendencies' (which follow the *direction* of the tempo change: up vs. down).

Finally, several studies have failed to take into account aspects of the musical stimulus that could influence the ease with which entrainment can be established (e.g., using a simple click; Bason & Cellar, 1972). This may include various rhythmic aspects that contribute to a sense of 'groove' - "the aspect of the music that induces a pleasant sense of wanting to move along with the music" (Janata et al., 2012, p. 56). These limitations provided the impetus for our investigation.

The Present Study

Previous studies have reported evidence of neural oscillations which entrain to external rhythms (Henry & Grahn, 2017; see, e.g., Thut et al., 2011). Thus, the first requirement for a hypothesized rhythmic entrainment mechanism is fulfilled. However, what has still not been convincingly demonstrated is that a listener's heart rate may align its period or a subdivision with a musical rhythm, and that this change in physiological rhythm induces a change in felt emotions (Juslin, 2019). Current evidence of musical induction of emotion through rhythmic entrainment is based on self-reports (see Juslin et al., 2016, 2022; Labbé & Grandjean, 2014) and must therefore be regarded as circumstantial.

The overall aim of the present study was thus to further test the rhythmic entrainment mechanism (addressing possible limitations in previous research) and to consider variables that could moderate its effects. We focused on entrainment of the *period* (as opposed to the phase), because it could be considered a prerequisite for all types of entrainment. Specifically, we investigated the following questions:

● *Can the tempo of a musical rhythm influence listeners' heart rate such that it changes in the direction of the tempo?*

Based on some previous studies, which found that respiration rate and/or heart rate can change *towards* the tempo of music (Etzel et al., 2006; Khalfa et al., 2008; Labbé Rodriguez, 2015; Nyklicek et al., 1997), we hypothesized that listeners' heart rate would change in the direction of a target tempo ('entrainment tendency') (H1).

● *Can the tempo of a musical rhythm influence listeners' heart rate such that it becomes aligned with the tempo?*

Based on preliminary and/or anecdotal evidence that internal bodily rhythms, such as heart rate and respiration, may entrain to musical rhythms (Bason & Celler, 1972; Harrer & Harrer, 1977; Kneutgen, 1970; Saperston, 1993), we hypothesized that listeners' heart rate would become aligned with a target tempo ('entrainment proper') (H2).

● *Does the entrainment process have any influence on listeners' experienced feelings?*

Based on theoretical arguments regarding rhythmic entrainment (Juslin, 2019, Ch. 19) and evidence of bottom-up effects of autonomic arousal on feelings (Levenson, 2014), we hypothesized that entrainment of the heart rate with the target tempo would influence listeners' feelings in accordance with the direction of the entrainment process (*high*-arousal feelings to a *faster* tempo, *low*-arousal feelings to a *slower* tempo) (H3). We further hypothesized that entrainment of the heart rate would be correlated with positively valenced feelings (Levitin, 2010, p. 54) (H4).

● *Is the ease with which entrainment is established affected by the direction of change?*

Although one might expect heart rate to more easily increase rapidly than to decrease rapidly (e.g., during critical events), theory suggests the opposite: due to a predominance of the parasympathetic nervous system in heart rate control (see Uijtdehaage & Thayer, 2000), deceleration may be more efficient. Furthermore, perceptual research suggests that listeners respond more quickly and with greater sensitivity to tempo decrease than to tempo increase (see Kuhn, 1974). Thus, we hypothesized (H5) that listeners would entrain more easily to a rhythm that is slower in tempo, than to a rhythm that is faster in tempo.

● *Does the magnitude of the attempted change in heart rate have any influence on the tendency towards entrainment?*

The present study featured both small (±3%) and large (±30%) magnitude conditions. It was hypothesized (H6) that a small magnitude would be more amenable toward entrainment because it is believed that the periodicities of two oscillators need to be fairly close for them to entrain (e.g., Aschoff, 1979). By contrast, a large magnitude would instead produce more general arousal effects (Hodges, 2010), without 'entrainment proper'.

● *Does a listener's movement in synchrony with the musical rhythm influence the ease with which entrainment is established?*

Rhythmic entrainment, as an emotion-induction mechanism, is not presumed to depend on external movements, since even 'passive' listening has been found to activate the relevant brain areas, such as the basal ganglia, the cerebellum, and the premotor cortex (e.g., Henry & Grahn, 2017). Nevertheless, the entrainment process may be *reinforced* by movements, since moving along with a rhythm improves perception of that rhythm (Henry & Grahn, 2017) and because entrainment processes manifested at different levels are believed to affect each other (Trost et al., 2017). Thus, we hypothesized that listeners would show greater tendencies towards entrainment to a musical rhythm when moving in synchrony with the music (through finger tapping) than when sitting still (H7).

Finally, the study included a co-variate, the *musical training* of the listener, which might moderate entrainment effects. Based on preliminary results that entrainment tendencies can be influenced by the level of expertise (Doelling & Poeppel, 2015), we hypothesized that listeners' entrainment would be (positively) correlated with their level of musical training (H8).

Method

Participants

Our power calculations showed that 36 participants were required for a within-subjects *t*-test (one-tailed), with a power of .90 and a *medium* effect size (as estimated using G*Power 3.1.9.7; Faul et al., 2007). We aimed to sample 40 participants, but managed to recruit 38. Two of them had to be removed, however, due to problems with their physiological measures.

Hence, 36 listeners, 17 females and 19 males, 21-56 years old (M = 25.58, SD = 6.69), were featured in the sample. They did not receive any compensation for their anonymous and voluntary participation. The aim was to include people who varied with regard to age, gender, occupation, education, and musical expertise. They were recruited by means of posters, social media, and a mailing list for music seminars. Twenty of the 36 participants played at least one musical instrument (of which guitar, piano, and strings were the most common), and 12 stated they had received music education. One participant reported a mild hearing problem, but was retained in the sample.

Musical Material

In selecting a musical stimulus, we attempted to strike a balance between reducing the potential impact of musical features other than rhythm and avoiding that the stimulus would be so impoverished that it would not be music-like anymore. One further requirement was that the piece should be possible to play back in a variety of tempi and still sound musically acceptable. However, because there are wide individual differences in resting heart rate (40-100 bpm), we needed to feature multiple pieces that could cover different tempo ranges in a satisfactory way, as confirmed by pilot tests. Although this meant that listeners might listen to different pieces, this was not regarded as a problem because entrainment was tested using within-subjects tests where listeners served as their own controls.

The choice ultimately fell on five instrumental pieces of so-called ambient music with strong and salient rhythms and just enough other musical features so as to avoid that listeners would become bored (Appendix A). All stimuli include rhythmic features known to create a strong sense of 'groove' (e.g., strong pulse, syncopation; Witek et al., 2014). Sound quality was adjusted so as to enhance bass frequencies of the rhythm, since researchers have suggested that this helps to stimulate the vestibular system - contributing to beat induction (Todd & Lee, 2015). Control measures - in terms of ratings of *familiarity* and *liking* on a scale from 0 to 4 - showed that the pieces were unfamiliar (M = 0.91, SD = 1.33), but reasonably well liked (M = 2.26, SD = 1.15).

All tempo manipulations were achieved by means of a *Roland CD-2u SD/CD* recorder device (Roland Corporation, Osaka), which makes it possible to change the tempo of a piece without changing the pitch, using advanced time-stretching algorithms. Pilot tests confirmed that listeners were unable to detect that a piece had been altered with regard to tempo. Using this device, the musical tempo could be instantly changed in accordance with a set target.

Measures

Heart Rate

Heart rate was estimated using measures of pulse rate. Although the two indices are technically different[1], differences between them tend to be small to non-existent in people without a heart condition. Thus, pulse rate may be used to measure heart rate for a normal, healthy heart. Pulse rate measures have the advantage that they are user-friendly.

