Hausmann, M., Hodgetts, S., Eerola, T. (2016). Music-induced changes in functional cerebral asymmetries. *Brain and Cognition,* 104, 58-71.

# Music-induced changes in functional cerebral asymmetries

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Running title: Music-induced changes in hemispheric asymmetries

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**Abstract**

After decades of research, it remains unclear whether emotion lateralization occurs because one hemisphere is dominant for processing the emotional content of the stimuli, or whether emotional stimuli activate lateralised networks associated with the subjective emotional experience. By using emotion-induction procedures, we investigated the effect of listening to happy and sad music on three well-established lateralization tasks. In a prestudy, Mozart's piano sonata (K.448) and Beethoven's Moonlight Sonata were rated as the most happy and sad excerpts, respectively. Participants listened to either one emotional excerpt, or sat in silence before completing an emotional chimeric faces task (Experiment 1), visual line bisection task (Experiment 2) and a dichotic listening task (Experiment 3 and 4). Listening to happy music resulted in a reduced right hemispheric bias in facial emotion recognition (Experiment 1) and visuospatial attention (Experiment 2) and increased left hemispheric bias in language lateralization (Experiment 3 and 4). Although Experiment 1-3 revealed an increased positive emotional state after listening to happy music, mediation analyses revealed that the effect on hemispheric asymmetries was not mediated by music-induced emotional changes. The direct effect of music listening on lateralization was investigated in Experiment 4 in which tempo of the happy excerpt was manipulated by controlling for other acoustic features. However, the results of Experiment 4 made it rather unlikely that tempo is the critical cue accounting for the effects. We conclude that listening to music can affect functional cerebral asymmetries in well-established emotional and cognitive laterality tasks, independent of music-induced changes in the emotion state.

**Keywords:** emotion induction; emotional valence; music; brain asymmetries; lateralization.

## 1. Introduction

The precise way the left and the right cerebral hemispheres contribute to emotion processing remains unclear. While some evidence suggests that emotion processing relies entirely on the right cerebral hemisphere (Borod et al., 1992; 1998), other studies suggest a left hemispheric contribution for processing emotions of positive valence (Jansari et al., 2011; Stafford and Brandaro, 2010) and/or approach motivation (Alves et al., 2009). The right hemisphere hypothesis originated from clinical observations of patients after unilateral lesions of the right cerebral hemisphere and postulates that the right hemisphere is superior for the expression and perception of emotion, regardless of emotional valance (Borod et al., 1998). The valence model of emotion lateralization was based on another set of lesion studies, suggesting that damage to the left frontal lobe was more likely to elicit negative/depressive emotional states. In contrast, patients who developed positive/manic emotional states were more likely to suffer from right hemispheric lesions, sparing the left (for a review see Silberman and Weingartner, 1986; Davidson, 1995).

To investigate emotion lateralization in healthy participants, the majority of studies focused on emotion perception, where participants have to identify the emotional content of auditory or visual stimuli, such as emotional facial expressions, emotional prosody, emotional words, etc. For example, Van Strien and Morpurgo (1992) showed that the central presentation of threatening words, as compared to non-threatening words, can reduce the typical left hemispheric advantage in a verbal task that required participants to report strings of letters presented to either the left visual field (LVF) or the right visual field (RVF), corresponding to the right and left hemispheres, respectively. The authors concluded that negative emotion induction can selectively activate right hemisphere processes. Ferry and Nicholls (1997) tried to replicate this finding by examining the effects of positive and negative emotions on a lateralized gap detection task. For each trial, participants in this study saw an emotive word in the middle of the screen followed by a target (a square) presented to either LVF or RVF. Participants were required to indicate whether the square contained a gap in its outer edge or not. In contrast to Van Strien and Morpugo (1992), this study did not show any evidence of RVF or LVF facilitation after presentation of positive or negative emotive stimuli, respectively. Therefore, it can be questioned whether the presentation of emotive words is sufficient to induce mood changes on a trial-by-trial basis.

The hemispheric substrates of perceiving emotional information are likely to be different from those involved in the subjective emotional experience (Davidson, 1995). Therefore, studies have investigated emotional lateralization by directly manipulating participants' current emotional state. Although several different emotion induction techniques have shown their effectiveness and validity, especially for inducing negative emotions (see Westermann et al., 1996, for a comprehensive review and meta-analysis), only a small proportion of laterality studies have used mood-induction procedures. For example, Gadea et al. (2005) investigated the effect of negative emotions on perceptual asymmetries by using the Velten procedure (Velten, 1968), which consisted of 60 self-referent statements gradually progressing from emotionally neutral to depressed. Perceptual asymmetries in this study were measured by a consonant-vowel dichotic listening task. In line with an increase in negative mood as measured by the PANAS mood scale (Watson et al., 1988), together with a 15% increase in cortisol levels, the results revealed the right ear advantage (REA) typically found in this task, and indicative a left dominant language lateralization, to be significantly reduced. As concluded by Gadea et al. (2005), the results were compatible with Kinsbourne's (1970) attentional-activation model suggesting that negative mood induction activated the right hemisphere, subsequently facilitating the reporting of verbal stimuli presented to the left ear, thereby reducing the REA.

The current paper focuses on using music to induce emotional states. Music listening has been shown to effectively induce negative and positive emotions (Gerrards-Hesse et al. 1994; Westermann et al., 1996; Västjfäll, 2002; Juslin and Laukka, 2004; Lundqvist et al., 2009). Critically, initial research was concerned with whether listeners simply perceived and processed the emotional content of musical stimuli, or whether listeners experienced changes in subjective emotional states in response to music (Juslin and Laukka, 2004). Lundqvist et al. (2009) yielded support for the latter notion. Participants listened to popular music with either a sad or happy expression, and it was found that happy music generated greater self-reported happiness, less sadness, more zygomatic facial muscle activity, greater skin conductance and lower finger temperature in contrast to sad music.

The effect of music on emotional states and its underlying functional brain activity has also been investigated using electrophysiological and neuroimaging techniques. For example, using electroencephalography (EEG), Schmidt and Trainor (2001) observed that asymmetry in frontal EEG activity differentiated the valence of musical emotions. Specifically, greater relative left frontal EEG activity was found after listening to joyful and happy musical excerpts, whereas greater relative right frontal EEG activity was found after listening to fearful and sad music. Although frontal EEG asymmetry did not differentiate the variation in the intensity of emotions between the musical excerpts, it was found that the overall frontal EEG activity decreased from fear to joy to happy to sad excerpts. Similarly, Altenmüller et al. (2002) investigated neural activation that accompanied participants' emotional response to positively and negatively valenced music stimuli from a range of genres (e.g., Jazz, Pop, classical music). Although Altenmüller et al. found a widespread bilateral fronto-temporal activation during music listening, this study found a strong lateralization when participants' emotional valence attributions of the perceived music were taken into account. Specifically, positive emotional attributions (e.g. "I like the music very much") were accompanied by an increase in left-temporal activation, whereas negative attributions (e.g. “I do not like the music at all”) revealed more bilateral activation with preponderance of the right fronto-temporal cortex. “Although emotional valence attributions cannot simply be taken as *emotions* itself, the judgements are closely linked to the emotions felt during listening” (Altenmüller et al., 2002, p. 2249). Therefore, the results suggest that it was the participants’ emotion experience rather than the emotional valence portrayed in music that was associated with lateralized brain activation.

In this context it is important to note that emotional experience and the emotional valence portrayed in music are not necessarily the same. In fact, many individuals enjoy listening to sad music (e.g., Vuoskoski et al., 2011). Also, given that their findings were marginally affected by music genre, Altenmüller et al. (2002) further concluded that the actual auditory brain activation was more determined by their affective emotional valence than by acoustical fine structure.

Another study combined functional magnetic resonance imaging (fMRI) and EEG with subjective measures of emotional reactions during passive listening to pleasant and unpleasant music masterpieces (Flores-Gutierrez et al., 2007). Similar to Altenmüller et al. (2002), the authors revealed a left-lateralised network including primary auditory cortex, posterior temporal, parietal and prefrontal regions when participants reported pleasant feelings. Conversely, a right-lateralised network including right fronto-polar and paralimbic regions was found when participants reported unpleasant states. Taken together, emotion induction studies that look at lateralization after music listening partly support the valence hypothesis of emotion experience, suggesting that the frontal regions of each hemisphere contribute asymmetrically to the experience of emotion (Heilman, 1997): positive emotions, induced by listening pleasant music, are related to a relative increase of activation in the left frontal lobe, and negative emotions, induced by listening to unpleasant music, are related especially to an increase in right frontal lobe activation.

The aim of the present study was to elaborate whether the effect of listening to happy and sad music on lateralization in an emotional and non-emotional/attention task is mediated by the music-induced emotion. In line with a previous study that revealed Mozart's piano sonata (K. 448) to be able to induce happy emotions (Thompson et al., 2001), listeners in our prestudy rated Mozart's piano sonata (as used in the original *Mozart-effect* studies, Rauscher et al., 1993), and Beethoven's Op. 27, No. 2 (*Moonlight Sonata*) as expressing happiness and sadness, respectively. Four experiments were performed in which we investigated the effects of music listening, and corresponding changes in mood, on three well established laterality tasks: i) an emotional chimeric faces task, originally developed by Levy et al., (1983) (Experiment 1), ii) a lateralized spatial attention task (visual line bisection; e.g., Hausmann, 2002; 2003a; 2003b) (Experiment 2), and iii) a verbal consonant-vowel dichotic listening task (Hugdahl, 1995, 2003) (Experiment 3 and 4). With reference to the valence hypothesis, it was hypothesised that listening to the happy excerpt will increase participants' positive emotions, thereby increasing left frontal activation, and consequently diminishing the right hemispheric bias typically reported for the emotional chimeric faces (Experiment 1) and visual line bisection task (Experiment 2). In line with this prediction, we predicted that listening to the happy excerpt increases the typical REA, left hemispheric dominance, in a verbal dichotic listening task (Experiment 3). In contrast, it was predicted that listening to the sad excerpt will increase participants' negative emotions, and consequently enhance the right hemispheric biases for both right hemisphere tasks and diminish the left hemisphere bias in verbal dichotic listening.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Participants.

