Sensorimotor synchronization to music reduces pain

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Abstract

Pain-reducing effects of music listening are well-established, but the effects are small and their clinical relevance questionable. Recent theoretical advances, however, have proposed that synchronizing to music, such as clapping, tapping or dancing, has evolutionarily important social effects that are associated with activation of the endogenous opioid system (which supports both analgesia and social bonding). Thus, active sensorimotor synchronization to music could have stronger analgesic effects than simply listening to music. In this study, we show that sensorimotor synchronization to music significantly amplifies the pain-reducing effects of music listening. Using pressure algometry to the fingernails, pain stimuli were delivered to $n = 59$ healthy adults either during music listening or silence, while either performing an active tapping task or a passive control task. Compared to silence without tapping, music with tapping (but not simply listening to music) reduced pain with a large, clinically significant, effect size ($d = 0.93$). Simply tapping without music did not elicit such an effect. Our analyses indicate that both attentional and emotional mechanisms drive the pain-reducing effects of sensorimotor synchronization to music, and that tapping to music in addition to merely listening to music may enhance pain-reducing effects in both clinical contexts and everyday life.

Introduction

Pain-reducing effects of music listening are among the most widely studied and most replicable effects of music in clinical settings[1,2]. For example, a recent meta-analysis by Kuhlmann et al.[2], with 7385 patients in 92 randomized controlled trials, reported that music listening interventions significantly reduce pain in surgical patients. However, across four different meta-analyses, the pain-reducing effects of music listening had only small to moderate effect sizes (and were inconsistent among the studies analyzed), which calls the clinical relevance of music for pain relief into question[1–4]. Notably, almost all of the studies included in the aforementioned meta-analyses used passive listening interventions (the study by Lee reports 10 music therapy studies using an active intervention such as group singing[3]), and to the best of our knowledge no study has compared pain-reducing effects between passive music listening and active engagement in music. The lack of research comparing pain-reducing effects between these two forms of music listening (i.e active vs. passive) is an important shortcoming because recent advances have proposed that active sensorimotor synchronization to music is associated with the activation of the endogenous opioid system (EOS), including the release of endorphins[5,6]. Notably, EOS activation supports both analgesia and social bonding[6]. Hence, recent evolutionary accounts have posited that the human capacity to synchronize movements to a musical pulse in a group (such as group singing, clapping, drumming, dancing) is an evolutionarily adaption because it stimulates social bonding[5–9]. However, to the best of our knowledge, the hypothesis of an EOS activation by sensorimotor synchronization to music has never been investigated. Accordingly, we set up a test with the premise that if sensorimotor synchronization to music indeed activates the EOS, then it should have larger pain-reducing effects than simply listening to music (pain-reduction is commonly used as a proxy of EOS activation[5–12].

The experimental design is illustrated in Fig. 1. We applied specific amounts of pain to the fingernails through the use of pressure algometry[13–15]. The experiment used a 2x2 within-subjects design in which participants either listened to music or underwent a silent control period (henceforth referred to as the within-subjects factor *Condition*) and either performed an active foot tapping task, or a passive control task with no movement (henceforth referred to as the within-subjects factor *Task*). As the dependent variable, perceived pain was rated on a scale ranging from 1 to 9 (1 = *very little*, 5 = *medium*, 9 = *very strong*). In addition, to pain ratings, participants provided ratings of their emotional state in terms of pleasantness as well as arousal, and then rated their familiarity with the music (also on scales ranging from 1 to 9). Emotion ratings were obtained to explore whether the mechanisms driving pain-reducing effects of sensorimotor synchronization to music include emotion (based on our previous work on music-evoked emotions[16] and previous research showing that modulatory effects of music on pain were mediated by the pleasantness of the emotions induced[17]. At the end of the experiment, participants also rated their preference for the music on a scale ranging from 1 to 9 (see Method). Familiarity and preference ratings were obtained to elucidate possible contributions of these factors on pain reduction[18].

In accordance with the well-established pain-reducing effects of music listening in clinical settings[1–4], we expected perceived pain to be reduced while listening to music compared with the silent control condition (independent of the task, i.e. independent of whether participants were tapping or not). Furthermore, consistent with the well-established effects of attention on pain[19–22], we expected pain-reducing effects of active tapping compared with no tapping (independent of the condition, i.e., independent of whether music or silence was presented), because active tapping requires increased attention on the part of the participants and thus distracts from perceived pain. Most importantly, we investigated whether participants felt less pain while actively tapping to music compared to passively listening to music, which would reveal, for the first time, analgesic effects of sensorimotor synchronization to music.