Pulse rate was measured based on the arterial pulse pressure, using the PPG 100C Pulse Plethysmogram Amplifier and the TSD200 photoplethysmogram transducer (Biopac Systems,

[1] *Heart rate* is the number of times the heart contracts in one minute, whereas *pulse rate* is the number of times the blood vessels expand and contract in one minute.

Santa Barbara, CA) attached to the index finger on the non-dominant hand. The TSD200 uses an infrared emitter and a photodiode detector, which transmits changes in infrared reflectance resulting from varying blood flow. Band-pass filters were used to remove frequencies below 0.05 Hz and above 10 Hz. Heart rate was measured in beats per minute (bpm).

Data were analyzed using the BIOPAC MP 150 System (Santa Barbara, CA) and the AcqKnowledge (software version 4.1). Three types of heart rate data were of interest: The *starting* heart rate of the listener just before the music began; the *target* heart rate of the listener (corresponding to the manipulated tempo, based on the listener's current heart rate and the experimental condition, e.g., '30% down'); and the *final* heart rate of the listener (based on the final 30 s of the stimulus presentation).

These data were used to analyze two contrasts: (a) *change* (the difference between the listener's 'starting' heart rate and 'final' heart rate, and (b) *distance* (the difference between the 'target' heart rate and the listener's 'final' heart rate). *Change* is an index of entrainment tendency (does the heart rate change in the right direction of the 'target'?) whereas *distance* is an index of entrainment proper (does the heart rate align with the 'target'?). In the case of perfect period entrainment, the value of *distance* should approach zero. Difference scores of *distance* were used to examine three moderators (i.e., direction, magnitude, and movement).

Emotional Feelings

Because rhythmic entrainment is conceptualized as a low-level mechanism that mainly influences levels of arousal, we adopted a dimensional approach to emotion (Russell, 1980). Thus, participants rated their subjective feelings, in terms of the two dimensions *arousal* (or *activation*) and *pleasure* (or *valence*). The *arousal* dimension ranges from *sleepy/passive* to *aroused/active*; the *pleasure* dimension ranges from *negative/miserable* to *positive/pleasant*. Both dimensions were rated on a scale, from -2 to +2, in response to the statement "describe your feelings while you listened to the music". In addition, the participants rated their *liking* and *familiarity* with respect to the musical stimulus (as control measures), and *how strongly connected they felt to the music* (a measure of 'intimacy', a proposed subjective correlate of entrainment; cf. Levitin, 2010). All were rated on a scale from 0 (*not at all*) to 4 (*a lot*).

Mechanism Indices

We also collected subjective data about mechanisms that may have occurred, using the *MecScale* (e.g., Juslin et al., 2014, 2022). This consists of eight questions, each targeting one of the mechanisms in the BRECVEMA theory (Juslin, 2013; Appendix B). Participants rated each item on a scale, from 0 (*not at all*) to 4 (*very much*). The *MecScale* items do not purport to measure the mechanisms directly, but can tap *subjective impressions* associated with them. The items have been predictive of both target mechanisms (Barradas et al., 2021; Juslin et al., 2014; Sakka & Juslin, 2018) and felt emotions (Juslin et al., 2015, 2022) in previous research. The items were included here primarily to help rule out that observed changes in felt emotion were caused by mechanisms *other* than entrainment.

Experimental Design

The experiment used a mixed factorial design that featured three independent variables: (a) *direction* (2 levels: up vs. down; within-subjects factor), (b) *magnitude* (2 levels: small vs. large; within-subjects factor), and (c) *movement* (2 levels: requested vs. not allowed; between-subjects factor). In addition to this 2 × 2 ×2 design, there was a pretest condition that featured non-rhythmical music (see Procedure). Dependent variables were measures of heart rate, self-reported feelings (arousal, valence), and subjective impressions of induction mechanisms. We also included level of musical training as a covariate.

Procedure

After the participants read their instructions and provided informed consent, the experimenters fitted them with the device for heart rate measurement. It was explained that this device should not be touched during the listening test, that watches and rings had to be removed, and that cell phones must be switched off.

Prior to the entrainment trials, there was a short pre-test during which the participants listened to a piece of instrumental music that lacked a clear rhythm (Appendix A). This test familiarized the participants with the procedure and the questionnaire, and served as a (non-rhythmic) control condition.

Then the actual entrainment trials followed. We generated a specific stimulus order (*3% up*, *30% down*, *30% up*, *3% down*), which was counterbalanced. The listeners were randomly assigned to one of the orders. Every trial started with a brief relaxation phase, in order to help the participant's heart rate to stabilize. By observing a moving average of the heart rate, using a smoothing-filter with 2.000 samples at 125 Hz to obtain a stable reading, the experimenters could select a musical piece with appropriate tempo range (Appendix A). Then, directly based on the participant's current heart rate, the experimenters instantly set the 'target' tempo of the music in accordance with the requirement of the experimental condition (i.e., faster or slower, small or large magnitude). The calculations of 'target' tempo based on current heart rate were handled by a computer algorithm.

Regardless of tempo, the participant listened to the musical stimulus for a total of 120 seconds during which the heart rate was measured continuously. In one experimental group the participant was asked to move in time with the music (through finger tapping), while in the other, the participant was asked to sit completely still. The experimenters observed the participant to verify that these instructions were followed. After the music, the participant responded to the questions about felt emotions and mechanism impressions.

The participants were tested individually in a dimly lit and sound-attenuated laboratory. They were asked to keep their eyes closed while listening to the music (to avoid distractions). The musical stimuli were played through a pair of high-quality headphones (*Shure SRH 1840*) at a carefully calibrated sound level (kept constant across participants). After the listening test, the participants were required to fill out a background questionnaire, and were also de-briefed about the experiment. All self-reports were obtained using the *MediaLab* software (Empirisoft corporation, New York). A complete experimental session lasted about 60 minutes. The study was approved by the Swedish Ethical Review Authority (dnr: 2021-05235).

Results

Heart Rate Measures

Change

The results concerning *change* show if the stimuli induced a change in listeners' heart rate, and whether the change was in the expected direction. Figure 1 shows means, standard errors, and standard deviations for 'starting' and 'final' heart rate in each condition. As may be seen, regardless of the condition, there was a minor increase in listeners' mean heart rate (mean d, across conditions = 0.203, a 'small' effect; Cohen, 1988).

(Insert Figure 1 about here)

In order to confirm these trends, we conducted a series of t tests (within-subjects) of the difference between the 'starting' and 'final' heart rates in each condition.[2] Table 1 presents the results. As seen, there was a significant increase in all experimental conditions except for *30% down*.[3] Careful inspection of Figure 1 suggests that the increases were slightly larger in the *up* conditions than in the *down* conditions, which is confirmed by the effect size measures shown in Table 1. They suggest a near-linear trend with the largest increase in heart rate occurring in the *30% up*, followed by the *3% up*, *3% down*, and *30% down* conditions. The pre-test, which

[2] We decided against using Bonferroni adjustment because (a) we only tested pre-planned hypotheses (as opposed to searching for significant effects), (b) we were not interested in the 'universal' null hypothesis (i.e., that all null hypotheses are true simultaneously), and (c) the modest listener sample (N = 36) meant that we needed to strike a balance between the risks of making Type I and Type II errors (Perneger, 1998).

[3] A check of individual data showed that in 76% of the cases, the results were in accordance with the mean trend (a small increase).

included non-rhythmic music, also produced a minor increase in heart rate, but this difference was not significant ($t(35) = -1.774$, $p = .085$, 95% CI [-0.201, 2.986], $d = 0.100$).