Sample size was based on the effect size of the mean laterality bias in a previous emotional chimeric faces study (Workman et al., 2000) that, similar to the current study, used six facial expressions of emotions (i.e., happiness, sadness, surprise, disgust, fear, and anger). According to the effect size (Cohen's $d = 1.54$) in this study, seven participants should be sufficient to find a significant laterality bias in the emotional chimeric faces task. This estimated sample size number was roughly doubled for each group condition.

The sample consisted of thirty-nine undergraduate students (21 female) who participated in this experiment in exchange for course credit. The mean age of the sample was 20.31 years ($SD = 1.16$). All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). The laterality quotient (LQ) provided by this test is calculated as $[(R - L) / (R + L)] \times 100$, resulting in values between -100 and 100 describing a continuum between consistent sinistrality and consistent dextrality, respectively. The mean LQ of the sample was 84.53 ($SD = 14.57$). All participants had normal or corrected-to-normal visual acuity. Participants did not use any medication affecting the CNS and did not have mood disorders. Participants were randomly allocated to one of three music conditions (happy excerpt, sad excerpt or silence/control). The three groups did neither differ in age, $F(2, 36) = 2.44$, *ns*, nor handedness, $F(2, 36) = 0.07$, *ns*.

**2.1.2. Apparatus and measures.** In order to identify two pieces of music that are perceived as particularly happy and sad, a prestudy was conducted. Twenty undergraduate students (10 male) aged between 19 and 21 years listened to five pieces of piano music for 2 min: Mozart's piano sonata in D major (K. 448); Beethoven's Moonlight Sonata (Op. 27, No. 2), Mozart's Piano Sonata in A Minor (K. 310); Beethoven's Piano Sonata No. 6 In F Major

(Op. 10, No. 2) and Mozart's Piano Sonata in C Major (K. 545). After listening, participants were required to rate the music according to a 6-point Likert scale (1= very sad, 6 = very happy). The highest rating was found for Mozart's K. 448 ($M$ = 5.15, $SD$ = 2.19) and the lowest for Beethoven's Op. 27, No. 2 ($M$ = 2.15, $SD$ = 3.35). Therefore, Mozart K. 448 and Beethoven Op. 72, No. 2, were chosen for the *happy* and *sad* emotion-induction conditions, respectively. Similar to Rauscher et al. (1993), participants listened to either Mozart or Beethoven for 10 min. Rather than ending abruptly at 10 min, each piece ended at the next phrase boundary. Music was presented in stereo through high-quality headphones via an HP Pavilion G Series laptop.

**2.1.3. State-Trait Cheerfulness Inventory.** In order to measure participants' emotional states before and after music listening, the 18 item State-Trait Cheerfulness Inventory - State (STCI-S<18>, Ruch et al., 1997) was used. The analysis of the STCI-S was restricted to two subscales that measure cheerfulness and bad mood. Ruch et al. (1997) characterised state cheerfulness as a state of pleasantness, excitation and relaxation, while bad mood was characterised as a state of unpleasantness and strain.

**2.1.4. Emotional Chimeric Faces (ECF).** The ECF task was adapted from Bourne and Gray (2011) and has been used in a recent study (Innes et al., in press). Participants were presented with vertically split chimeric faces; one half of each face showed a neutral expression, the other half showed an emotional expression (anger, disgust, fear, happiness, sadness or surprise). In contrast to previous studies, however, averages of facial expressions were used for the left and right side images and the images contributing to the right and left sides of the final stimulus were joined together using a graduated fade across the midline. For each facial expression, 10 commonly used exemplars from the Ekman and Friesen face set (1976) were averaged together (Tiddeman et al., 2001) and made symmetrical to create a prototypical facial expression. Following the same methods as Burt and Perrett (1997), the chimeric emotional face stimuli were then produced by gradually fading from one prototypical facial expression to the other across centre of the face. Hair and other features outside of the face were then masked to produce the final images for presentation. Emotional stimuli were counterbalanced with respect to the side the emotion appeared in. Stimuli also included wholly neutral faces, making seven possible face stimuli. Two face stimuli were presented simultaneously on each trial, one below the other (see Figure 1). In each case, the bottom image was a mirrored version of the top image. The neutral face stimuli were removed from analysis. A total of 48 chimeric-face trials were presented, in half of these, the face with the emotion of the left appeared at the top, and vice versa. The task took less than 10 min to complete.

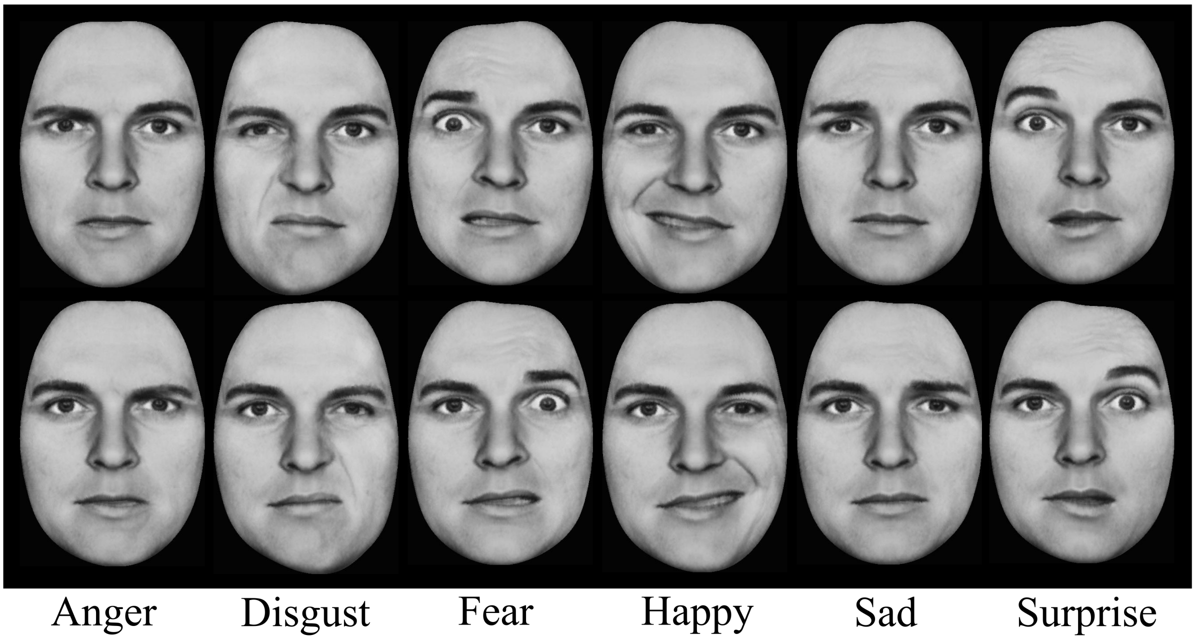


**Figure 1**. Emotional chimeric face stimuli according to six basic emotions (anger, disgust, fear, happy sad, and surprise). The top faces show the emotional face expression on the left side of the face, while the bottom faces show the emotional expressions on the right.

Participants were instructed to indicate via button press which of two chimeric faces (either with the emotional face expression of the left or right) appeared more emotional. Each stimulus was presented for 4000 ms. The LQ for this task was calculated according to Bourne and Gray (2011) as [number of LVF choices – (total number of trials – number of LVF choices)] ÷ total number of trials, resulting in LQs between -1 and 1, indicating right visual field/left hemisphere bias and left visual field/right hemisphere bias, respectively.

**Procedure.** After participants completed the Edinburgh Handedness Inventory and STCI-S questionnaire, they listened to either Mozart or Beethoven for 10 min. The control group did not listen to any music and instead, sat in silence for 10 min. All participants then completed the second STCI-S<18> questionnaire, followed by the ECF task.

**2.2. Results**

**2.2.1. STCI-S scores.** To investigate whether music-induced changes in emotion, STCI-S scores of the Cheerfulness and Bad mood subscales were subjected to two separate 2 × 2 × 3 ANOVAs with Time of measurement (before, after music listening) as a within-subjects factor, and Music condition (happy excerpt, sad excerpt, silence) and sex as between-subject factors. The analysis revealed a significant Time by Music condition interaction for Cheerfulness, $F(2, 33) = 4.20$, $p = .024$, $\eta_p^2 = .20$, and Bad mood, $F(2, 33) = 8.78$, $p = .001$, $\eta_p^2 = .35$. No other effect was significant, all $F < 3.47$, *ns*. Simple comparisons (one-tailed, motivated by the hypothesis and previous findings) revealed an increase in Cheerfulness after listening to the happy excerpt, $t(13) = 1.97$, $p = .035$, and decrease in Bad mood, $t(13) = 2.54$, $p = .012$. In contrast, Cheerfulness was reduced after listening to the sad excerpt, $t(12) = 2.15$, $p = .026$, together with an increase in Bad mood, $t(13) = 2.40$, $p = .016$. The control group revealed no changes in Cheerfulness, $t(11) = 0.44$, *ns*, but an increase in Bad mood, $t(11) = 2.37$, $p = .037$, two-tailed. Although changes in emotions followed the emotion portrayed in music, both groups differed only marginally after music listening in Cheerfulness, $t(25) = 1.44$, $p = .08$, and did not differ in Bad mood, $t(25) = 0.58$, $p = .28$ (see Table 1).

**Table 1.** *Means and standard deviations of the STCI-S subscales (Cheerfulness and Bad mood) before and after music/silence exposure in Experiment 1.*

| | Cheerfulness | | Bad mood | |
|---|---|---|---|---|
| | Before | After | Before | After |
| Silence (*n* = 12) | 26.50 (3.99) | 27.08 (5.33) | 14.92 (4.99) | 16.92 (5.63)* |
| Sad music (*n* = 13) | 26.77 (5.85) | 23.85 (5.16)* | 15.69 (4.99) | 17.69 (4.92)* |
| Happy music (*n* = 14) | 25.21 (5.63) | 26.86 (5.67)* | 18.71 (6.58) | 16.50 (5.74)* |

*p < .05, indicating significant differences between STCI scores before and after music/silence exposure.