Results

Figure 2 shows the mean data of the perceived pain, dependent on *Condition* (listening to music, or silent control condition), and *Task* (performing the active tapping task, or the passive control task). A linear mixed effects (LME) analysis indicated significant main effects of both *Condition* (β = -0.72, *SE* = 0.20, *p* = .027), and *Task* (β = -0.20, *SE* = 0.07, *p* = .005), reflecting that the perceived pain was reduced while listening to music (compared to silence; see red vs. blue violin plots in Fig. 2), and while performing the active tapping task (compared with the passive control task; see darker vs. lighter colors in Fig. 2). Importantly, the pain-reducing effect of the active tapping task was descriptively larger while listening to music (*mean difference* = 0.28 scale points, *SE* = 0.08, *d* = 0.46) than during silence (*mean difference* = 0.12 scale points, *SE* = 0.09, *d* = 0.17). To explore this result pattern in detail, we conducted a simple slope analysis with *Task* as predictor and *Condition* as moderator. This simple slope analysis revealed a significant effect of the *Task* only while listening to music (β = -0.29, *SE* = 0.10, *p* = .005) but not during silence (β = -0.12, *SE* = 0.10, *p* = .225). Consequently, the difference in perceived pain was most pronounced between music with tapping vs. silence without tapping *(mean difference* = 0.93 scale points, *SE* = 0.13, see dashed grey horizontal lines in Fig. 2), with a large effect size of $d = 0.93$ (effect sizes are interpreted according to Cohen's convention[23]).

Emotional mechanisms underlying the pain-reducing effect of sensorimotor synchronization to music. To test our assumption that the mechanisms driving the pain-reducing effect of sensorimotor synchronization to music include emotion, we computed two additional LME analyses. For detailed information on the experimental design and data analysis for both analyses see Supplementary Information. The first included only music trials and the factors *Task*, *Preference* and *Familiarity.* The dependent variable was perceived pain. Figure 3 shows the preference effect on the perceived pain for the music trials only, separately for the active tapping task and the passive control condition. Consistent with the first analysis reported above, our second analysis also revealed a significant main effect of *Task* (β = -0.28, *SE* = 0.10, $p = .006$) with reduced perceived pain for the active vs. passive task. Importantly, this analysis further revealed a significant main effect of *Preference* (β = -0.14, *SE* = 0.03, $p < .001$), indicating that pain ratings decreased with increasing preference for the music excerpts. The interaction of the factors *Task* and *Preference* was not significant (β = -0.04, *SE* = 0.05, $p = .453$) and notably, no effect of the covariate *Familiarity* was observed (β = 0.03, *SE* = 0.02, $p = .222$).

The second LME analysis on involved emotional mechanisms examined the effect of *Condition* and *Task* on the perceived pleasantness. Results revealed a significant main effect of *Condition* (β = 1.02, *SE* = 0.25, $p = .009$), reflecting that perceived pleasantness was higher while listening to music (compared to silence; see red vs. blue violin plots in Fig. 4). In addition, this LME analysis revealed a trend for an interaction of *Condition* and *Task* ($p = .073$), indicating that the perceived pleasantness of the active tapping task was descriptively larger while listening to music (*mean difference* = 0.18 scale points, *SE* = 0.08, $d = 0.30$) than during silence (*mean difference* = 0.06 scale points, *SE* = 0.11, $d = -0.07$). The difference in perceived pleasantness between music with tapping vs. silence without tapping *(mean difference* = 1.08 scale points, *SE* = 0.16, see dashed grey horizontal line in Fig. 4) had a large effect size[23] of $d = 0.86$. The main effect of *Task* was not significant (β = 0.06, *SE* = 0.07, $p = .391$). A descriptive analysis of arousal ratings is provided in Supplementary Table S1.

