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International Journal of Psychophysiology 61 (2006) 57 – 69

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

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Cardiovascular and respiratory responses during musical mood induction

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Received 18 October 2005; received in revised form 20 October 2005; accepted 27 October 2005
Available online 3 February 2006

Abstract

Music is used to induce moods in experimental settings as well as for therapeutic purposes. Prior studies suggest that subjects listening to certain types of music experience strong moods and show physiological responses associated with the induced emotions. We hypothesized that cardiovascular and respiratory patterns could discriminate moods induced via music. 18 healthy subjects listened to 12 music clips, four each to induce happiness, sadness, and fear, while cardiovascular and respiratory responses were recorded using an electrocardiogram and chest strain-gauge belt. After each clip subjects completed a questionnaire. Subjects consistently reported experiencing the targeted mood, suggesting successful mood induction. Cardiovascular activity was measured by calculating time domain measures and heart rate changes during each clip. Respiratory activity was measured by total, inspiration, and expiration lengths as well as changes in mean respiration rate during each clip. Evaluation of individuals' patterns and mixed-model analyses were performed. Contrary to expectations, the time domain measures of subjects' cardiovascular responses did not vary significantly between the induced moods, although a heart rate deceleration was found during the sadness inductions and acceleration during the fear inductions. The time domain respiratory measures varied with clip type: the mean breath length was longest for the sad induction, intermediate during fear, and shortest during the happiness induction. However, analysis using normalized least mean squares adaptive filters to measure time correlation indicated that much of this difference may be attributable to entrainment of respiration to characteristics of the music which varied between the stimuli. Our findings point to the difficulty in detecting psychophysiological correlates of mood induction, and further suggest that part of this difficulty may arise from failure to differentiate it from tempo-related contributions when music is used as the inducer.

Keywords: Music; Mood; Cardiovascular and respiratory responses

1. Introduction

A large literature, in both healthy and psychiatric individuals, has investigated the psychological, biological, and neural correlates of mood. Experiments in this literature have explored the effects of mood on overall health, immune system function, memory, attention, and perception (Cacioppo et al., 2000). However, in the context of a laboratory achieving successful emotional induction may be very difficult since induction techniques are limited by ethical and experimental feasibility. Musical mood induction is an attractive option to induce moods in experimental settings since subjects consistently report experiencing strong emotions in response to music (Juslin and Sloboda, 2001). Music has been used for mood induction in a wide variety of experiments, both alone and combined with other stimuli (for review, see Gerrards-Hesse et al., 1994). For example, music has been used in combination with reading self-referential statements (Mayer et al., 1995; Richell and Anderson, 2004), with lighting (Davey et al., 2003), to study autobiographical recall (Setliff and Marmurek, 2002), salivary cortisol levels (Clark et al., 2001; Hucklebridge et al., 2000), and emotional face judgments (Bouhuys et al., 1995). A growing literature has also investigated the changes in the brain that arise from inducing strong moods via music (reviewed in Lewis, 2002). For instance, music excerpts that were pleasurable for specific individuals were associated with reliable activation of emotion-related processing regions of the brain (Blood and Zatorre, 2001). These and other findings have supported that idea that music is processed in a special way by

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doi:10.1016/j.ijpsycho.2005.10.025

the brain (Peretz, 2001) and can tap powerfully into the neural circuitry that generates emotional responses.

It is generally accepted that large and reliable changes in physiological states are associated with emotional responses, regardless of the manner in which the emotional response was induced. There is consensus that such physiological changes are a reliable correlate of certain psychiatric disorders, including anxiety and panic disorders and depression (Berntson and Cacioppo, 2004; Berntson et al., 1998; Grossman, 1983; Wientjes, 1992). However, whether specific physiological patterns for each unique normal emotional state exist is controversial (e.g. Collet et al., 1997; Hagemann et al., 2003; Levenson and Ekman, 2002). A meta-analysis and literature review by Cacioppo et al. (2000) highlighted the inconsistent results found in studies searching for distinct emotion-specific patterns of physiological activity, but indicated that autonomic activation may be greater in negative than positive valenced states. Two psychophysiological measures thought to index emotional states are respiration and cardiovascular patterns.