Distance

Having found that the musical stimulus influenced the heart rate of listeners and that it did so in the direction of the intended manipulation for two of the four conditions, we wanted to check if any of the conditions produced ‘entrainment proper’ (i.e., tempo alignment). Thus, we considered the data on *distance*, indicating whether the listener’s ‘final’ heart rate aligned with the ‘target’ (the musical tempo) or not.

Figure 2 shows the means, standard errors, and standard deviations for ‘final’ heart rate and ‘target’ heart rate. Careful inspection suggests that, in general, the ‘final’ tempo diverged from the ‘target’ in all conditions except *3% up*. This was confirmed by carrying out a series of *t* tests (within-subjects) of the difference between the ‘final’ and ‘target’ heart rate in each condition: see Table 2. There was a highly significant difference between ‘final’ and ‘target’ heart rate in all conditions, except for *3% up*. Considered in isolation, the data for the *3% up* condition fulfilled the formal requirement for ‘entrainment proper’, because the ‘final’ heart rate was virtually indistinguishable from the ‘target’.

(Insert Figure 2 about here)

Moderators

We carried out a three-way mixed ANOVA of the *distance* data, in terms of difference scores. The analysis featured the three moderators of the experimental design with *Direction* (2 levels, up vs. down) and *Magnitude* (2 levels, small vs. large) as within-group factors, and *Movement* (2 levels, requested vs. prohibited) as between-group factor.

The results are summarized in Table 3. As may be seen, there was no significant main or interaction effect involving *Movement*. Conversely, there was a significant main effect of *Direction*, which mainly reflects that listeners’ heart rate increased in *all* conditions. For this reason alone, listeners' heart rate data were closer to their 'targets' in the *up* conditions. This effect was qualified, however, by a significant interaction between *Direction* and *Magnitude*, a 'strong' effect (partial $\eta^2 = 0.912$; e.g., Ferguson, 2009). When the 'target' involved a large change, *distance* increased (because the heart rate showed a small increase in all conditions); and this effect was obviously modulated by direction (along the lines explained above).

To examine if individual tendencies towards entrainment were associated with musical expertise, we computed the Pearson correlation between individual *distance* scores across all conditions and individual level of *musical training* (indexed by degree of musical instrument playing and formal music education). The two measures were not associated ($r(34) = 0.035$, $p = .838$), indicating that musically trained listeners' heart rates did not entrain with the music to a greater extent than those of untrained listeners.

Self-reports

Feelings

In order to investigate the effects of the tempo manipulation on the listeners' self-reports of felt *arousal* and *valence*, we carried out a one-way ANOVA with *experimental condition* as within-subjects factor (5 levels) on each rating scale. For *arousal*, the results revealed a highly significant effect ($F(4,148) = 29.069$, $MS = 22.087$, $p < .001$, $\eta^2 = 0.440$, a 'moderate' effect size; see Ferguson, 2009). As seen in Figure 3 (upper panel), the effect was primarily attributable to the difference between the control condition and the four rhythmic conditions. 'Post hoc' tests in terms of Tukey HSD confirmed that only the contrasts involving the control condition were significant ($p < .001$) and that the differences among the four rhythmic conditions were not. In other words, self-reported *arousal* did not vary depending on tempo-change direction, but was relatively high in general (see Figure 3).

(Insert Figure 3 about here)

As regards the *valence* ratings, we did not find any significant effect ($F(4,148) = 1.813$, $MS = 1.518$, $p = .129$, $\eta^2 = 0.047$). Inspection of the lower panel in Figure 3 suggests that *valence* was rated a little higher for the control condition, but none of the contrasts was significant, as indicated by 'post hoc' tests (Tukey HSD). In general, the mean ratings of *valence* were high, showing that listeners experienced mainly positive affect. One can discern a somewhat linear tendency for valence to increase, from the *down* conditions to the *up* conditions, but this may simply reflect random variability. Self-reports of 'intimacy' (i.e., how strongly connected the listeners felt to the music; a possible correlate of entrainment) were low overall ($M = 1.336$).

Mechanism Indices

In an attempt to rule out the possibility that emotion-induction mechanisms other than rhythmic entrainment had influenced the results, we examined the listeners' mean ratings of the *MecScale* items (Appendix B). The results are shown in Figure 4, in terms of the ratings of all items, across the rhythmic conditions (upper panel); and the ratings of the *entrainment* item in each condition (lower panel). As can be seen in the upper panel, the rhythmic stimuli produced high ratings on the *entrainment* item (*Did the music have a strong and captivating pulse/rhythm?)*, but not on the other items. A one-way ANOVA with *item* as within-subjects factor (8 levels) yielded a highly significant overall effect ($F(7,1057) = 95.305$, $MS = 93.950$, $p < .001$, $\eta^2 = 0.387$, a "moderate" effect), while 'post hoc' tests (Tukey HSD) confirmed that the *entrainment* item received higher mean ratings than all the other items (all *p's* < .001). Note, however, that a few listeners rated the visual imagery item highly also (see Figure 4).

(Insert Figure 4 about here)

The lower panel in Figure 4 suggests that the *entrainment* item was rated similarly high in the four rhythmic conditions, albeit low in the control condition. A one-way ANOVA, with *condition* as within-subjects factor (5 levels), yielded a highly significant overall effect

($F(4,148) = 66.983$, $MS = 45.092$, $p < .001$, $\eta^2 = 0.644$, a "large" effect). 'Post hoc' tests confirmed that the ratings of the *entrainment* item did not differ significantly among the rhythmic conditions, but that all of these were significantly different from the control condition ($p < .001$).

Discussion

The present study aimed to explore rhythmic entrainment and possible moderators of its effects. The results were clear but not as expected: Although the music had significant effects on listeners' heart rate ($d = .203$), we did not obtain any evidence of rhythmic entrainment, as indicated by either heart rate or self-reported feeling. Overall, the listeners' heart rate did not align with the 'target' tempo (i.e., 'entrainment proper'), nor did it change in the direction of the target tempo (i.e., 'entrainment tendency').

Technically speaking, and when considered in isolation, the data in the *3% up* condition *did* fulfill the requirement for 'entrainment proper', because the 'final' heart rate was virtually indistinguishable from the 'target'. However, when viewed in context, it appears unlikely that these data were the result of entrainment, because regardless of the direction and size of tempo change, we found a (roughly) similar small increase in heart rate. This increase was smaller in the 'down' conditions than in the 'up' conditions - but it was an increase nevertheless. It is key that the design featured manipulations of both magnitude and direction: Had we only featured an upward direction and a small magnitude (3%), we would (erroneously) have concluded that entrainment *did* occur. Instead, we found that listeners' heart rate increased approximately 3% regardless of the experimental condition.

Largely as a consequence of this finding, we could not support any of our hypotheses: We did *not* find that listeners' heart rate changed in the direction of the 'target' tempo (H1), that listeners' heart rate became aligned with the 'target' (H2), that the entrainment process influenced listeners' feelings in accordance with the direction of the entrainment (H3), that entrainment induced positive feelings (H4), that listeners entrained more easily to a slower rhythm than to a faster rhythm (H5), that a small tempo change was more amenable toward entrainment (H6), that listeners showed greater tendency toward entrainment when moving in synchrony with the music than when remaining still (H7), or that entrainment tendencies were correlated with level of musical training (H8). Most of the hypotheses were obviously dependent on having obtained entrainment.

How can the results be explained? One possibility is that the hypothesis that rhythmic entrainment is a mechanism for musical induction of emotions is wrong. Such a conclusion seems premature, however, considering the relatively limited number of proper tests of the hypothesis carried out so far. Another possibility is that despite our best efforts, the stimuli used did not present the ideal conditions for entrainment to occur. However, our findings offer few clues about what could be done to improve the conditions.