Discussion

Our results show that participants felt less pain while actively tapping to music, compared with merely listening to music. This finding indicates that sensorimotor synchronization to music has analgesic effects. Compared to music listening without tapping, tapping to music elicited a moderate pain-reducing effect, and compared to the silent control condition without tapping, tapping to music elicited a large, clinically significant[23] pain-reducing effect ($d = 0.93$). Our observation of a reduction of perceived pain while passively listening to music (compared with silence) is well in accordance with previously reported pain-reducing effects of music listening in clinical settings[1–4]. Likewise, our finding of a significant reduction of perceived pain while actively tapping (compared to the passive control task, independent of whether music or silence was presented) is consistent with the well-established analgesic effects of distracting attention from a painful stimulus[19–22]. Notably, our findings are consistent with the hypothesis that sensorimotor synchronization to music reduces pain by virtue of EOS activation[6], thus supporting psychological accounts on the effects of movement synchronization to music on social bonding[5–9], trust[24,25], and cooperation[26], as well as evolutionary accounts on the adaptive utility of music due to the promotion of social bonding by coordinated, synchronized musical activity[8].

We also investigated potential mechanisms underlying the analgesic effects of sensorimotor synchronization to music. So far, the (causal) mechanisms underlying the pain-reducing effects of (passive) music listening are not fully understood, but previous work has implicated attentional and emotional mechanisms as the two main candidates[27–29]. Our study was purposefully set up in a way that both music perception (compared to silence) and the active tapping task (compared to the passive control task) likely distracted participants' attention away from the pain stimulus[30]. Hence, tapping to music would have the strongest attention-capturing effect, resulting in the largest pain-reducing effects. However, the finding that tapping in silence did not significantly reduce pain (compared with silence without tapping) indicates that the attentional distraction by the tapping cannot alone explain the pain reducing effects of tapping to music.

In addition, we hypothesized that sensorimotor synchronization to music would activate the EOS. Because EOS activation has well-documented effects on analgesia and pleasure[16,31], emotional mechanisms are likely involved in the analgesic effects of sensorimotor synchronization to music. To test this assumption, we analyzed participants' ratings of their emotional state in terms of their perceived pleasantness, preference for the music, and familiarity with the music. Familiarity was included in this analysis due to a possible association between familiarity of music and (musical) preference, e.g it had been reported that the (dopaminergic) reward network is activated more strongly by familiar than unfamiliar music[18,32,33]. Results showed that perceived pain was significantly reduced when listening to strongly preferred music (unaffected by familiarity), consistent with previous research on preference in the context of pain-reducing effects of music (e.g., participants tolerate painful stimuli significantly longer when listening to their own preferred music[34–37]. Moreover, our findings indicate that tapping to music was perceived as more pleasant than merely listening to music, suggesting that it was more rewarding to tap to the music, also consistent with a stronger EOS activation.

In conclusion, our findings demonstrate that sensorimotor synchronization to music significantly impacts pain perception and can amplify the well-established pain-reducing effect of merely listening to music. Our results have wide-ranging implications for the use of music in clinical settings (as an adjunct treatment of pain)[38], in music therapy (e.g. for chronic pain)[39], and in everyday life (for the management of acute pain). Moreover, our findings support the recent social bonding hypothesis of music, and thus the significance of music in the evolution of humans[6]. Finally, our results shed new light on the mechanisms underlying pain reduction with music, showing that such effects are driven by social bonding, attention, emotion, and preference.

Methods

Participants. A naive random sample 59 participants was included in the data analysis (age range 19 to 35 years, M = 22.15 years, SD = 3.22, 29 females), based on an a-priori sample size estimation using G*Power (version 3.1.9.6)[40] which indicated that for the detection of a small to medium effect size (d = 0.4)[23] with an α-level of 0.05 and a statistical power of 90% (one-tailed), a sample of n = 59 is required. Exclusion criteria were use of any prescription drugs, psychiatric or neurological disease, hearing impairment, and history of substance dependence (according to self-report). Participants did not consume alcohol nor any medicine for the treatment of pain at least 24 hours prior to the experiment. None of the participants had musical anhedonia according to the Barcelona Music Reward Questionnaire (M = 81.06, SD = 11.37)[41]. The study was carried out in accordance with the guidelines of the Declaration of Helsinki and approved by the Regional Committee for Medical and Health Research Ethics for Western Norway (Reference Number: 2019/1031). The study was registered as a clinical trial at ClinicalTrials.gov (registration number NCT05267795), and the trial was first posted on 04/03/2022. All participants provided written informed consent before enrollment and received a monetary compensation of 200 NOK following participation in the experiment.

Stimuli. Music stimuli were presented with an average sound pressure of approximately 60 dB SPL over Beyerdynamic DT 770-PRO 250 Ohm headphones. 10 instrumental music experts were selected, each 30 seconds long (song characteristics are provided in Supplementary Table S2). Each excerpt was played twice during the experimental task, once during the active task and once during the passive task. Stimuli were delivered using the Matlab-based toolbox Cogent 2000 (version 1.33).