**2.2.2. Emotional Chimeric Faces Task.** To investigate the effect of music on emotion lateralization, LQs of the ECF task were subjected to a 3 × 2 × 6 ANOVA with Condition (happy music, sad music, silence) and sex as between-subjects factors, and Emotional face expression (anger, disgust, fear, happy, sad, surprise) as a within-subject factor. The grand average mean ($M$ = 0.139, $SEM$ = 0.053) was significantly different from zero, $F(1, 33)$ = 6.87, $p$ = .013, $\eta_p^2$ = .17, indicating the expected overall LVF/RH bias. One sample t-tests against the test score zero revealed a significant LVF/RH bias for the control, $t(11)$ = 3.16, $p$ = .009, and Beethoven conditions, $t(12)$ = 2.68, $p$ = .020, but not for the Mozart condition, $t(13)$ = -0.91, $p$ = .379. The main effect of Music condition was also significant, $F(2, 33)$ = 4.54, $p$ = .018, $\eta_p^2$=.22. No further effects were significant, all $F$ < 2.78, *ns*. Post hoc *t*-tests (Bonferroni, two-tailed) revealed that LQ in the happy music condition was significantly smaller than LQs in the sad music condition, $t(25)$ = 2.69, $p$ = .013, and in the silence condition, $t(24)$ = 2.88, $p$ = .008. No difference was found between the sad music and silence condition, $t(23)$ = 0.11, $p$ = .91 (Figure 2).

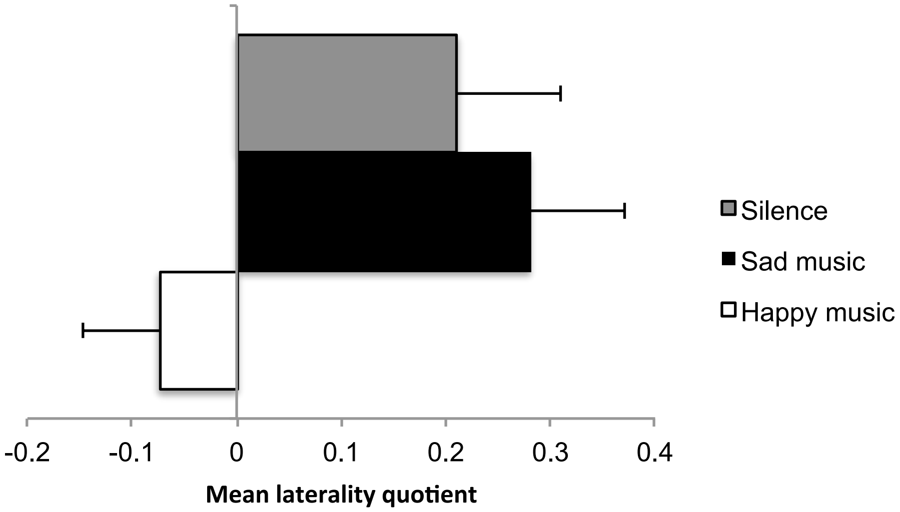


**Figure 2.** Mean laterality quotient (LQ) and standard error means in the Emotional chimeric faces task according to music condition (happy music, sad music, silence/control). Positive LQs indicate a left visual field/right hemisphere bias, negative LQs indicate a right visual field/left hemisphere bias.

**2.2.3. Mediation analysis.** The results of Experiment 1 revealed that listening to the happy excerpt induced significant emotional changes and reduced the right hemispheric bias in the ECF task. To further investigate whether listening to the happy excerpt affected emotion lateralization directly or whether the effect was mediated through the music-induced change in emotion, a parallel mediation analysis was performed using the MEDIATION macro for SPSS (Hayes and Preacher, 2014). The hypothetical mediation model included Music condition as multicategorical independent variable, changes in cheerfulness and bad mood scores (scores after music – scores before music) as mediators, and the overall ECF laterality bias as dependent variable. Simple indicator (dummy) coding was used with silence/control group as reference. Bias-corrected bootstrap confidence intervals (95%) for interference about indirect effects were used with 5000 samples (generated by stratifying the resampling in each group). Total effects model (*c* paths) and mediation model (*c’* paths) with contrast codes are shown in Figure 3.

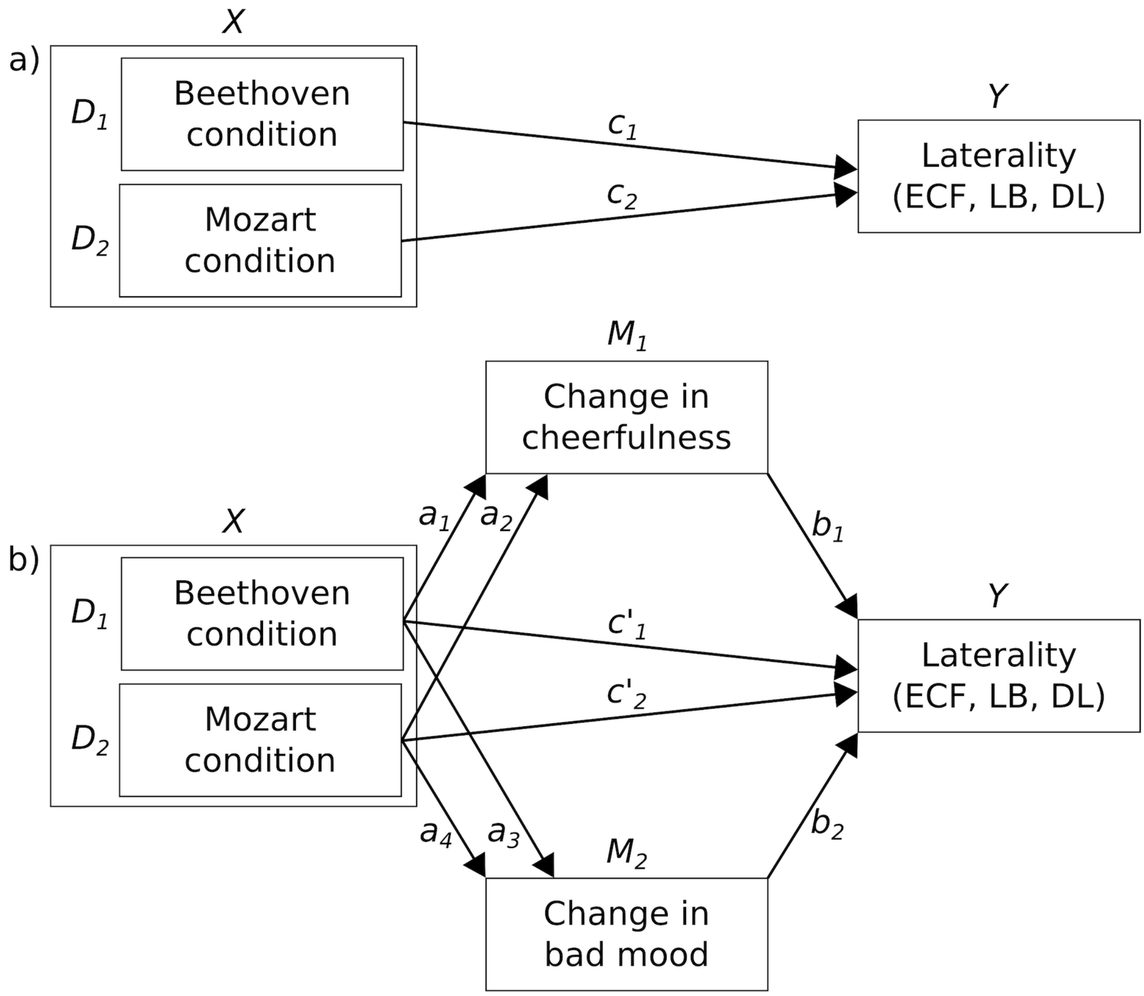


**Figure 3.** Mediation model in path diagram form corresponding to a model with a multicategorical independent variable with 3 categories (silence/control, sad music, happy music) and with two mediators, change in cheerfulness ($M_1$) and change in bad mood ($M_2$) through which the music condition (X) exerts its effect on different laterality measures (Y) (Figure 3b). Of interest are the indirect effects of X, quantified as the products of a and b, and the direct effects, quantified as c'. The total effect of X and Y, denoted by c in Figure 3a, is the sum of X's direct and indirect effects on Y, that is c = c' + ab. When X is multicategorical, the total (c), direct (c') and indirect effects (ab) are quantified with a set of parameter estimates which are based on mean group differences. $D_1$ codes the sad music condition, $D_2$ codes the happy music condition, and the silence/control group functions as the reference group and receives a code of 0 on $D_1$ and $D_2$. For more details on mediation analyses with multicategorical variables, see Hayes and Preacher (2014).

The mediation analysis revealed that music condition statistically predicted the ECF bias, $R^2$ = .219, $F(2, 36) = 5.06$, $p = .012$, with the Mozart group ($D_2$) contributing significantly to the model, $p = .012$, not the Beethoven group ($D_1$), $p = .909$. The two mediators added to this prediction accounted for additional 8.7% of explained variance, $R^2 = .306$, $\Delta R^2 = .087$, $F$(4,

34) = 3.75, *p* = .012. However, the relative indirect effects of music conditions on the ECF bias through changes in cheerfulness were not significant (sad music = 0.081, *SE* = 0.077, 95% CI [-.007, .297], sad music = -0.025, *SE* = 0.041, 95% CI [-.147, .033]). Similarly, indirect effects of music condition on ECF bias through changes in bad mood were not significant (sad music = 0.000, *SE* = 0.022, 95% CI [-.050, .049], happy music = -0.031, *SE* = 0.079, 95% CI [-.209, .105]). The regression coefficients are shown in the supplemental material.