1.1. Respiration patterns

A number of studies have suggested that the experience of emotional states is accompanied by respiratory changes (reviewed in Boiten et al., 1994; Ritz, 2004; Wientjes, 1992). One of the most well-established connections is between anxiety-related states and respiratory changes (e.g. Bass and Gardner, 1985; Grossman, 1983; Wientjes, 1992). Wientjes (1992) suggests that hyperventilation may be a normally occurring passive coping response in situations of pain, apprehension, anxiety, or fear. Stressful or effortful mental tasks also can increase respiration rate, and respiratory disregulation is associated with several diagnostic groups, including depression, panic disorder, and anxiety (Boiten et al., 1994; Wientjes, 1992). Evidence that voluntary alteration of respiration patterns can change subjective emotions (such as by reducing anxiety in a stressful situation) also suggests interactions between emotion and respiration (Bass and Gardner, 1985; Boiten et al., 1994; Grossman, 1983).

Other research has probed for specific respiratory patterns for basic emotions. Bloch et al. (1991) quantitatively and qualitatively described unique patterns of respiration for each of six different emotion types (joy/laughter, sadness/crying, fear/anxiety, anger/aggression, erotic love, and tenderness) in trained actors. Particular patterns of respiration accompanied specific emotions; for instance fear/anxiety correlated with frequent pauses, increased respiratory rate, increased respiratory rate variability, and increased inspiration time relative to expiration time. Wientjes (1992) describes four breathing patterns associated with emotional states: rapid and shallow respiration in tense anticipation/anxiety, rapid and deep respiration in excitement/arousal/fear/anger/joy, slow and shallow respiration in passive grief/depression, and slow and deep respiration during sleep/deep relaxation. In an experiment using autobiographical recall mood induction Collet et al. (1997) found significant differences in instantaneous respiratory frequency between emotional states: shortest mean breath lengths occurred during happiness, whereas the longest mean breath lengths were found in surprise, anger, disgust, and intermediate breath lengths occurred during fear and sadness. Boiten (1998) studied respiration changes during moods induced by emotional movie clips and found significantly shorter inspiratory duty cycle, shorter post-expiratory pause length, and greater total breath length variability for the positive films when compared to the negative films. These data indicate that respiratory measures may provide a sensitive correlate of emotional experiences induced in a variety of ways.

1.2. Heart rate variability patterns

Heart rate variability may provide another measure of mood, although whether heart rate variability patterns are distinct for each emotional state is debated. A number of studies reported increased heart rate during anger, fear, and sadness (Collet et al., 1997; Levenson, 1992; Levenson et al., 1990), while others reported increased heart rate during anger, fear, and sadness compared to happiness (Ekman et al., 1983; Levenson and Ekman, 2002). Heart rate during disgust has been reported to be lower than during anger, fear, and sadness (Levenson et al., 1990). Schwartz et al. (1981) found emotion-specific (happiness, sadness, anger, and fear) changes of diastolic and systolic blood pressure and heart rate while subjects performed autobiographical recall mood induction. Palomba et al. (2000) measured heart and respiration rate during viewing films designed to elicit either a threat/anxiety, disgust (surgery/mutilation), or neutral state, and reported an increase in respiration rate while viewing all films, an increase in heart rate during the threat/anxiety film, and a slight decrease during the disgust and neutral films.

Other researchers have not found evidence of differences in heart rate between specific emotions, but rather an increased heart rate across all emotions compared to a neutral state (e.g. Neumann and Waldstein, 2001; Prkachin et al., 1999). Sinha et al. (1992) found changes in blood pressure and vascular resistance between emotional states but not in heart rate. Stemmler (1989) did not find respiration or heart rate differences between emotional conditions (fear, anger, happiness, control, induced by real-life task manipulation and autobiographical recall), although differences were reported in other psychophysiological measures (also Gendolla et al., 2001).