It does *not* seem likely that the findings were due to (a) listeners not finding the music engaging (rated arousal levels were quite high); (b) listeners not enjoying the music (rated valence was positive); or (c) the music not being sufficiently rhythmic (ratings of the item 'did the music have a strong and captivating pulse/rhythm?' were high). Nor does it appear that the music engaged other mechanisms (e.g., memory) in a way that would interfere with the entrainment process (as indicated by listeners' ratings on the *MecScale*). A few listeners reported *visual imagery* (perhaps enhanced by instructions to keep eyes closed), though this high-level mechanism should hardly prevent rhythmic entrainment (a presumed automatic process at a lower level of the brain) from occurring.

It is possible that the participants were nervous due to the testing situation and that this might have affected their heart rate. However, nervousness would be expected to produce an increase in heart rate and a ceiling effect preventing further increases. Here, we *did* find an increase (albeit no decrease). It is true that heart rate measures are highly variable and prone to artifacts, but this type of variability should arguably affect all conditions equally. Thus, it cannot explain why we failed to obtain a differential effect of tempo on heart rate. Perhaps it could be argued that entrainment may involve *subdivisions* of the beat, rather than only strict alignment with the beat; but the idea that such subdivisions might explain why the heart rate increased in all conditions regardless of tempo stretches credulity.

To be sure, this study was limited in a number of ways. For example, it included only a single musical genre (ambient instrumental music); it manipulated tempo in terms of just two magnitudes; it used a single procedure; and it featured a nonrandom sample of listeners. Note however that previous studies have used other stimuli, magnitudes, procedures, and listeners; and yet they have also failed to obtain entrainment (Mütze et al., 2020; van Dyck et al., 2017).

It is, of course, possible that the entrainment mechanism works in a different manner. One may argue that it is not linked to heart rate, but rather to a more direct neural resonance in the brain, or that it mainly works through breathing processes (which however are related to heart rate). This could then help to explain the lack of heart rate entrainment in this study. Still, it could not explain why we found no entrainment effects of tempo manipulations on self-reported arousal or valence. We think it is perfectly possible, even likely, that neural entrainment to the rhythm occurred at some level of the brain of the listeners, but that is not the issue: The issue is whether entrainment can influence the emotional feelings of listeners.

Our data are more consistent with a *general* 'arousal effect' of music (Berlyne, 1971; Hodges, 2010). This effect on heart rate and feeling is most likely the result of a brain stem mechanism (Juslin & Västfjäll, 2008). However, it does not appear to be the kind of *startle* reaction to extreme or sudden acoustic events indexed by the *brain stem reflex* item in the *MecScale*. A startle reflex typically involves a (brief) heart rate deceleration, followed by a strong acceleration, which soon tails off (Andreassi, 2007; see e.g., Juslin et al., 2014). The arousal we observed here occurred toward the end of a two-minute stimulus, which did not feature any extreme events. Nor are the data consistent with a simple orienting response (attention), which typically involves a heart rate deceleration (Andreassi, 2007).

The observed arousal is more likely the result of a 'defensive' so-called 'N' response (see Westman & Walters, 1981), which can occur independently of startle and orienting responses. The 'N' response does not require extreme stimuli; it reflects more broadly the arousal potential of an acoustic stimulus (e.g., speed, volume, complexity; Berlyne, 1971), as hard-wired in the brain. Hence, we could speculate that the small increase in arousal in response to the music vis-à-vis silence reflects a brain stem response to the moderate sound intensity, deep bass, and strong rhythm pattern of the music. Because the 'N' response does not quite 'habituate' (e.g., Westman & Walters, 1981), the arousal remained, even after two minutes of listening. In addition, because the 'N' response is responsive to acoustic features in a dose-dependent fashion, it can explain why the music tended to induce larger heart-rate increases the higher the target tempo was relative to the listener's heart rate.

Although some researchers appear to take for granted that rhythmic entrainment may induce emotions (Trost et al., 2017), there is so far little empirical evidence to confirm that this is the case. Our failure to obtain entrainment effects on heart rate is consistent with the findings of some other recent studies (e.g., Labbé Rodriguez, 2015; Mütze et al., 2020; van Dyck et al., 2017). To be clear, we do not rule out that there are circumstances under which entrainment via heart rate or some other route may occur and evoke emotions. For instance, perhaps entrainment only induces emotions when the listener is in the physical presence of musicians, or in conjunction with some other emotion induction mechanism.

However, it appears rather urgent to find the circumstances under which entrainment may occur. The development of procedures that may reliably induce entrainment would be valuable, not just for future research on musical emotions, but also for the investigation of various neurological disorders. Rhythmic entrainment is one of the most crucial induction mechanisms for the successful application of music in motor rehabilitation for movement disorders (Thaut, 2008). Understanding the emotional effects of entrainment may help to render such applications even more effective.

What can we conclude, then, based on these and similar findings? It is quite common in science to empirically observe a phenomenon for which one lacks a proper explanation. Here, the opposite is true: We have the explanation but have yet to clearly observe the phenomenon. In other words, it seems that musical induction of emotions via rhythmic entrainment remains a seemingly plausible hypothesis in need of empirical evidence.

References

Agostino, P. V., Peryer, G., & Meck, W. H. (2008). How music fills our emotions and helps us keep time. *Behavioral and Brain Sciences, 31(5),* 575-576. https://doi.org/10.1017/S0140525X0800530X

Andreassi, J. L. (2007). *Psychophysiology* (5th ed.). Erlbaum.

Aschoff, J. (1979). Circadian rhythms: influences of internal and external factors on the period measured in constant conditions. *Zeitschrift für Tierpsychologie, 49,* 225-249. https://doi.org/10.1111/j.1439-0310.1979.tb00290.x

Barradas, G. T., Juslin, P. N., & Badia, S. B. (2021). Emotional reactions to music in dementia patients and healthy controls: Differential responding depends on the mechanism. *Music & Science.* https://doi.org/10.1177/20592043211010152

Bason, P. T., & Celler, B. G. (1972). Control of the heart rate by external stimuli. *Nature, 273(5362),* 279-280. https://doi.org/10.1038/238279a0

Becker, J. (2004). *Deep listeners: Music, emotion, and trancing.* Indiana University Press.

Berlyne, D. E. (1971). *Aesthetics and psychobiology.* Appleton Century Crofts.

Bernardi, L., Porta, C., Casucci, G., Balsamo, R., Bernardi, N. F., Fogari, R., & Sleight, P. (2009). Dynamic interactions between musical, cardiovascular, and cerebral rhythms in humans. *Circulation, 119(25),* 3171-3180. https://doi.org/10.1161/CIRCULATIONAHA.108.806174

Clayton, M. (2012). What is entrainment? Definition and applications in musical research. *Empirical Musicology Review, 7(1-2),* 49-56. https://doi.org/10.18061/1811/52979

Clayton, M., Jakubowski, K., Eerola, T., Keller, P., Camurri, A., Volpe, G., & Alborno, P. (2020). Interpersonal entrainment in music performance: Theory, method and model. *Music Perception, 38(2),* 136-194. https://doi.org/10.1525/mp.2020.38.2.136

Clayton, M., Sager, R., & Will, U. (2005). In time with the music: The concept of entrainment and its significance for ethnomusicology. *European Meetings in Ethnomusicology, 11,* 3-75.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences.* Academic Press.

Craig A. D. (2016). Interoception and emotion: A neuroanatomical perspective. In L. F. Barrett, M. Lewis, & J. M. Haviland-Jones (Eds.), *Handbook of emotions* (3rd ed., pp. 215-233). Guilford.