**2.3. Interim summary.** Experiment 1 observed the predicted increase in cheerfulness and decrease in bad mood after listening to Mozart and Beethoven, respectively. In addition, and in line with our hypothesis, listening to music affected the right hemispheric bias in the ECF task. While participants in the Beethoven group and control group revealed the typical right hemispheric bias, participants in the Mozart condition showed the bias to be significantly reduced and shifted slightly to the left. The results suggest that listening to Mozart can reduce the right hemispheric bias in emotion lateralization, independently from the emotional valence of the facial expression. Although music condition affected both emotional state and the laterality bias in the ECF task, the latter was not mediated by music-induced emotional changes.

## 3. Experiment 2

Experiment 1 revealed that the well-established right hemispheric asymmetries in an ECF task (i.e. LVF bias for chimeric faces with emotional expressions) was significantly reduced after listening to the happy excerpt, whereas the typical right hemispheric bias was found in the sad excerpt condition and control group. Previous research in clinical populations suggests that emotional tasks are more sensitive to emotional state than non-emotional tasks (e.g. Mathews and MacLeod, 1985; Kaspi et al., 1995; Gotlib and McCann, 1984; Klieger and Cordner, 1990). To investigate whether the effect observed in Experiment 1 is specific to emotion lateralization or can be replicated in a lateralized task that is purely cognitive in nature, we conducted Experiment 2. When asked to manually bisect horizontal lines in the center, participants usually deviate towards the left of the veridical center (e.g., Hausmann et al., 2002; 2003a; 2003b) – a phenomenon called *pseudoneglect* (Bowers and Heilman, 1980a).

According to Kinsbourne's (1970) attentional-activation model, functional cerebral asymmetries result from the adoption of a cognitive set, which asymmetrically activates one of the cerebral hemispheres. The visuo-spatial nature of the LB task activates the right hemisphere so that attention is directed to the contralateral side of space. 'Cognitive set' in this context has been interpreted as corresponding to a form of tonic or long-lasting arousal-attentiveness (Bowers and Heilman, 1980b). This experiment used the visual line bisection (LB) task under the same three music conditions as in Experiment 1. If listening to happy music, and positive emotional changes, affects the cognitive set and activates the left hemisphere, Kinsbourne's model would predict a reduction of right hemisphere engagement in allocation of spatial attention and hence a reduction in the left LB bias (similar to Experiment 1), whereas the typical left bisection bias should not be affected in the sad excerpt and control condition.

### 3.1. Methods

**3.1.1. Participants.** Forty-seven undergraduate students (26 male) aged between 18 and 22 years ($M$ = 20.64, $SD$ = 0.74) participated in this experiment. Sample sizes were chosen in order to match or somewhat exceed those in Experiment 1. The mean handedness LQ (Oldfield, 1971) was 26.25 ($SD$ = 60.88, ranging from -100 to 100). Participants were again randomly allocated to one out of three music conditions. The three groups did not differ in age $F(2, 44) = 0.54$, *ns*, nor handedness, $F(2, 44) = 0.71$, *ns*. All participants had normal or corrected-to-normal visual acuity. Participants did not use any medication affecting the CNS and did not have mood disorders.

**3.1.2. Music condition.** The same music stimuli were used as in Experiment 1. All music was presented to participants in stereo through Sony MDR-NC60 High Quality Noise Cancelling Headphones via an Apple iPod.

**3.1.3. Line bisection (LB) task.** The LB task is a well-established measure of right hemispheric functioning in visuospatial attention and was identical to that used in previous studies (e.g. Hausmann et al., 2002; 2003a; 2003b; Najt et al., 2013). The task was comprised of 17 horizontal, black lines of 1 mm width on a white sheet of A4 paper. Line length ranged from 96 mm to 210 mm. The stimuli sheet was laid in front of the participant's midline and participants were instructed to bisect each line into two parts of equal length by marking the subjective mid-point with a pencil. The experimenter covered the lines after they were bisected to ensure participants were not biased by previous bisections. Participants completed the LB task with each hand. There was no time restriction. Deviations from the veridical centre of each line were measured to 0.5 mm accuracy. The directional bias was calculated as a percentage score in order to account for individual line length: [(measured left half - true half] ÷ true half) × 100. Negative values indicate a leftward bias, while positive values indicate a rightward bias. Absolute scores were also calculated to examine potential group differences in accuracy.

**3.1.4. Procedure.** The experimental procedure was identical to Experiment 1. Participants were randomly allocated either to the Mozart, Beethoven or silence (control) group. All participants then completed the Edinburgh Handedness Inventory (Oldfield, 1970) and the STCI-S (Ruch et al., 1997). Participants listened for 10 min to either happy music, sad music, or sat in silence. Participants were then required to complete a second STCI-S. All participants then completed the visual line bisection task, which took less than 10 min to complete.

### 3.2. Results

**3.2.1. STCI-S scores.** Similar to Experiment 1, STCI-S scores were subjected to two separate 2 × 2 × 2 mixed ANOVAs with Time of measurement (before, after) as a within-subjects factor, and Group (happy music, sad music) and Sex as between-subject factors. For the silence/control group of Experiment 2, the STCI scale was only administered once, directly before performing the LB task. For Cheerfulness, the Time by Group interaction approached significance, $F(1, 26) = 3.82$, $p = .06$, $\eta_p^2 = .128$. No other effect approached significance, all $F < 1.76$, *ns*. Simple comparisons (one-tailed) revealed a non-significant increase in Cheerfulness after listening to the happy excerpt, $t(14) = 1.08$, $p = .15$, and decrease in Bad mood, $t(14) = 1.19$, $p = .13$. In contrast, Cheerfulness was significantly reduced after listening to the sad excerpt, $t(14) = 1.87$, $p = .04$, and Bad mood was increased, $t(13) = 3.32$, $p = .003$. Consequently, both music groups differed significantly in Cheerfulness, $t(28) = 1.90$, $p = .03$, and Bad mood, $t(28) = 2.02$, $p = .03$ (see Table 2).

**Table 2.** *Means and standard deviations of the STCI-S subscales (Cheerfulness and Bad mood) before and after music/silence exposure in Experiment 2.*

| | Cheerfulness | | Bad mood | |
|---|---|---|---|---|
| | Before | After | Before | After |
| Silence (*n* = 17) | - | 28.24 ± 4.74 | - | 15.35 ± 6.26 |
| Sad music (*n* = 15) | 26.93 ± 5.20 | 24.60 ± 6.40* | 15.80 ± 5.63 | 19.93 ± 7.77* |
| Happy music (*n* = 15) | 27.33 ± 5.00 | 28.73 ± 5.47 | 16.87 ± 6.29 | 14.40 ± 7.25 |

*$p < .05$, indicating significant differences between STCI scores before and after music/silence exposure.

**3.2.2. Directional LB bias.** Percentage deviation scores were subjected to a 2 × 3 × 2 ANOVA with repeated measures with Hand used (left, right) as a within-subject variable, and Music condition (happy music, sad music, silence) and sex as between-subjects factors. The main effect of Music condition was significant, $F(2, 41) = 7.48$, $p = .002$, $\eta_p^2=.27$ (see Figure 4). One sample t-tests against the test score zero revealed a significant rightward bias for the Mozart condition, $t(14) = 4.79$, $p < .0001$. The leftward bias for the Beethoven, $t(14) = -0.07$, $p = .944$, and control condition, $t(16) = -1.59$, $p = .132$, were not significant. No other effect approached significance, all $F < 1.18$, *ns*. Post hoc *t*-tests (Bonferroni) revealed that the unusual rightward bias in the happy music condition ($M = 2.54$, $SD = 2.06$) differed significantly from the bias in both the sad music condition ($M = -0.06$, $SD = 3.01$), $t(28) = 2.76$, $p = .01$, and silence condition ($M = -0.92$, $SD = 2.38$), $t(30) = 4.36$, $p < .001$. The leftward bias did not differ between the sad music condition and control group, $t(30) = 0.91$, $p = .37$ (Figure 4). The same ANOVA for absolute deviations did not reveal any significant effects, all $F < 2.38$, *ns*, indicating no differences in bisection accuracies across groups and Music conditions.

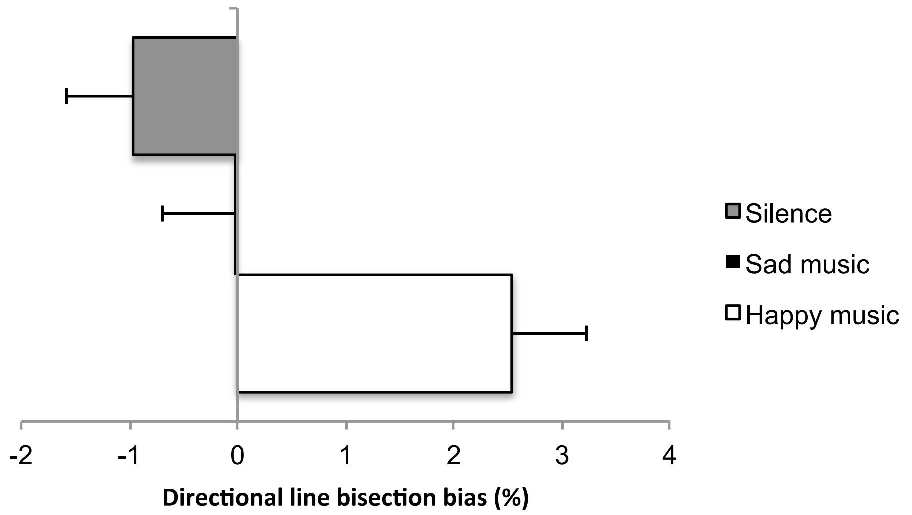


**Figure 4.** Directional bias (%) and standard error means in visual line bisection according to condition (happy music, sad music, silence/control). Positive deviations indicate a left hemisphere bias, negative deviations indicate a right hemisphere bias.