1.3. Coordination of respiration with external signals

It is known that respiration is influenced by factors other than physiological requirements, in addition to factors that induce emotions. For example, respiration has been shown to coordinate to rocking frequency in newborns (Sammon and Darnall, 1994), steps while walking (Loring et al., 1990), passive leg movement (Gozal and Simakajornboon, 2000), and bicycle peddling (Kohl et al., 1981). This coordination may occur without conscious awareness (e.g. Haas et al., 1986; Kohl et al., 1981). Haas et al. (1986) recorded subjects' respiration while they listened to a metronome and four musical pieces of varying rhythms and tempos, either with or without tapping to the perceived beat. Many subjects synchronized their respiration to musical rhythms without reporting a conscious effort at coordination, and more synchronization was found to pieces with simple, as opposed to complex, rhythmic structures.

1.4. Psychophysiological reactions to music

A subset of the literature examining physiological reactions while listening to music explicitly relates these reactions to those described in psychophysiological studies of specific emotions (reviewed in Krumhansl, 2002). Rickard (2004) found differences in skin conductance and "chills" but not heart rate or skin temperature between inductions. Nyklícek et al. (1997) measured a large number of measures of respiratory and cardiovascular activity while subjects listened to music chosen to induce specific emotional states (happiness, sadness, serenity, agitation) or neutral stimuli. The respiratory measures were found to best distinguish between the states (increase in happiness/agitation relative to sadness/serenity); few differences were found in the cardiovascular measures other than those attributable to respiratory effects. Similar results were reported by (Krumhansl, 1997): increased respiration rate during the clips chosen to induce happiness and fear compared to baseline and heart rate deceleration during the sadness induction.

The present study expands the literature of psychophysiological measurements of musically induced emotions by examining individual changes in physiological activity during the stimuli and coordination of respiration with the music. The goal of the present study was to determine whether consistent cardiovascular and respiratory changes occur while subjects experience emotions induced by music. We chose our music stimuli in a pilot study based on its ability to reliably induce reports of strong happiness, sadness, and fear in the listeners. We hypothesized that (a) the induction of emotion would be associated with reliable changes in heart rate and respiration, and that (b) these changes in heart rate and respiration would differ systematically between the different induced moods. It was expected that changes would be consistent with those reported in previous studies: decreased respiration and heart rate during sadness compared to fear or happiness inductions, with the measures highest on the happiness inductions and intermediate during fear.

2. Materials and methods

2.1. Participants

Eighteen subjects (10 females and 8 males) participated in the experiment. Subjects were screened to be neurologically and psychiatrically healthy, right-handed, with normal hearing (confirmed using audiometry), and without professional or college-level music experience. The subjects ranged in age from 31 to 74 years (M=50, Mdn=50); the distribution of ages was similar for the males (M=48, Mdn=48) and females (M=52, Mdn=51). Respiration recordings were not taken from five subjects (3 females and 2 males) due to a change in experimental protocol. Subjects provided informed consent prior to participation and were compensated for their time.

2.2. Stimuli

Music stimuli were selected from a large pool of potential stimuli using a pilot study. The chosen stimuli produced the most intense and specific reported experience of each target emotion: happiness, sadness, and fear (details are presented in Johnsen, 2004). The stimuli consisted of 12 music clips; four different clips were chosen to induce each target mood (fear, sadness, or happiness). Details of each stimulus appear in Table 1. The stimuli were short classical music selections taken from movie soundtracks ranging in length from 74 to 189 s (M=136 s). Stimuli of various lengths were used so that each clip could form a musically complete unit. The stimuli are labeled by a letter indicating the targeted mood (H=happiness, F=fear, S=sadness) and a number indicating its place in the presentation order (the presentation order was the same for all subjects). The music was selected based on how well it induced each specific mood; no effort was made to match tempo, mode, or pitch. The stimuli were presented via headphones at a loud, but comfortable, volume.