Doelling, K. B., & Poeppel, D. (2015). Cortical entrainment to music and its modulation by expertise. *Proceedings of the National Academy of Sciences, 112(45),* E6233-E6242. https://doi.org/10.1073/pnas.1508431112

Dousty, M., Daneshvar, S., & Haghjoo, M. (2011). The effects of sedative music, arousal music, and silence on electrocardiography signals. *Journal of Electrocardiology, 44(3),* 396. https://doi.org/10.1016/j.jelectrocard.2011.01.005

Etzel, J. A., Johnsen, E. L., Dickerson, J., Tranel, D., & Adolphs, R. (2006). Cardiovascular and respiratory responses during musical mood induction. *International Journal of Psychophysiology, 61(1),* 57-69. https://doi.org/10.1016/j.ijpsycho.2005.10.025

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39 (2)*, 175-191. https://doi.org/10.3758/bf03193146

Ferguson, C. J. (2009). An effect size primer: A guide for clinicians and researchers. *Professional Psychology, Research and Practice, 40(5),* 532-538. https://doi.org/10.1037/a0015808

Gaston, E. T. (1968). *Music in therapy.* Macmillan.

Harrer, G., & Harrer, H. (1977). Music, emotion, and autonomic function. In M. Critchley & R. A. Henson (Eds.), *Music and the brain.* (pp. 202-216). William Heinemann.

Henry, M., & Grahn, J. (2017). Music, brain, and movement: Time, beat, and rhythm. In R. Ashley & R. Timmers (Eds.), *The Routledge companion to music cognition* (pp. 63-73). Routledge.

Hodges, D. A. (2010). Psychophysiological measures. In P. N. Juslin & J. A. Sloboda (Eds.), *Handbook of music and emotion: Theory, research, applications* (pp. 279-311). Oxford University Press.

Huygens, C. (1669). Instructions concerning the use of pendulum-watches for finding the longitude at sea. *Philosophical Transactions, 4(47),* 937-976. https://doi.org/10.1098/rstl.1669.0013

Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology. General, 141(1),* 54-75. https://doi.org/10.1037/a0024208

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review, 96(3),* 459-491. https://doi.org/10.1037/0033-295X.96.3.459

Juslin, P. N. (2013). From everyday emotions to aesthetic emotions: Toward a unified theory of musical emotions. *Physics of Life Reviews, 10(3),* 235-266. https://doi.org/10.1016/j.plrev.2013.05.008

Juslin, P. N. (2019). *Musical emotions explained.* Oxford University Press.

Juslin, P. N. (in press). Major theories of emotion causation and their applicability to music: The case for multi-level approaches. *Music Perception.*

Juslin, P. N., Barradas, G., & Eerola, T. (2015). From sound to significance: Exploring the mechanisms underlying emotional reactions to music. *American Journal of Psychology, 128(3),* 281-304. https://doi.org/10.5406/amerjpsyc.128.3.0281

Juslin, P. N., Barradas, G. T., Ovsiannikow, M., Limmo, J., & Thompson, W. F. (2016). Prevalence of emotions, mechanisms, and motives in music listening: A comparison of individualist and collectivist cultures. *Psychomusicology: Music, Mind, and Brain, 26(4),* 293-326. https://doi.org/10.1037/pmu0000161

Juslin, P. N., Harmat, L., & Eerola, T. (2014). What makes music emotionally significant? Exploring the underlying mechanisms. *Psychology of Music, 42(4),* 599-623. https://doi.org/10.1177/0305735613484548

Juslin, P. N., Liljeström, S., Västfjäll, D., Barradas, G., & Silva, A. (2008). An experience sampling study of emotional reactions to music: Listener, music, and situation. *Emotion, 8(5),* 668-683. https://doi.org/10.1037/a0013505

Juslin, P. N., Sakka, L. S., Barradas, G. T., & Lartillot, O. (2022). Emotions, mechanisms, and individual differences in music listening: A stratified random sampling approach. *Music Perception, 40(1),* 52-83. https://doi.org/10.1525/mp.2022.40.1.55

Juslin, P. N., & Västfjäll, D. (2008). Emotional responses to music: The need to consider underlying mechanisms. *Behavioral and Brain Sciences, 31(5),* 559-575. https://doi.org/10.1017/S0140525X08005293

Keil, C., & Feld, S. (1994). *Music grooves.* University of Chicago Press.

Khalfa, S., Roy, M., Rainville, P., Dalla Bella, S., & Peretz, I. (2008). Role of tempo entrainment in psychophysiological differentiation of happy and sad music? *International Journal of Psychophysiology, 68(1),* 17-26. https://doi.org/10.1016/j.ijpsycho.2007.12.001

Koelsch, S., Jäncke, L., (2015). Music and the heart. *European Heart Journal, 36(44),* 3043-3049. https://doi.org/10.1093/eurheartj/ehv430

Kotz, S. A., Ravignani, A., & Fitch, W. T. (2018). The evolution of rhythm processing. *Trends in Cognitive Sciences, 22(10),* 896-910. https://doi.org/10.1016/j.tics.2018.08.002

Krabs, R. U., Enk, R., Teich, N., & Koelsch, S. (2015). Autonomic effects of music in health and Crohn's disease: The impact of isochronicity, emotional valence, and tempo. *PloS One, 10(5),* e0126224. https://doi.org/10.1371/journal.pone.0126224

Kuhn, T. L. (1974). Discrimination of modulated beat tempo by professional musicians. *Journal of Research in Music Education, 22(4),* 270-277. https://doi.org/10.2307/3344764

Labbé Rodríguez, C. (2015). *Entrainment as a psychological mechanism of emotion induction in music listening.* Doctoral dissertation, University of Geneva, Geneva, Switzerland.

Labbé, C., & Grandjean, D. (2014). Musical emotions predicted by feelings of entrainment. *Music Perception, 32(2),* 170-185. https://doi.org/10.1525/mp.2014.32.2.170

Levenson, R. W. (2014). The autonomic nervous system and emotion. *Emotion Review, 6(2),* 100-112. https://doi.org/10.1177/1754073913512003

Levitin, D. J. (2010). *The world in six songs: How the musical brain created human nature.* Aurum.

McNeill, W. H. (1995). *Keeping together in time.* Harvard University Press.

Mütze, H., Kopiez, R., & Wolf, A. (2020). The effect of a rhythmic pulse on the heart rate: Little evidence for rhythmical 'entrainment' and 'synchronization'. *Musicae Scientiae, 24(3),* 377-400. https://doi.org/10.1177/1029864918817805

Nyklíček, I., Thayer, J. F., & Van Doornen, L. J. P. (1997). Cardiorespiratory differentiation of musically-induced emotions. *Journal of Psychophysiology, 11(4),* 304-321.

Perneger T. V. (1998). What's wrong with Bonferroni adjustments. *BMJ (Clinical research ed.), 316(7139),* 1236-1238. https://doi.org/10.1136/bmj.316.7139.1236

Russell, J. A. (1980). A circumplex model of affect. *Journal of Personality and Social Psychology, 39(6),* 1161-1178. https://doi.org/10.1037/h0077714

Sakka, L. S., & Juslin, P. N. (2018). Emotional reactions to music in depressed individuals. *Psychology of Music, 46(6),* 862-880. https://doi.org/10.1177/0305735617730425

Saperston, B. M. (1993). *Method for influencing physiological processes through physiologically interactive stimuli. U.S. Patent No. 5267942*. Utah State University Foundation (UT). Retreived from http://www.freepatentsonline.com/5267942.html.

Scherer, K. R. (2000). Psychological models of emotion. In J. Borod (Ed.), *The neuropsychology of emotion* (pp. 137-162). Oxford University Press.

Scherer, K. R., & Coutinho, E. (2013). How music creates emotion: A multifactorial process approach. In T. Cochrane, B. Fantini, & K. R. Scherer (Eds.), *The emotional power of music: Multidisciplinary perspectives on musical arousal, expression, and social control* (pp. 121-145). Oxford University Press.