**3.3.3. Mediation analysis.** To further investigate whether listening to happy excerpt affected the lateralization bias in spatial attention directly or whether the effect was mediated through music-induced emotional changes, mediation analysis was performed. In contrast to Experiment 1, however, Experiment 2 determined mood scores for the silence/control condition only once (see above). Therefore no changes in STCI scores were computed for this group. In the mediation analysis of Experiment 2, $D_1$ coded the happy music condition, and the sad music condition functioned as the reference group and received a code of 0 on $D_1$. In line with Experiment 1, the mediation analysis revealed that the happy music condition statistically predicted the LB bias, $R^2$ = .214, $F$(1, 28) = 7.62, $p$ = .010, with again the happy music group ($D_1$) contributing significantly to the model, $p$ = .010. The two mediators added to this prediction accounted for only additional 2% of explained variance, $R^2$ = .234, $\Delta R^2$ = .020, $F$(3, 26) = 2.65, $p$ = .070. The relative indirect effects of the happy excerpt condition on the LB bias through changes in Cheerfulness and Bad mood were not significant (happy excerpt = -0.040, *SE* = 0.754, 95% CI [-1.561, 1.461], happy excerpt = 0.439, *SE* = 0.797, 95% CI [-.656, 3.182], respectively). The regression coefficients are shown in the appendix.

**3.4. Interim summary.** Experiment 2 observed the predicted increase in cheerfulness and decrease in bad mood after listening to the happy excerpt and sad excerpt, respectively. In addition, and in line with our hypothesis and Experiment 1, listening to music affected the right hemispheric bias in the LB task. While participants in the sad excerpt group and control group revealed a LB bias in the normal range, participants in the happy music condition showed the bias to be significantly reduced and shifted to the right of the veridical center. The results suggest that listening to happy music can activate the left hemisphere, regardless whether the task is emotional (Experiment 1) or cognitive in nature, and consequently reduce the right hemispheric bias in spatial attention. Although music condition affected both mood state and the laterality bias in the line bisection task, the latter was not mediated by changes in mood.

## 4. Experiment 3

Experiment 1 and 2 revealed reduced right hemispheric asymmetries after listening to the happy excerpt, whereas the laterality biases after listening to the sad excerpt were unaffected and statistically identical to the biases of the control groups. Following the valence model of emotion processing, the results are compatible with Kinsbourne's (1970) attentional-activation model, suggesting that listening to the happy music activated the left hemisphere, thereby reducing the typical right hemispheric bias in both the ECF and LB task. The mediation analyses revealed, however, that the left hemispheric activation was not mediated by music-induced changes in emotion. If listening to happy music reduces the laterality bias in two right hemispheric tasks via activating the left hemisphere, we would predict the opposite in a left dominant task, that is, an increase in the REA/left hemispheric advantage in a verbal dichotic listening task. This prediction was tested in Experiment 3.

To increase the sensitivity of the emotional state measurement, the 30 items version of the STCI mood questionnaire was used in Experiment 3, instead of the short form (18 items) used in Experiment 1 and 2. Both the standard STCI-S<30> and short form STCI-S<18> provide scores for the same constructs. However, whereas the STCI-S<18> provides a measurement of short-lived changes, or emotional states, in such cases when the assessment should be quick and economic and not interfere too much with the emotional changes taking place, the STCI-S<30> provides a more reliable and fine-grained assessment (Ruch et al., 1996).

### 4.1. Methods

**4.1.1. Participants.** Sixty-seven undergraduate students (36 male) aged between 19 and 24 years (*M* = 20.67, *SD* = 0.91) participated in this experiment. Sample sizes were chosen in order to match or somewhat exceed those in Experiment 1 and 2. The mean handedness LQ (Oldfield, 1971) was 70.15 (*SD* = 43.65, ranging from -100 to 100). As in the previous experiments, participants were randomly allocated to one of three music conditions (happy music, sad music, or silence/control). The three groups did neither differ in age, $F(2, 64) = 1.18$, *ns*, nor handedness, $F(2, 64) = 0.53$, *ns*. All participants had normal or corrected-to-normal visual acuity. Participants did not use any medication affecting the CNS and did not have mood disorders.

**4.1.2. Music condition.** The same music stimuli were used as in Experiment 1 and 2. All excerpts were presented to participants in stereo through Bose Quiet Comfort 15 Acoustic Noise Cancelling Headphones and played on a MacBook Pro laptop.

**4.1.3. Music enjoyment.** Given that the level of subjective musical enjoyment can differ from the emotional valence portrayed in music (Altenmüller et al., 2002), we also asked participants of Experiment 3 to indicate how much they enjoyed listening to music, or sat in silence, on a 6-point Likert scale (1 = very much, 6 = not at all).

**4.1.4. Bergen dichotic listening (DL) task.** The Bergen DL task was identical to that used in previous studies (e.g. Hugdahl, 1995, 2003). The stimuli set consisted of six consonant-vowel syllables, i.e. /ba/, /da/, /ga/, /ka/, /pa/, /ta/, spoken by a native English male voice in constant intonation and intensity. The syllables were presented dichotically simultaneously, resulting in 36 different dichotic stimulus pairs (e.g. /ba/-/pa/), also including six homonymic pairs (e.g., /ba/-/ba/). Stimulus pairs were presented through headphones with an inter-stimulus interval of 4000 ms. Participants ~~gave~~ indicated the syllable they have heard by pointing to a corresponding syllable shown on an A4 page in from of them. The percentage of correct left ear reports, and correct right ear reports were scored separately, and used for the calculation of laterality index (as an indicator of ear advantage) according to the formula: Laterality index = [(right ear – left ear) ÷ (right ear + left ear)] × 100. The homonymous pairs were not included in the final score.

**4.1.5. Procedure.** The experimental procedure was identical to Experiment 1 and 2. Participants were randomly allocated one of three music conditions and listened for 10 min to either the happy excerpt, sad excerpt, or sat in silence before doing the dichotic listening task. The task took less than 10 min to complete.

### 4.2. Results

**4.2.1. STCI-S scores.** Similar to Experiment 1 and 2, mood scores were subjected to two separate 2 × 2 × 3 mixed ANOVAs with Time of measurement (before, after) as a within-subjects factor, and Group (happy music, sad music, silence) and Sex as between-subject factors. The Time by Group interaction was significant for both Cheerfulness, $F(2, 61) = 6.69$, $p = .002$, $\eta_p^2 = .180$, and Bad mood, $F(2, 61) = 10.24$, $p < .001$, $\eta_p^2 = .251$. No other effect was significant (all $F < 3.73$, *ns*). Simple comparisons (one-tailed) revealed a non-significant increase in Cheerfulness after listening to the happy excerpt, $t(22) = 1.32$, $p = .10$, and a significant decrease in Bad Mood, $t(21) = 2.53$, $p = .01$. Cheerfulness was significantly reduced after listening to the sad excerpt, $t(22) = 3.64$, $p = .001$, and Bad mood was increased, $t(19) = 3.01$, $p = .003$. No significant changes in emotion state were found for the silence condition, both $t(21) < 1.34$, *ns*. Consequently, after listening to music, both music groups differed significantly in Cheerfulness, $t(43) = 3.41$, $p = .001$, and the difference approached significance for Bad mood, $t(43) = 1.92$, $p = .06$ (see Table 3).

**Table 3.** *Means and standard deviations of the STCI-S subscales (Cheerfulness and Bad mood) before and after music/silence exposure in Experiment 3.*

| | Cheerfulness | | Bad mood | |
|---|---|---|---|---|
| | Before | After | Before | After |
| Silence (*n* = 22) | 27.18 ± 5.59 | 26.36 ± 5.38 | 16.86 ± 6.24 | 16.09 ± 5.34 |
| Sad music (*n* = 23) | 27.91 ± 4.37 | 23.78 ± 5.50** | 14.39 ± 3.45 | 18.61 ± 6.07** |
| Happy music (*n* = 22) | 27.68 ± 4.59 | 29.05 ± 4.81 | 17.23 ± 7.48 | 15.09 ± 6.25** |

*p < .05, ** < .01, one-tailed, indicating significant differences between STCI-S scores before and after listening to music.

**4.2.2. Music enjoyment.** The score reflecting how much participants enjoyed listening to music, or sitting in silence, was subjected to a 3 × 2 ANOVA with Music condition (happy music, sad music, silence) and sex as between-subjects factors. The ANOVA did not reveal any group differences, all $F < 1.00$, *ns*.

**4.2.3. Bergen DL task.** To investigate the effect of music on language lateralization, LIs of the Bergen DL task were subjected to a 3 × 2 ANOVA with Music condition (happy music, sad music, silence) and sex as between-subjects factors. The grand average mean ($M = 10.46$, $SD = 2.72$) was significantly different from zero, $F(1, 61) = 16.93$, $p < .001$, $\eta_p^2 = .22$, indicating the expected overall REA bias. One sample t-tests against the test score zero revealed a significant REA bias for the Mozart condition, $t(21) = 5.73$, $p < .0001$. The REA bias for the Beethoven, $t(22) = 0.38$, $p = .705$, and control condition, $t(21) = 1.38$, $p = .181$, were not significant. The main effect of Music condition was also significant, $F(2, 61) = 7.69$, $p = .001$, $\eta_p^2 = .20$; as well as the main effect of sex, $F(1, 61) = 5.67$, $p = .020$, $\eta_p^2 = .09$, indicating a numerically larger REA in men ($M = 15.41$, $SD = 3.45$) than women ($M = 4.72$, $SD = 4.12$). The interaction was not significant, $F(2, 61) = 0.05$, *ns*. Post hoc t-tests (Bonferroni, two-tailed) revealed a larger REA in the happy music condition ($M = 23.34$, $SD = 4.07$) than in the sad music condition ($M = 1.47$, $SD = 3.83$), $t(43) = 3.92$, $p < .001$, and in the silence condition (*M* = 7.00, *SD* = 5.06), $t(42) = 2.52$, $p = .016$. No difference was found between the sad music and silence group, $t(43) = 0.88$, $p = .39$ (Figure 5). All significant effects remained when only right-handers were included in the analyses.