Table 1
Stimuli details

Clip name	Film name	Track name	Target mood	Presentation order	Length (s)	Dominant tempo (beats/min)
H1	Charlie!	Cancan a Paris Boulevard	Happiness	1	138	115
F2	Dangerous Liaisons	Tourvels Flight	Fear	2	101	61
H3	A Midsummer Nights Sex Comedy	Vivace non troppo	Happiness	3	122	124.5
F4	Crimson Tide	Alabama	Fear	4	130	42.5
S5	Vertigo	Madeleine and Carlottas Portrait	Sadness	5	99	65
H6	Gone with the Wind	Mammy	Happiness	6	140	85.3
S7	Backdraft	Brothers	Sadness	7	140	44
S8	Out of Africa	Alone on the Farm	Sadness	8	149	68
F9	Vertigo	Vertigo Prelude and Rooftop	Fear	9	100	60
H10	Dances with Wolves	The Buffalo Hunt	Happiness	10	162	105
S11	Spartacus	Blue Shadows and Purple Hills	Sadness	11	74	58
F12	Henry V	The Battle of Agincourt	Fear	12	124	115.3

2.3. Procedure

After briefing the subject and obtaining informed consent, the electrodes and respiratory belt were placed. The subjects then completed inventories and tasks to allow time to acclimate to the laboratory setting prior to mood manipulation. Subjects completed various written measures, including inventories of current mood and previous musical experience. Participants then closed their eyes and rested for 1 min, then rested for another minute as neutral auditory stimuli (tone sequences) were presented through the same headphones used for music presentation. The subjects were given the following instructions:

> "In this task, I will play for you some excerpts of background music, the sort you often hear in the background of TV shows and movies. As you listen to each clip, I would like you to continually rate the strength of the emotions you are feeling using this dial from "weak" to "strong," with "moderate" in between. You may move the dial as much or as little as you like based on your own responses to the music. There is no right or wrong answer to this task. What's most important is that your ratings are based on how you feel in response to the music."

Three sample clips were played, followed by the 12 experimental music stimuli (in the fixed randomized order). Physiological data was collected and subjects adjusted the dial to reflect the intensity of their emotional experience while listening to the stimuli. Following each clip participants completed a questionnaire that assessed current happiness, sadness, and fear on a Likert scale ranging from 0 "not at all (happy, sad, fearful)" to 9 "very (happy, sad, fearful)." Additionally, the questionnaire asked the subject to rate the level of "activation/energy" they experienced during the music (scale from 0 "none" to 9 "very much"), to select one word that best represented the emotion expressed by the music (regardless of their experience), and whether they had previously heard the music. After the final stimulus the recording equipment was removed, subjects were debriefed, thanked, and dismissed.

2.4. Physiological measures

2.4.1. Recording equipment

Respiratory activity was recorded with a TSD201 Respiratory Effort Transducer manufactured by BIOPAC Systems, Inc. (Santa Barbara, CA). The transducer consists of an elastic belt attached to a strain gauge which generates an electric signal proportional to the amount of tension on the belt, which in turn is caused by changes in chest circumference due to breathing. The belt was wrapped around the subject at the approximate height of the sternum and fastened to be snug but not uncomfortably tight. The subject was asked to take several deep breaths while the signal was examined to ensure that it rose and fell with respiration without exceeding maximum range. The EKG was taken with electrodes in the lead II configuration (an Ag–AgCl electrode placed over the right carotid artery in the neck and on the lower left flank; electrodes on the palms served as the ground for the entire system). Both signals were recorded at 1000 Hz using AcqKnowledge v. 3.7 (BIOPAC Systems, 2003).