Stupacher, J., Witek, M. A. G., Vuoskoski, J. K., & Vuust, P. (2020). Cultural familiarity and individual musical taste differently affect social bonding when moving to music. *Scientific Reports, 10(1),* Article 1. https://doi.org/10.1038/s41598-020-66529-1

Thaut, M. H. (2008). *Rhythm, music, and the brain: Scientific foundations and clinical applications*. Routledge.

Thaut, M. H., McIntosh, G. C., & Hoemberg, V. (2015). Neurobiological foundations of neurologic music therapy: Rhythmic entrainment and the motor system. *Frontiers in Psychology, 5,* Article 1185. https://doi.org/10.3389/fpsyg.2014.01185

Thut, G., Schyns, P. G., & Gross, J. (2011). Entrainment of perceptually relevant brain oscillations by non-invasive rhythmic stimulation of the human brain. *Frontiers in Psychology, 2,* Article 170. https://doi.org/10.3389/fpsyg.2011.00170

Todd, N. P. M, & Lee, C. S. (2015). The sensory-motor theory of beat induction 20 years on: A new synthesis and future perspectives. *Frontiers in Human Neuroscience, 9,* Article 444. https://doi.org/10.3389/fnhum.2015.00444

Trost, W., Labbé, C., & Grandjean, D. (2017). Rhythmic entrainment as a musical affect induction mechanism. *Neuropsychologia, 96,* 96-110. https://doi.org/10.1016/j.neuropsychologia.2017.01.004

Uijtdehaage, S. H. J, & Thayer, J. F. (2000). Accentuated antagonism in the control of human heart rate. *Clinical Autonomic Research, 10(3),* 107-110. https://doi.org/10.1007/BF02278013

van Dyck, E., Six, J., Soyer, E., Denys, M., Bardijn, I., & Leman, M. (2017). Adopting a music-to-heart rate alignment strategy to measure the impact of music and its tempo on human heart rate. *Musicae Scientiae, 21(4),* 390-404. https://doi.org/10.1177/1029864917700706

Westman, J. C., & Walters, J. R. (1981). Noise and stress: A comprehensive approach. *Environmenal Health Perspectives, 41,* 291-309. https://doi.org/10.1289/ehp.8141291

Witek, M. A., Clarke, E. F., Wallentin, M., Kringelbach, M. L., & Vuust, P. (2014). Syncopation, body-movement and pleasure in groove music. *PloS one, 9,* e94446. https://doi.org/10.1371/journal.pone.0094446

Zentner, M. (2010). Homer's prophecy: An essay on music's primary emotions. *Music Analysis, 29(1-3),* 102-125. https://doi.org/10.1111/j.1468-2249.2011.00322.x

Table 1

Significance Tests of Change from Starting Heart Rate to Final Heart Rate

Condition	Diff.	$t_{(35)}$	p	95% CI	Cohen's d
30% down	-1.08	-1.57	.125	[-0.31, 2.46]	0.139
3% down	-1.43	-2.80	.008	[0.39, 2.47]	0.183
3% up	-1.81	-2.28	.029	[0.20, 3.42]	0.203
30% up	-2.87	-5.04	<.001	[-4.02, -1.71]	0.288

Table 2

Significance Tests of Distance Between Final Heart Rate to Target Heart Rate

Condition	Diff.	$t_{(35)}$	p	95% CI
30% down	24.46	28.84	<.001	[22.74, 26.18]
3% down	3.79	7.66	<.001	[2.79, 4.80]
3% up	-0.07	-0.09	.925	[-1.66, 1.52]
30% up	-17.89	-11.60	<.001	[-21.03, -14.76]

Table 3

Summary of Analyses of Variance for the Moderators Direction, Magnitude, and Movement

	MS	*F*	*p*	η^2
Main effects				
Direction	19199.35	442.05	<.001*	0.929
Magnitude	70.46	2.41	.130	0.066
Movement	43.59	1.27	.269	0.036
Interactions				
Direction x Magnitude	13315.50	351.95	<.001*	0.912
Direction x Movement	4.29	0.10	.755	0.003
Magnitude x Movement	5.77	0.20	.660	0.006
Direction x Magnitude x Movement	4.18	0.11	.742	0.003

Note. df = Effect (1), Error (34); η^2 = partial eta-squared

Figure 1

Means, Standard Errors, and Standard Deviations of the Listeners' Starting Heart Rate and Final Heart Rate

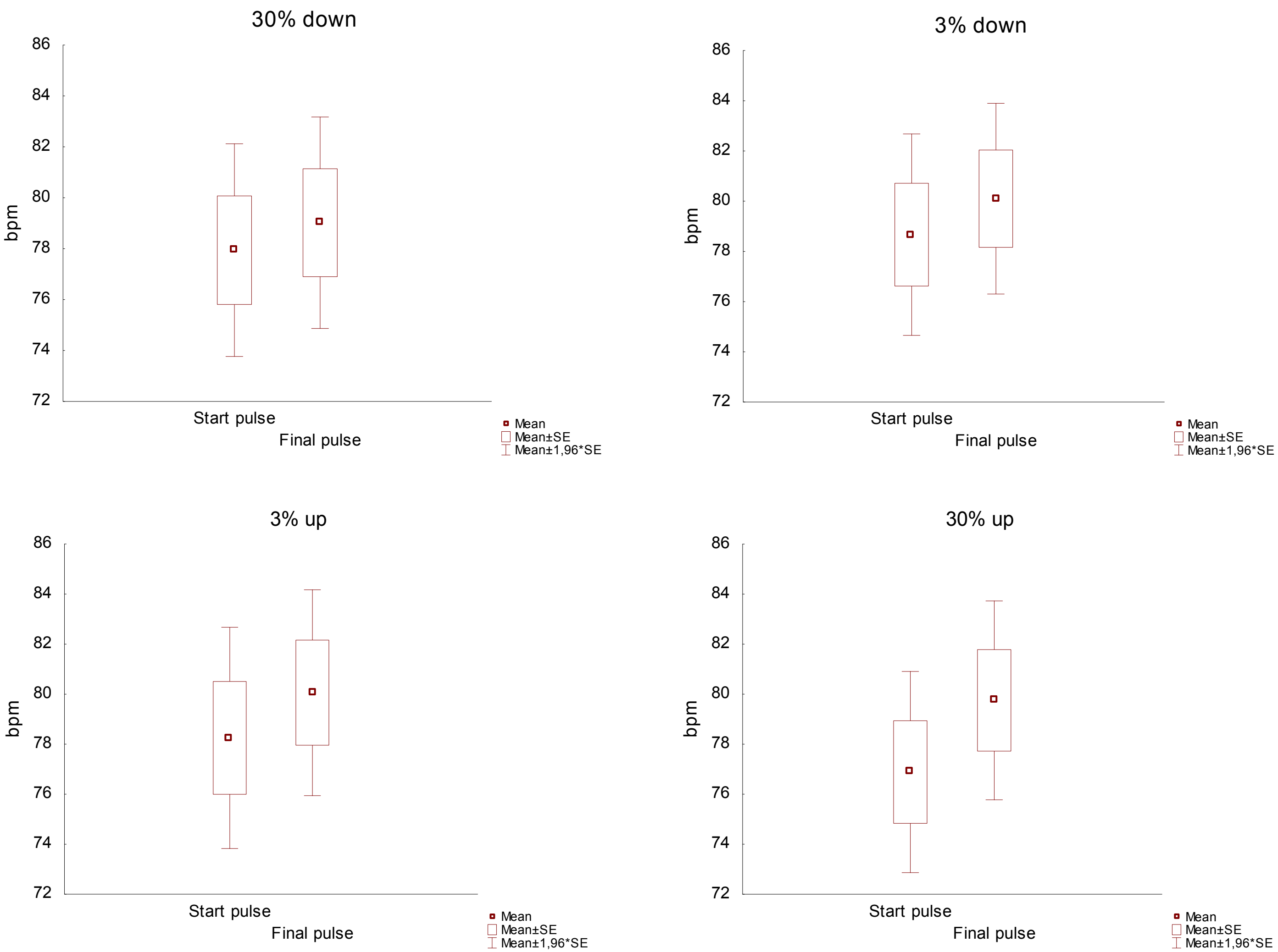


Figure 2

Means, Standard Errors, and Standard Deviations of the Listeners' Final Heart Rate and Target Heart Rate