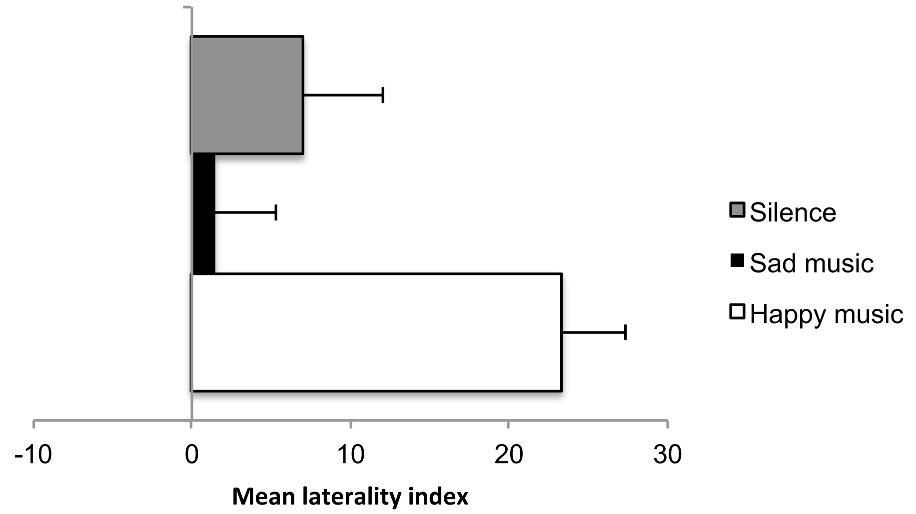


**Figure 5.** Mean laterality index and standard error means in the Bergen dichotic listening task according to music condition (happy music, sad music, silence/control). A positive bias indicates a REA (i.e., left hemisphere advantage), a negative bias indicates a left ear advantage (i.e., right hemisphere bias).

**4.2.4. Mediation analysis.** To investigate whether listening to music affected the REA in DL directly or whether the effect was mediated through music-induced changes in emotional state, a mediation analysis was performed. The mediation analysis was identical to Experiment 1 (Figure 2b). The mediation analysis revealed that music condition statistically predicted the REA bias, $R^2 = .177$, $F(2, 64) = 6.87$, $p = .002$, with the happy music group ($D_2$) contributing significantly to the model (p = .010), not the sad music group ($D_1$) ($p = .369$). The two mediators added to this prediction accounted for only additional 1.8% of explained variance, $R^2 = .195$, $\Delta R^2 = .018$, $F(4, 62) = 3.75$, $p = .009$ (Table 2). However, similar to Experiment 1 and 2, the relative indirect effects of music conditions on the dichotic listening bias through changes in cheerfulness were not significant (sad music = 2.567, *SE* = 2.549, 95% CI [-.0783, 9.860], happy music = -1.691, *SE* = 1.933, 95% CI [-7.563, .0592]).

Similarly, indirect effects of music condition on REA through changes in bad mood were not significant (sad music = -2.983, *SE* = 3.940, 95% CI [-12.496, 3.585], happy music = 0.815, *SE* = 1.345, 95% CI [-.683, .186]). The regression coefficients are shown in the supplemental material.

**4.3. Interim summary.** In line with Experiment 1 and 2, Experiment 3 revealed the predicted increase in cheerfulness and decrease in bad mood after listening to the happy and sad excerpts, respectively. In addition, and in line with our hypothesis, listening to music affected the REA in the verbal DL task. In comparison to the REA in the sad music group and control group, participants in the happy music condition showed an REA that was significantly increased. In line with Experiment 1 and 2, Experiment 3 suggests that listening to happy music can increase the left hemispheric bias in language lateralization. Although music condition affected both STCI-S scores and the laterality bias, the latter was not mediated by changes in emotional state.

## 5. Experiment 4

Due to the fact that all previous experiments found that happy music-induced changes in lateralization not to be mediated by music-induced changes in emotional state, Experiment 4 aimed to identify the acoustic and musical features of the Mozart's piano sonata in D major (K. 448) that might have activated the left hemisphere responsible for the reported effects.

The most easily communicated emotions in music are happy and sad, both in the context of Western music (Gabrielsson and Juslin, 1996) and in non-Western cultures (Laukka et al., 2013). These emotions are conveyed via a combination of musical features, although the central ones are considered to be tempo, mode, and timbre (Schellenberg et al., 2000; Eerola et al., 2013). Music that sounds happy typically has fast tempo, is in major mode, has high number of events, utilises bright sounds and is performed in with fast note attacks. By contrast, music expressing sadness is slow, utilises dark timbre, relative few events, and has been composed in a minor mode. Several studies manipulating these central features in music have established their contribution to the happy-sad distinction (e.g., Dalla Bella et al., 2001; Hunter et al., 2010).

In the present study, we extracted ten acoustic and musical features that typically differentiate *happy* from *sad* music. The extraction was carried out for 5-s segments of the pieces that were analysed with 50% overlapped short-term analysis windows using MIR Toolbox (Lartillot et al., 2008, for technical details of these core features, see Eerola, 2011). In addition, the extracted feature values were compared to a reference excerpts (Resnicow et al., 2004), consisting of recorded piano examples portraying happy and sad expression that were also validated by self-report ratings of emotions.

The stimulus properties were analysed in terms of the known differences in the cues for conveying happy and sad expression in music, outlined theoretically by Juslin and Scherer (2005) and corroborated empirically by subsequent studies (Eerola et al., 2013; Juslin and Lindström, 2013). Happy music is assumed to be (1) louder, (2) using faster note attacks, having higher (3) event density, (4) tempo, (5) pulse clarity, (6) spectral centroid, (7) register, and in typically using major (8) mode in comparison to sad music. These predictions were borne out by the analysis, which yielded the predicted differences for (1) dynamics (root average of the square of the amplitude), $t(147) = 19.1$, $p < 0.001$, (2) note attack time (in s), $t(196) = 9.15$, $p < 0.001$, (3) event density (number of events/second), $t(237) = 6.25$, $p < 0.001$, (4) tempo (beat per minute), $t(224) = 4.53$, $p < 0.001$, (5) pulse clarity, $t(245) = 6.94$, $p < 0.001$, (6) spectral centroid (in Hz), $t(243) = 13.2$, $p < 0.001$, (7) register (in MIDI pitch), $t(226) = 5.49$, $p < 0.001$, (8) mode (positive coefficient for major, negative minor), $t(228) = 9.52$, $p < 0.001$ (see Table 4). The same features did not yield statistical differences between these two samples compared to the values obtained from the reference set, all $t < 2.29$, *ns*, except for register, $t(10) = 3.68$, $p < .001$), where the happy reference set had a lower mean pitch (*M* = 63.04, *SD* = 1.66) than the happy excerpt in our experiment (*M* = 65.51, *SD* = 2.67).

**Table 4.** *Means and standard deviations of the musical and acoustic features for the two stimuli.*

| Feature (prediction§) | Happy excerpt | Sad excerpt |
|---|---|---|
| Dynamics (+/−) | 0.0486 ± 0.0188 | 0.0158 ± 0.0050* |
| Attack (−/+) | 0.046 ± 0.005 | 0.053 ± 0.008* |
| Event density (−/+) | 1.49 ± 0.68 | 1.01 ± 0.51* |
| Tempo (+/−) | 123.82 ± 17.9 | 52.18 ± 13.32 * |
| Pulse clarity (+/−) | 0.42 ± 0.13 | 0.32 ± 0.11* |
| Spectral centroid (+/−) | 841.53 ± 89.54 | 705.07 ± 73.31* |
| Register (+/−) | 65.51 ± 2.67 | 63.35 ± 3.46* |
| Mode (+/−) | 0.10 ± 0.13 | -0.09 ± 0.17 * |

§ Based on Juslin and Scherer (2005).
*$p < .001$

It has been shown in several behavioral experiments that the fundamental feature that separates happy expression from sad in music is tempo. For instance, 5-year-old's categorization of music into happy and sad is only affected by tempo whereas older children and adults also rely on mode (Dalla Bella et al., 2001). In a similar vein, the ratings of perceived and felt emotions of happiness and sadness by adults have also been shown to be more heavily dependent on tempo than on mode (e.g., Hunter et al., 2010; Khalfa et al., 2005), and this pattern has even been observed in a cross-cultural study (Fritz et al., 2009). Moreover, a recent magnetoencephalography (MEG) study (Okomoto et al., 2009) revealed that hemispheric asymmetries in the MEG responses did not depend on a specific sound type but rather on spectral and temporal variances, which are differentially encoded into neural activity in the cochlea. Specifically, this study found that the neural response elicited by changes in the temporal structure of the acoustic stimulus were larger in the left hemisphere than in the right hemisphere. The opposite was found for spectral stimulus changes. The results are in line with previous studies suggesting that the left hemisphere has a better temporal resolution (Tallal et al., 1993). Drawing from this idea that it is particularly the complex temporal structure that distinguishes happy and sad expression in music and is the underlying reason for the induced emotions as well, we focused on tempo of the music as a possible explanation of the previously observed lateralization differences.

To investigate whether the lateralization concerning the happy excerpt observed in the previous three experiments were elicited by the temporal structure, the final experiment (Experiment 4) used Mozart's piano sonata in D major (K. 448) in three different tempi: original (i.e., identical to one used Experiments 1-3), fast (+25% tempo) and slow (-25% tempo) by keeping unwanted changes in other acoustic/musical features to a minimum. If tempo is the critical acoustic feature of the effects reported here, listening to the fast and slow Mozart piece should, respectively, increase or decrease the REA/left hemispheric advantage bias in the Bergen DL task relative to the original Mozart tempo.

**5.1. Methods**

**5.1.1. Participants.** Sixty-five undergraduate students (32 male) aged between 19 and 23 years ($M$ = 20.32, $SD$ = 1.00) were included in this experiment. Please note that the 22 participants of the original happy music/Mozart condition were taken from Experiment 3. Sample sizes were chosen in order to match those in Experiment 3. The mean handedness LQ (Oldfield, 1971) was 74.81 ($SD$ = 44.45, ranging from -85.71 to 100). Participants were randomly allocated to one out of three Mozart tempo conditions (original, slow or fast). The three groups did neither differ in age, $F(2, 62) = 0.89$, *ns*, nor handedness, $F(2, 62) = 0.74$, *ns*.