Pressure Algometry. Pain was applied by the experimenter using a Wagner Force One Pressure Algometer (Wagner Instruments, Greenwich, USA). The equipment head (used to apply the pressure) had a diameter of 12mm and a surface area of 113mm^2. Pain stimuli were delivered to index, middle and ring fingers of both hands. For each participant, pain thresholds were determined separately for each of the six fingers used for pain delivery, prior to the actual experiment. The average value of these pain thresholds was then computed, and for the actual experiment, only 50% of the participant’s average pain threshold was delivered as pain stimulus in each of the 40 experimental trials (e.g., if a participant had an average pain threshold of 5 kg, then a pressure stimulus of 2.5 kg was applied in the actual experiment). During the entire experiment, the applied pressure was measured with a 10 Hz sampling rate using MESURgauge Plus by Mark-10 (version 2.0.5). The statistical analysis of these data showed that neither the applied pressure, nor the duration of applied pressure, differed significantly for the within-subjects factors *Condition* (music, silence; pressure intensity: $F(1,58) = 0.33$, $p = .568$; pressure duration: $F(1,58) = 1.62$, $p = .209$), nor *Task* (active, passive; pressure intensity: $F(1,58) = 0.33$, $p = .568$; pressure duration: $F(1,58) = 0.66$, $p = .419$). Likewise, no significant interaction between *Condition* and *Task* was observed for the pressure intensity ($F(1,58) = 1.00$, $p = .321$), nor for pressure duration ($F(1,58) < 0.01$, $p > .999$). Thus, we can exclude the possibility that the pain ratings of participants were simply an artifact of faulty stimulus delivery (note that the experimenter was also blinded to avoid any systematic differences of pain stimulus delivery between the experimental trial types). For further information see Supplementary Information and Supplementary Table S3.

Procedure. 40 experimental trials were delivered, 10 for each experimental trial type (Music Active, Music Passive, Silence Active, Silence Passive). The experimenter was blinded during the entire experimental procedure. Each trial started with an instruction screen where participants were either instructed to tap their right foot like a metronome (active tapping task) or to relax (passive control task). Then, participants pressed the space bar and either music started to play, or a silent period started, and participants either had to tap or relax (depending on the trial type), while looking at a fixation cross in the middle of the screen. After 20 seconds the experimenter applied pressure with the Algometer to a fingernail for 10 seconds. Then (after the pain application had stopped), participants indicated the pain they felt at the end of the pain application on a 9-point scale (1 = *very little*, 5 = *medium*, 9 = *very strong*), followed by a pleasantness rating (1 = *very uncomfortable*, 5 = *medium*, 9 = *very comfortable*) and an arousal rating (1 = *very calm*, 5 = *medium*, 9 = *very activated*). In music trials, participants also rated to which extent they were familiar with the music (1 = *not at all*, 5 = *partially known*, 9 = *well known*). Participants were aware that the experimenter could not see their ratings (so that they would not feel influenced in any way). Each trial lasted about one minute (thus, the experiment had a duration of approximately 40 minutes). After completing all 40 experimental trials, participants listened to the 10 music excerpts again and indicated their preference for each excerpt on a 9-point scale (1 = *strongly disliked*, 5 = *medium*, 9 = *strongly liked*).

Experimental Design & Data Analysis. Data analysis was computed using R (version 4.0.4) including the R Stats, R Base, and ggplot 2 (version 3.3.3)[42] packages. Figures were graphically edited with CorelDraw Graphics Suite version 21.0.0.593 (Corel Corporation, Ottawa, Ontario, Canada). We conducted an LME analysis on single trial level, as this analysis allowed to reduce interindividual variance introduced by participants and music excerpts, and decrease the risk for false positives[43]. The analysis was applied by the use of the lme4package (version 1.1-26)[44]. The model included the two categorical fixed-effects factors *Condition* (music [+0.5] and silence [-0.5]) and *Task* (active [+0.5] and passive [-0.5]) as well as their interaction as predictors for the perceived pain in each individual experimental trial (rated on a scale ranging from 1 to 9). Furthermore, the model included the Participants and music Excerpts as random-effects factors. The model was estimated by using a restricted maximum likelihood approach[45]. The α-level for significance was 0.05. We estimated degrees of freedom and *p*-values with the Satterthwaite approximation implemented in the lmerTest package (version 3.1)[46]. We used the R package influence.ME (version 0.9-9)[47] to test the data for statistical outliers on the participant level. No outliers were detected, and the model was conducted with a sample of 59 participants. Especially in clinical contexts the lack of statistical significance does not necessarily mean that a treatment has no effect[48,49]. Therefore, and to comprehensively explore the pattern of results, we resolved the interaction between *Condition* and *Task* with a simple slope LME analysis implemented in the R package jtool (version 2.1.2)[50]. In addition, we calculated Cohen's *d* effect size[23] by the use of the R package lsr (version 0.5)[51] because this effect size measure is taken as one of the most important indicators of clinical significance[49].