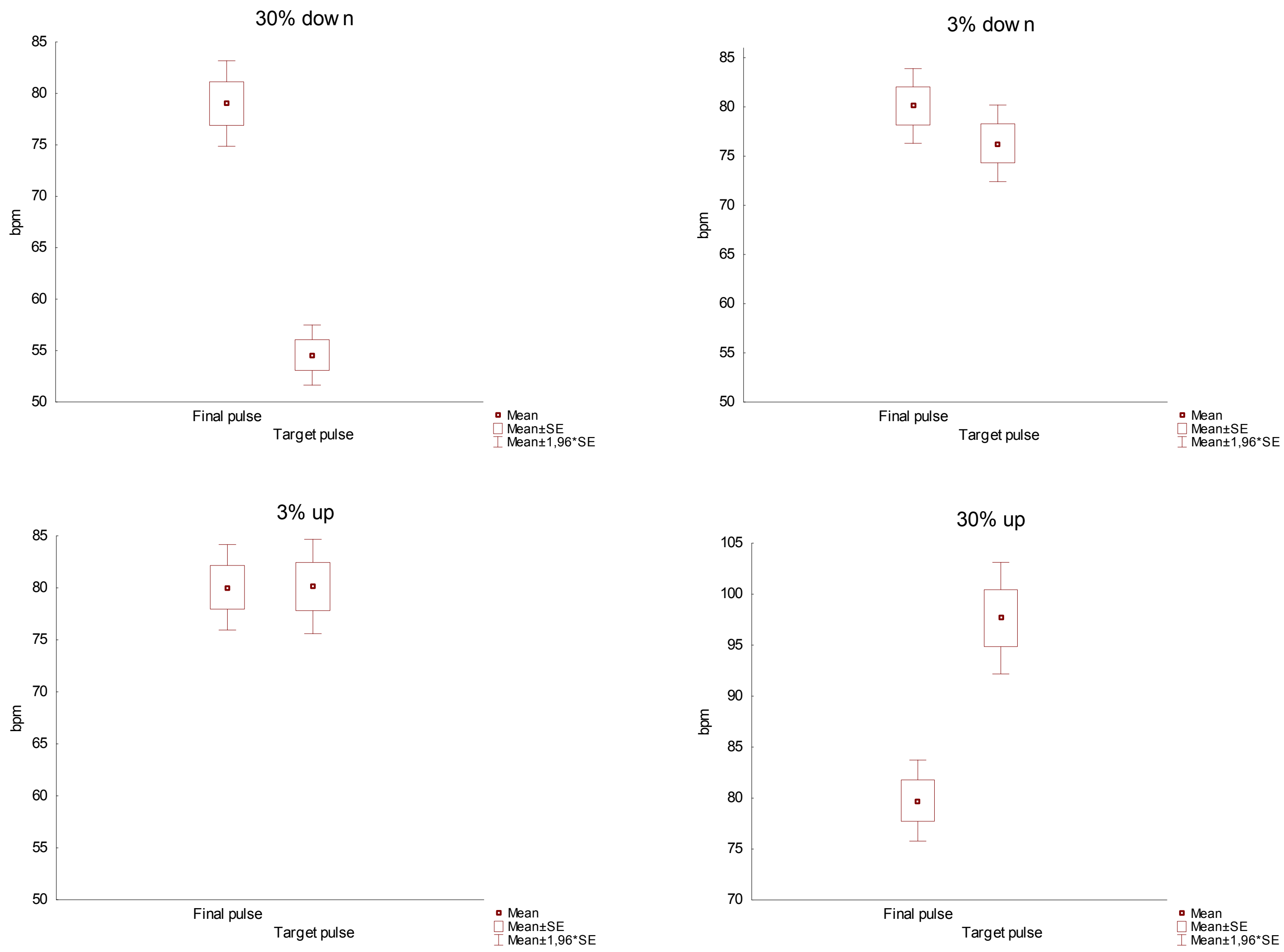
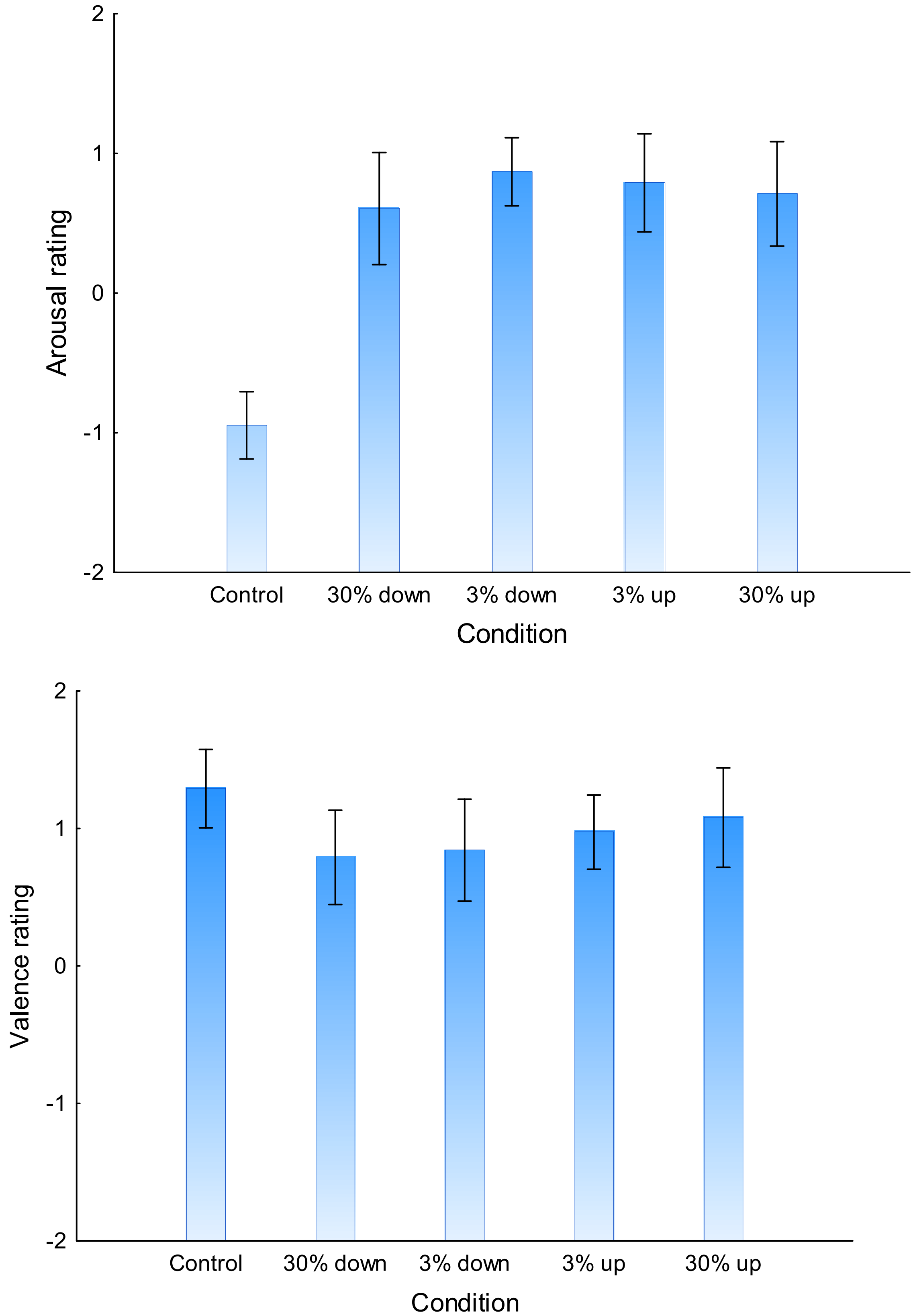