All participants had normal or corrected-to-normal visual acuity. Participants did not use any medication affecting the CNS and did not have mood disorders.

**5.1.2. Music condition**. Three different Mozart conditions were used. As noted above, data of the original Mozart condition was taken from Experiment 3. Although this Mozart's sonata has been subjected to tempo and mode manipulation previously (Husain et al., 2002), we wanted retain the comparability to Experiments 1-3. For the other two Mozart conditions, tempo was manipulated by time-stretching the original sound file used in Experiment 1-3 with professional quality software (Logic Pro) using phase-vocoding technique that leaves pitch, expressive variations, dynamics and timbre intact (for a similar manipulation, see Ilie and Thompson, 2006). For creating a faster and slower version, time-stretching was set to ±25% of the duration of the Mozart recording used in Experiments 1-3, which had a tempo of 121 BPM (beats per minute). These manipulations yielded 177 (fast) and 106 (slow) BPM versions of the sonata. These versions were within plausible ranges of the sonata and resemble the tempo manipulations of the same sonata in Husain, Thompson and Schellenberg (2002). To set the stimuli to equal duration (10 min), the fast version was looped in a way that preserved the structural segments of the sonata, whereas the slow version was trimmed near the 10 min mark. All music was presented to participants in stereo through Bose Quiet Comfort 15 Acoustic Noise Cancelling Headphones and played on a MacBook Pro laptop.

**5.1.3. Bergen DL task.** The Bergen DL task and procedures were identical to Experiment 3.

**5.2. Results**

**5.2.1. STCI-S scores.** STCI-S scores were subjected to two separate 2 × 2 × 3 mixed ANOVAs with Time of measurement (before, after) as a within-subjects factor, and Tempo condition (original, slow, fast) and Sex as between-subject factors. The 3-way interaction was significant for both Cheerfulness, $F(2, 59) = 7.86$, $p = .001$, $\eta_p^2 = .210$, and Bad mood, $F(2,$

59) = 3.49, $p$= .037, $\eta_p^2$ = .106. No other effect was significant, all $F$ < 3.51, *ns*). Simple comparisons (one-tailed) revealed a non-significant increase in Cheerfulness after listening to the original Mozart tempo, $t(21)$ = 1.34, $p$ = .10, and a significant decrease in Bad Mood, $t(21)$ = 3.07, $p$ = .006. Neither the slow nor the fast tempi elicited any emotional changes, for both Cheerfulness and Bad mood, all $t$ < 1.00, *ns* (see Table 5).

**Table 5.** *Means and standard deviations of the STCI-S subscales (Cheerfulness and Bad mood) before and after music exposure in Experiment 4.*

| | Cheerfulness | | Bad mood | |
|---|---|---|---|---|
| Mozart | Before | After | Before | After |
| Original ($n$ = 22) | 27.68 ± 4.59 | 29.05 ± 4.81 | 17.23 ± 7.48 | 15.09 ± 6.25** |
| Slow ($n$ = 21) | 27.71 ± 7.12 | 29.10 ± 6.11 | 14.62 ± 5.60 | 14.71 ± 4.69 |
| Fast ($n$ = 22) | 26.77 ± 4.39 | 27.45 ± 4.76 | 16.00 ± 4.85 | 15.05 ± 4.42 |

** $p$ < .01, *one-tailed, indicating significant differences between STCI-S scores before and after listening to music. Note: Data for the original Mozart group are identical to Table 3.*

**5.2.2. Bergen Dichotic Listening Task.** To investigate the effect of Mozart played in three different tempi on language lateralization, LIs of the Bergen Dichotic Listening task were subjected to a 3 × 2 ANOVA with Tempo condition (original, slow, fast) and sex as between-subjects factors. The intercept effect was significant, $F(1, 59)$ = 127.26, $p$ < .0001, $\eta_p^2$ = .683, indicating an expected overall REA. One sample t-tests against the test score zero revealed significant REAs for all Tempo conditions (original: $t(21)$ = 5.73, $p$ < .0001, slow: $t(20)$ = 5.44, $p$ < .0001, fast: $t(16)$ = 8.01, $p$ < .0001). The main effect of sex was also significant, $F(1, 59)$ = 8.45, $p$ = .005, $\eta_p^2$ = .125, indicating larger REA in men ($M$ = 31.06, $SD$ = 14.53) than women ($M$ = 18.35, $SD$ = 19.34). More importantly, the large REA/LH was consistent across all three Tempo conditions and did not vary with tempo. Neither the main effect of Tempo condition nor the interaction approached significance, both $F$ < 0.11, *ns* (Figure 6).

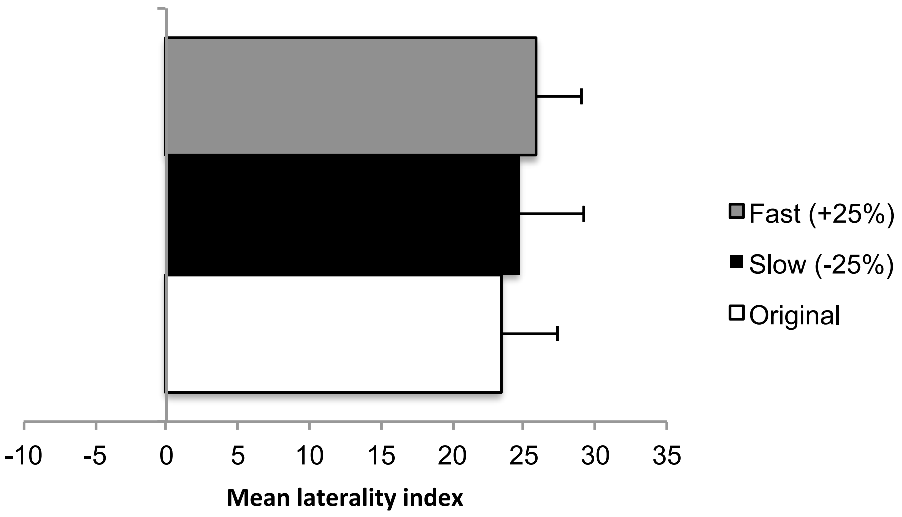


**Figure 6.** Mean laterality index (LI) and standard error means in the Bergen DL task according to three tempo conditions (original, slow/-25% tempo, fast/+25% tempo). Positive LIs indicates a right ear advantage/left hemisphere bias, negative LI indicates a left ear advantage/right hemisphere bias.

**5.3. Interim summary.** The tempo modulation of Mozart's piano sonata in D major (K. 448) did not reveal any changes on the REA in the DL task. The large REA was almost identical across all three tempo conditions, basically replicating the Mozart-induced increase in REA observed in Experiment 3. Interestingly, only the original Mozart piece resulted in a reduction in Bad mood. The tempo-modified versions of Mozart's piano sonata had no effect on mood. In addition, and in line with previous findings (e.g., Hiscock et al., 1994; Voyer, 2011) men showed a larger language lateralization than women (but see also Hirnstein et al., 2013, who only found small effects of sex). The results suggest that listening to Mozart's piano sonata in D major (K. 448) increases the left hemispheric bias in language lateralization independent of the tempo modulation. Due to the fact that only the original Mozart tempo resulted in changes in the emotional state, and given that all three tempo conditions increased the bias in language lateralization (as compared to the silence group in Experiment 3), the findings further suggest that the effect of listening to Mozart on hemispheric asymmetries is not mediated by music-induced changes in emotional state.

## 6. General discussion

The aim of the present study was to investigate the effects of listening to happy and sad music on hemispheric asymmetries in two well-established right hemispheric tasks (i.e., ECF and LB) and one well-established left hemispheric task (i.e., verbal DL). Overall, the results of Experiment 1-3 revealed that listening to the happy or sad excerpts significantly changed emotional states in the predicted direction. While listening to the happy excerpt increased cheerfulness and decreased bad mood, the opposite occurred after listening to Beethoven. In line with previous research (Westermann et al., 1996), the results support the idea that listening to music can reliably induce positive and negative emotions.

More importantly, the results also revealed that listening to music for 10 min can affect the biases in laterality tasks that are considered to provide reliable and valid estimates of functional brain asymmetries. An effect of music on functional cerebral asymmetries was found in all experiments. Specifically, the right hemispheric biases typically found in both ECF (Experiment 1) and visual LB (Experiment 2) were significantly reduced after listening to Mozart, as compared to the Beethoven and silence conditions. In addition, an increased left dominant bias after listening to Mozart was observed in the verbal DL task (Experiment 3), suggesting that listening to Mozart's piano sonata activates the left hemisphere.

The results of the current study are in line with previous research focussing on the effect of music on emotional state and functional brain asymmetries (e.g. Altenmüller et al., 2002; Flores-Gutierrez et al., 2007) and may be explained in terms of Kinsbourne's (1970) model of attentional-activation. Kinsbourne's model proposes that attentional asymmetries arise when a secondary process that is lateralised to one hemisphere is able to activate that hemisphere. In turn, this activity biases attention in the primary task, such as ECF and LB biases toward the contralateral visual field, or the DL bias to the contralateral ear. At first glance, the present findings may result from Mozart-induced positive emotions, thus activating the left hemisphere as suggested by the Valence model, which in turn biases spatial attention to the contralateral side and increasing the left hemispheric bias in DL. However, this explanation is rather unlikely because the Beethoven-induced negative emotions did not affect laterality in directions opposite to those in the Mozart condition. Also, the mediation analysis in Experiment 1-3, revealed a direct effect of music on laterality biases. Therefore, although listening to Mozart and Beethoven changed self-reported mood, the effect of music listening on laterality was not mediated by music-induced changes in mood.