Declarations

Data availability

Data supporting the findings of this study will be provided by the senior author upon reasonable request.

Code availability

The R scripts used for the analyses, statistics and visualizations presented in this article will be provided by the senior author upon reasonable request.

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Contributions

L.W conducted the experiment, analyzed the results and wrote the original draft. S.S conceived the experiment, analyzed the results and reviewed the original draft. L.B analyzed the results and reviewed the original draft. S.P contributed to the methodology and reviewed the original draft. S.K. conceived the experiment, provided resources and supervision and essentially reviewed and edited the original draft.

Competing interests

The authors declare no competing interests.

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Figures

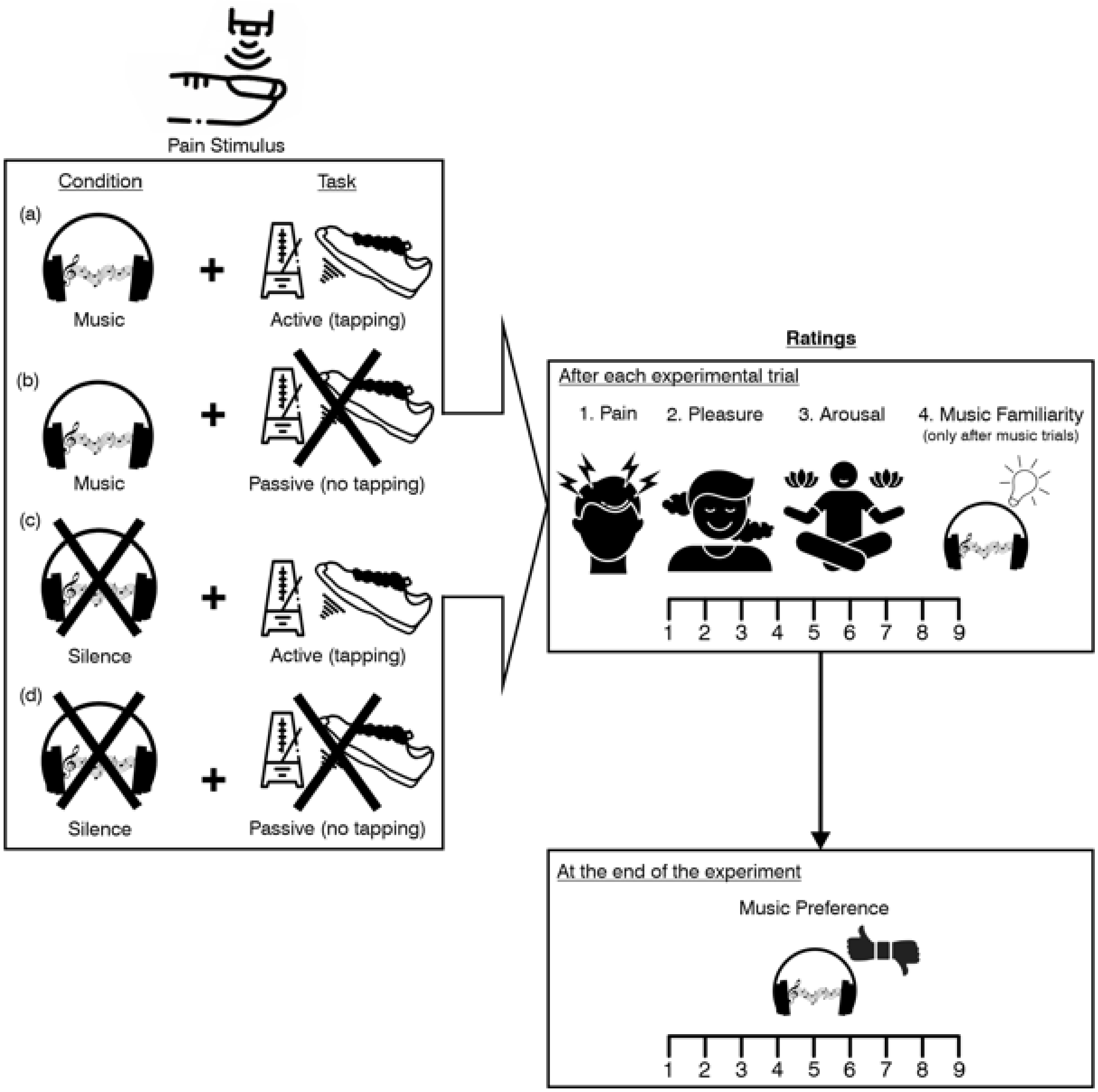

Figure 1

Experimental design. The experiment used a 2x2 design with the within-subject factors *Condition* (music, silence) and *Task* (active, passive), resulting in four experimental trial types: (**a**) *Music Active* (music with tapping); (**b**) *Music Passive* (music without tapping); **(c)** *Silence Active* (silence with tapping); and (**d**) *Silence Passive* (silence without tapping). The allocation of the music excerpts to the task (active, passive) was random, and the order of the four experimental trial types was counterbalanced. Specific pain levels were applied on the participants' fingernails in each of 40 experimental trials using pressure algometry. At the end of each trial (after the presentation of a music excerpt or after a silent period), participants rated (1) their perceived pain, (2) their emotional state with regard to felt pleasantness and (3) felt arousal, as well as (4) their familiarity with the music excerpt (only during trials with music). All ratings were provided on a scale ranging from 1 to 9. After the 40 experimental trials, participants provided preference ratings for each musical excerpt (also using a scale ranging from 1 to 9).