Figure 3

Mean Ratings of Arousal and Valence as a Function of Experimental Condition

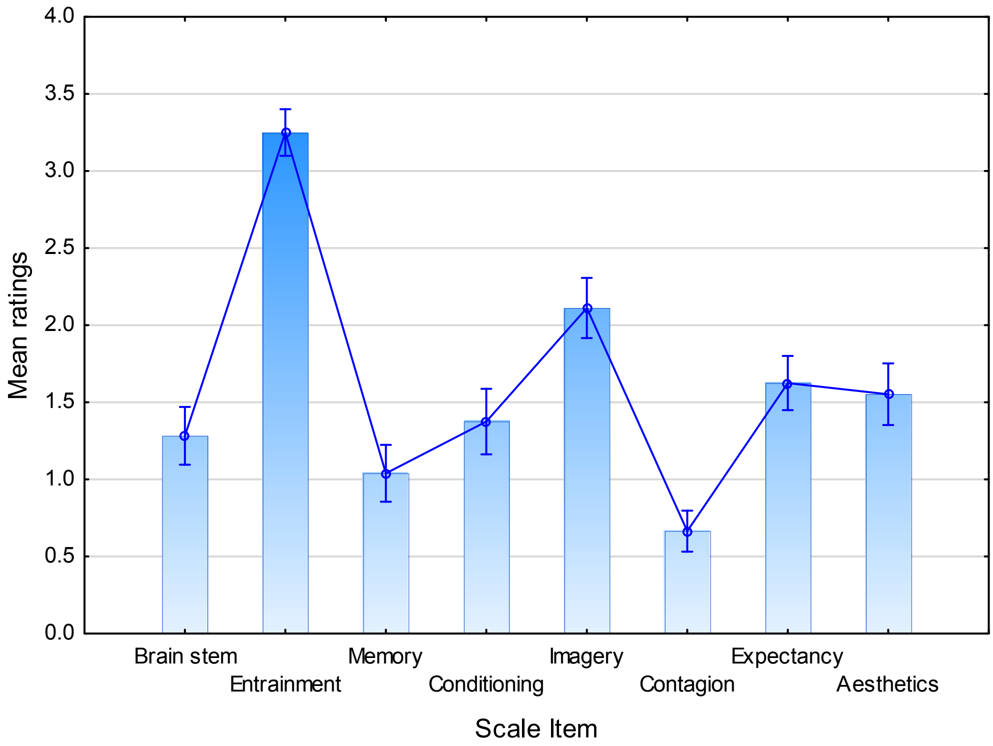


Note. Vertical bars denote 0.95 confidence intervals

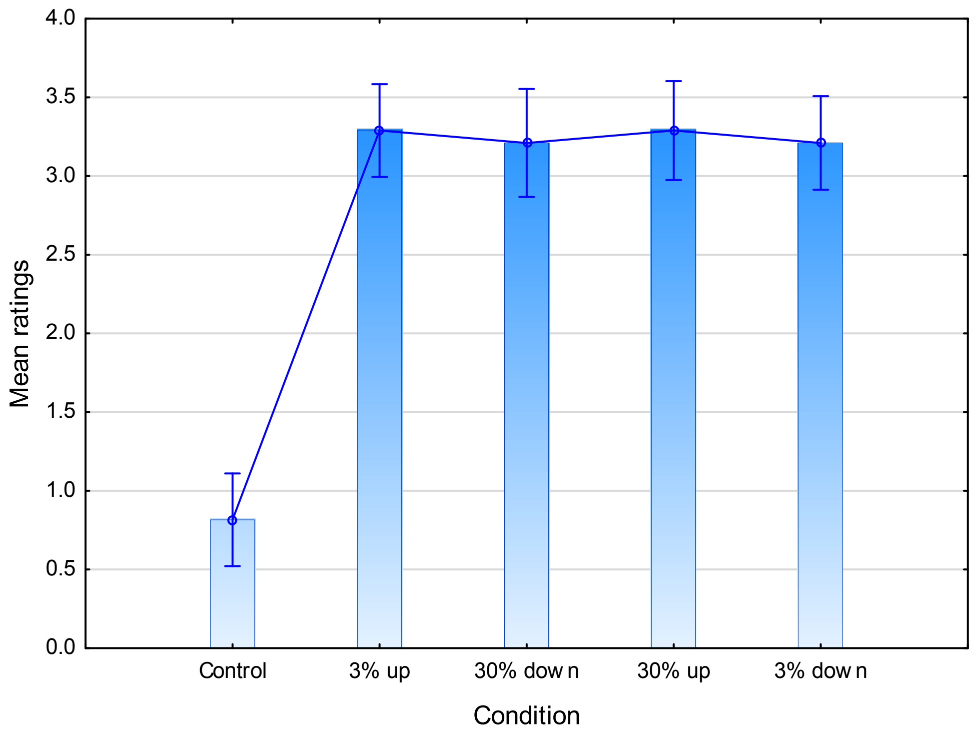
Figure 4

(A) *Mean Ratings of the Eight MecScale Items Across the Four Rhythmic Conditions*
(B) *Mean Ratings of the Entrainment Item as a Function of Experimental Condition*

A



B



Note. Vertical bars denote 0.95 confidence intervals

Rhythmic Entrainment of Heart Rate as a Mechanism for Musical Emotion Induction

Appendix A: Musical Stimuli

Title	Artist	Org tempo[1]	Range[1]	Use[2] (%)
Seafly	Fresh Moods	50	35-55	17
Leave the World Behind	Axwell et al.	63,5	55-68	22
Event	Shiny Objects	76	68-80	18
Full Moon	Klaada	93	80-95	22
Life's Casino	Sounds from the ground	97	95-135	21
Sea Waves	Marco Rinaldo	-	-	(Control)

[1] Indicates tempo of music in beats per minute (bpm)
[2] Indicates percentage of test trials that used the piece

Rhythmic Entrainment of Heart Rate as a Mechanism for Musical Emotion Induction

Appendix B: Mechanism Items *(MecScale)*

Did the music feature an event that startled you? (BR)

Not at all 0 1 2 3 4 *Very much*

Did the music have a strong and captivating pulse/rhythm? (RE)

Not at all 0 1 2 3 4 *Very much*

Did the music trigger a vivid memory of a particular event? (EM)

Not at all 0 1 2 3 4 *Very much*

Did the music evoke emotional associations (to phenomena, objects, or persons)? (EC)

Not at all 0 1 2 3 4 *Very much*

Did the music evoke any inner images while you were listening? (VI)

Not at all 0 1 2 3 4 *Very much*

Were you 'touched' by the emotional expression of the music? (CO)

Not at all 0 1 2 3 4 *Very much*

Was it difficult to guess how the music (e.g., the melody) would develop over time? (ME)

Not at all 0 1 2 3 4 *Very much*

Did the music make you reflect on its aesthetic qualities? (AJ)

Not at all 0 1 2 3 4 *Very much*