An alternative explanation of the observed effects might be the level of subjective musical enjoyment, as opposed to the emotional valence portrayed in the music. As noted by Altenmüller et al. (2002), while emotional valence and subjective enjoyment are intrinsically related, the relationship is not always straightforward. For example, it is possible to hold an affinity for, and thus enjoy listening to, a musical piece that induces a sad emotional state. Indeed, enjoyment of music has been shown to influence functional asymmetries in spatial attention in patients with hemispatial neglect (Chen et al., 2013; Soto et al., 2009). Soto et al. (2009) found that listening to subjectively preferred music improved patients' performance of target detection, star cancellation, line bisection, reading, and perceptual report. This fMRI study also revealed the left inferior frontal gyrus, left dorsolateral prefrontal cortex and cingulate gyrus as regions sensitive to preferred music. Moreover, this study revealed that music-related activity in the left orbitofrontal cortex was functionally connected to activity in spared right hemisphere regions. Thus, if participants in the current study enjoyed listening to Mozart more than listening to Beethoven, this may also explain the increased left hemispheric activity and subsequently changes in functional cerebral asymmetries. However, this explanation is also rather unlikely because all three music condition groups in Experiment 3 did not differ in enjoyment.

A further possible explanation for the present findings concerns the differences between the musical pieces, other than emotional valence or musical enjoyment. The current study revealed that Mozart's piano sonata in D major (K. 448) and Beethoven's Moonlight sonata differed in several basic musical and acoustic features such as dynamics, articulation event density, rhythm attack time, timbre centroid, tonal mode and rhythm tempo. This is in line with previous research identifying the primary musical cues that contribute to emotional expressions (e.g., Eerola et al., 2013; Gagnon and Peretz, 2003; Hunter et al., 2010; Gabrielsson and Lindström, 2010; Eerola et al., 2012). Furthermore, functional cerebral asymmetries have been reported for processing such features (Okamoto et al., 2007; 2009; Zatorre and Belin, 2001). Using MEG, Okamoto et al. (2009) investigated the time course of neural activity in response to auditory stimuli that differed in either spectral or temporal features. It was found that while processing spectral changes elicited greater activity in the right hemisphere, processing temporal change elicited greater activity in the left hemisphere. This finding is in line with previous studies showing that the left hemisphere has a better temporal resolution (e.g., Tallal et al., 1993) and that changes in musical tempo entrain activity in the left motor cortex (Daly et al., 2015). Therefore, it is possible that changes in lateralization after listening to Mozart found in the current study is due to greater left hemisphere activity resulting from the fast tempo and greater temporal variation of Mozart's piano sonata.

Experiment 4 was designed to test this hypothesis but revealed that different tempi of Mozart's piano sonata did not modulate language lateralization. In fact, the increased left hemispheric bias in the DL was replicated across all tempo conditions. This suggests that either the tempo modulation was not strong enough, although ±25% was more substantial than the tempo changes in some past studies, e.g., ±11% in Ilie and Thompson (2006) and close to common ±33% manipulations carried out with synthetic stimuli, see Webster and

Weir (2005), and Gagnon and Peretz (2002) or that other musical and acoustic features were relevant in which Mozart's piano sonata in D major (K. 448) and Beethoven's Moonlight sonata differed (see above).

The tempo modulation in Experiment 4 is also interesting because it was the most direct manipulation of *arousal* in the current study. Arousal is another important dimension of emotional responding, referring to the degree of physiological activation or to the intensity of an emotional response (Sloboda and Juslin, 2001). Listening to sad music has been shown to decrease heart rate and skin conductance but increase blood pressure, whereas listening to happy music can reduce depth of respiration (Krumhansl, 1997). Other evidence indicates that frontal EEG activity reflects the emotional valence of music as well as its ability to induce arousal (Schmidt and Trainor, 2001). For example, it has been shown that the overall amount of frontal EEG activity is greater for intense music than for calm music. Although several previous studies showed that especially tempo manipulations in music induces changes in arousal (e.g., Balch and Lewis, 1999; Husain et al., 2002), such manipulations in the current study failed to yield a parametric modulation of lateralization. It should be noted, however, that previous studies reporting changes in arousal with fast and slow musical tempi used larger tempo differences across conditions than the current study. Balch and Lewis (1999) reported changes in arousal with fast (140 bpm) and slow (60 bpm) musical tempi. In the study by Husain et al. (2002), the fast and slow conditions of the happy music excerpt (Mozart) affecting arousal (not mood) were 165 bpm and 60 bpm, respectively. The tempi of the three Mozart versions in the current study were less different, approximately 93 bpm (slow), 124 bpm (original) and 155 bpm (fast), as compared to 52 bpm for the sad music excerpt. This suggests that the tempo manipulation in the current study was perhaps not discriminative enough to produce parametrical changes in lateralization.

To fully understand why listening to Mozart's piano sonata can modulate functional cerebral asymmetries, future studies should manipulate several musical and acoustic factors systematically, and also include more standardised non-music audio material that is emotionally neutral (e.g., similar to those stimuli used by Okamoto et al., 2009). Moreover, future studies may include direct measures of arousal as well as mood assessments that are particularly sensitive in capturing between- as well as within-group differences. Finally, future studies should also investigate the extent to which the effects of music condition extend beyond the 10 to 15 min periods during which the participants engaged in the laterality tasks by varying the listening time and including delay periods as independent variable, as suggested by Rauscher et al. (1993).

It is interesting to note that the same Mozart's piano sonata for Two Pianos in D major (K. 448) was used for studies on the *Mozart effect* (Rauscher et al., 1993). The highly controversial Mozart effect refers to the finding that spatial abilities temporarily improve after listening to this Mozart piece. The classic study by Rauscher et al. (1993) compared participants' spatial ability after listening to either Mozart's piano sonata, Albinoni's adagio in G minor, or after sitting in silence. Superior spatial-temporal reasoning was found after listening to Mozart as compared to silence. In contrast, no performance difference was found when participants listened to Albinoni's adagio compared to silence. As noted before, however, the Mozart effect is highly controversial because it has not been consistently replicated (for a review, see Pietschnig et al., 2010). Rauscher and Shaw (1998) argued that numerous replication failures can primarily be explained by the different spatial tasks that have been used. The original study by Rauscher et al. (1993) used non-verbal, spatial-temporal tasks. Follow-up studies by the same authors (Rauscher et al., 1995; Rauscher and Shaw, 1998) replicated the Mozart effect only for the Paper-Folding-and-Cutting task, which requires temporal series of spatial processes. The authors concluded that the influence of

Mozart's piano sonata on spatial abilities depends on the temporal nature of the spatial tasks, probably by modulating cortical processes located particularly in the right hemisphere (Rauscher et al., 1995). As pointed out by Schellenberg (2001), however, the temporal/non-temporal distinction cannot explain why so many studies did not replicate the original findings. Based on a meta-analysis, Chabris (1999) concluded that studies with less arousing control conditions are more likely to replicate the Mozart effect. Following this idea, Thompson et al. (2001) provided empirical evidence that the Mozart effect is most likely an artifact of mood and arousal, with cognitive arousal being predominantly a right hemisphere function (Heller and Nitschke, 1997; Robertson et al., 1998, Tucker et al., 1999), as are spatial tests.

Although the current study focused on functional cerebral asymmetries rather than cognitive performance – and the relationship between the degree of asymmetry and cognitive performance is not as clear-cut (e.g., Hirnstein et al., 2014; Hirnstein et al., 2010) – the current findings suggested that it is rather the left hemisphere that is modulated by Mozart's piano sonata. The idea that the left hemisphere might play a key role is partly in line with a recent study that applied continuous theta burst stimulation (cTBS) on the left hemisphere (Picazio et al., 2013). Although no general Mozart effect on spatial performance was found in this study, the cTBS induced down-regulation of neuronal excitability in the left hemisphere before listening to Mozart interfered with the performance in an embodied mental rotation task.

While the current findings present a number of avenues for further investigation, they demonstrate that functional cerebral asymmetries can be influenced by external stimuli, such as music. This raises questions concerning potential implications for mood disorders associated with atypical functional asymmetries (Bruder et al., 1992; 1994; 1999; Jaeger et al., 1987). Indeed, a recent review by Lin et al. (2011) argues that music is capable of influencing numerous neurobiological processes that indicate a potentially important role for music in psychological treatment. Moreover, clinical studies have demonstrated that music therapy may provide an effective alternative or allied treatment for disorders associated with atypical functional asymmetries such as depression (for a review, see Maratos et al., 2008) and schizophrenia (for a review, see Mössler et al., 2011). Further studies suggest that such clinical findings may be underpinned by the effect of music on hemispheric asymmetries. Field et al. (1998) investigated the effect of music on atypical, increased right frontal EEG activity in depressed patients. This study demonstrated that listening to popular music for 23 minutes reduced right frontal activity during and immediately after listening. More recently, studies have revealed atypical functional cerebral asymmetries in spatial attention in patients with schizophrenia (Cavézian et al., 2007), depression (Okubo, 2010), and generalised anxiety disorder (He et al., 2010). Therefore, further research could investigate whether the beneficial effects of music on clinical symptoms is partly mediated by music-induced changes in hemispheric asymmetries in such clinical populations.

In conclusion, the current findings demonstrate that listening to Mozart influences emotional states. Listening to Mozart resulted in increased cheerfulness and reduced bad mood, while listening to Beethoven resulted in the opposite. All experiments of the current study also observed robust Mozart-induced changes in hemispheric asymmetries as measured by well-established emotional and cognitive laterality tasks. However, the music–induced changes in laterality were neither mediated by the induced emotion nor did they depend on personal musical enjoyment. Although basic musical and acoustic features are more likely to account for these effects, a simple tempo manipulation did not modulate the Mozart-induced effect on language lateralization but revealed a reliable left-hemispheric increase in activation across all tempo conditions. Future research will hopefully identify the features that accounted for the Mozart effect on functional cerebral asymmetries and will further increase our understanding of the potential for music as a tool for the treatment of emotional and cognitive impairments in psychological disorders.

**Acknowledgment**

We thank Jemima Hindle, Juliette Hoffmann, Lisa Koba and Robert Seymour for their assistance with data collection, and all 216 participants for their cooperation.

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