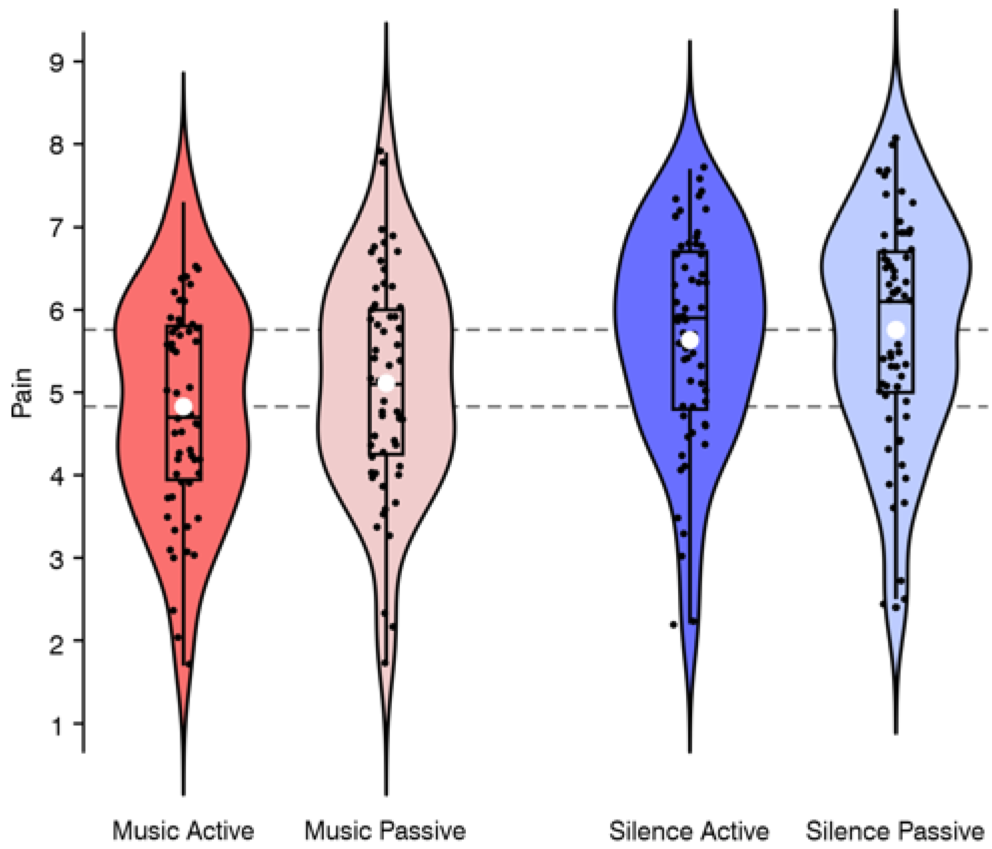

Figure 2

Within-subjects perceived pain per experimental condition. The violin plots show the distribution density of the perceived pain (rated on a scale ranging from 1 to 9) during music (red) or silence (blue) while performing either an active tapping task (darker colors) or a passive control task (lighter colors). The embedded box-and-whisker plots represent the 25th and the 75th percentiles of the distributions, respectively. Upper and lower whiskers extend from the hinge to the largest/smallest value no further than 1.5 * inter-quartile range. The vertical lines in the boxes indicate median values, and the white disks indicate the means. The black dots show the jittered data points, and the dashed grey horizontal lines in the background represent the mean difference of the perceived pain between music with tapping and silence without tapping. Note here that the pain-reducing effect of music with tapping (Music Active, dark red) compared with silence without tapping (Silence Passive, light blue) has a large effect size (d = 0.93).

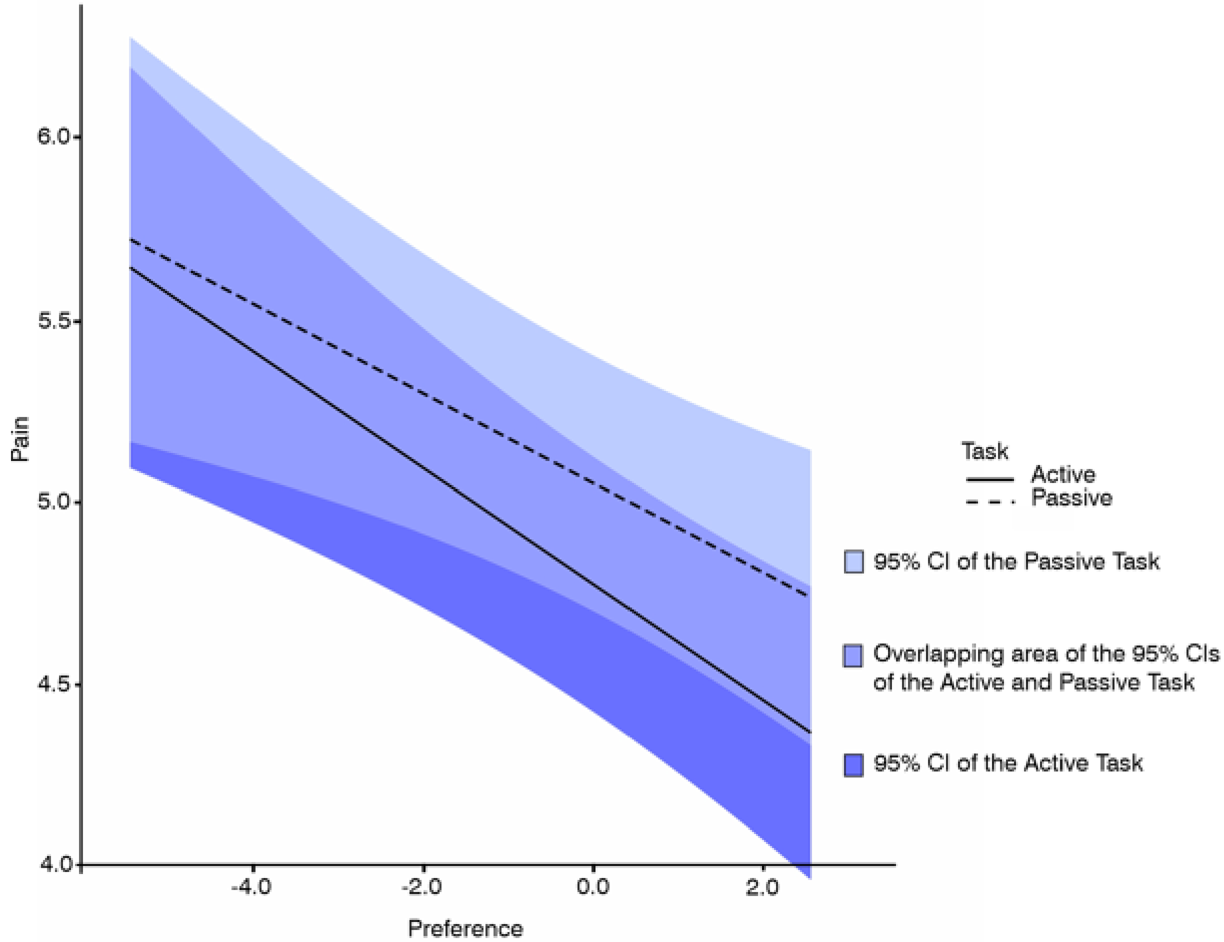

Figure 3

Preference effect on the perceived pain for the music trials. Data are shown separately for the active tapping task and the passive control task. Perceived pain (rated on a scale ranging from 1 to 9) was reduced with increasing preference (rated on a scale ranging from 1 to 9 and mean-centered) and while performing the active tapping task (solid black line) compared to the passive control task (dashed black line). Blue shaded areas represent the respective 95% Confidence Intervals (CIs) and their overlapping area.

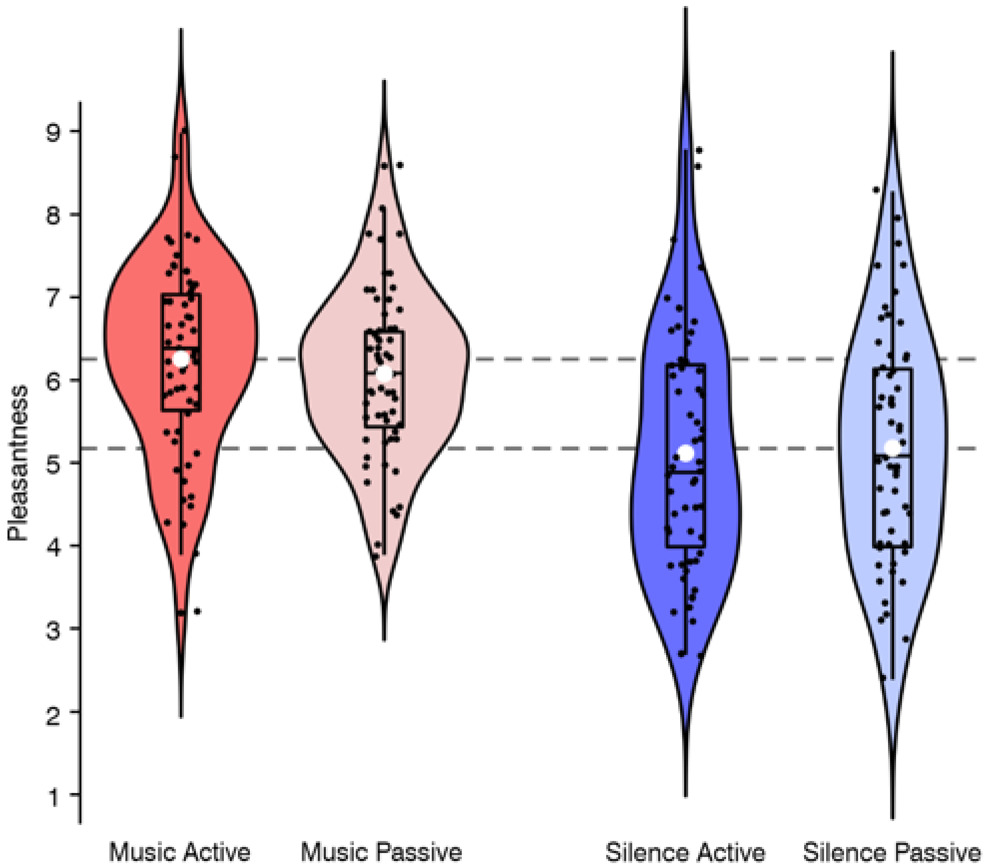

Figure 4

Within-subjects perceived pleasantness per experimental condition. The violin plots show the distribution density of the perceived pleasantness (rated on a scale ranging from 1 to 9) during music (red) or silence (blue) while performing either an active tapping task (darker colors) or a passive control task (lighter colors). Note that pleasantness ratings were highest for trials in which participants were tapping to the music. The embedded box-and-whisker plots represent the 25th and the 75th percentiles of the distributions, respectively. Upper and lower whiskers extend from the hinge to the largest/smallest value no further than 1.5 * inter-quartile range. The vertical lines in the boxes indicate median values, and the white disks indicate the means. The black dots show the jittered data points, and the dashed grey horizontal lines in the background represent the mean difference of the perceived pleasantness between music with tapping and silence without tapping.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformationPainMusic.docx