2.4.2. Derivation of measures

The time that each normal R wave, inspiration, expiration, and pause occurred was found using the computer program and methods described by Etzel et al. (2004, 2005) and visually verified for accuracy. The occurrence times were converted to RR interval, total breath length, inspiration length, and expiration length series for analysis. Statistical measures were derived from the physiological recordings of each clip for a 65-s period starting 9 s after clip onset. The first 9 s of each clip were omitted to allow orienting responses to pass and subjects to start experiencing the target mood. The 65-s analysis period was used since it is the longest length that could be derived from all the clips. All statistical testing used a 0.05 significance level and was performed using R (R Development Core Team, 2003).

Two types of statistical analyses were performed. The first used two typical time-domain measures of heart rate variability (SDNN and SDSD) to summarize each subject's responses during the mood inductions and then compared these measures across conditions using mixed models.[1] SDNN is a measure of total heart rate variability, and is calculated by the standard deviation of the RR interval series (RR intervals are the amount of time between adjacent normal R waves in the EKG) (Berntson et al., 1997; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). SDNNresp, the equivalent measure estimating total respiratory variability, was defined as the standard deviation of the breath length series. SDSD, the standard deviation of successive differences, is the standard deviation of the difference between adjacent entries in the RR interval series (Malik and Camm, 1995; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). SDSD is a measure of short-term heart rate variability (e.g. Hoyer et al., 2002; Morrow et al., 2000). The equivalent measure, SDSDresp, was calculated as the standard deviation of the difference in total breath length of adjacent breaths.

Respiratory sinus arrhythmia (RSA) was estimated using the peak-valley technique as defined by Ritz (Ritz, 2003; Ritz et al., 2001). In brief, the peak-valley estimate of RSA is the mean time difference between the longest and shortest RR interval within each breath, with the requirement that the longest RR interval must occur after the shortest (Berntson et al., 1997;

[1] Mixed model analysis was performed using the *lme* function in R (call: lme(fixed=meanRRLen~clip, data=mgd, random=~1|subID, na.action=na.omit)). The fixed effects were defined with the clip name as the primary covariate, the subject was used for the random effects, with the default general positive-definite symmetric covariance structure. Contrast tests were performed following significant clip effects using the *estimable* function to test for differences between clip types.

Grossman et al., 1990; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). As calculated here, the RSA score for each breath is the difference (in ms) between the longest and shortest inter-beat (RR) interval occurring within the breath. If the shortest RR interval does not occur before the longest the breath is assigned a score of zero. Each breath was defined trough-to-trough, with the first RR interval in the breath starting at the first R wave after the start of the breath, and the last RR interval ending with the first R wave after the end of the breath. The mean of the RSA scores for all breaths in a clip was the clip's RSA estimate.

The second type of analysis was designed to identify changes in the physiological measures during each mood induction. This was done by calculating mean heart rate and mean respiration rate changes from baseline at regular intervals ("bins"). The mean heart rate change from baseline was calculated in 1 s intervals during the 65-s analysis period for each clip and subject[2], while the mean respiration rate was calculated for 5 s intervals.[3] The shape of these changes was summarized for each mood induction type using lowess curves and significance of differences between the curves was estimated using permutation analysis.

The pattern of mean heart and respiration rate changes after the stimuli was plotted using lowess curves to summarize responses within and between subjects. Lowess curves were calculated using the R *lowess* function (Cleveland, 1981). The lowess (also known as "loess") method calculates a locally weighted least-squares line through the data. The resulting line is often similar to the mean but less sensitive to outliers and more appropriate for longitudinal data sets with unequal variances (Diggle, 2002). Statistical significance of the lowess curves describing the responses over time was assessed by calculating null bands by permutation testing for each curve (background information on permutation testing is available in Edgington, 1995; Good, 2001; Ludbrook and Dudley, 1998). Null bands indicate where the lowess curves describing the data fall under the null hypothesis (no relationship between the physiological changes and type of mood induction) (Buja and Rolke, 2005; Swayne et al., 2005). If the true lowess line falls outside its null bands the line is considered unlikely to have occurred by chance. The null bands for each curve were set at the 95% and 5% quantile lines resulting from lowess curves for 1,500 permutations of the data set. Each permutated data set was created by randomly reassigning the induction type label within each subject then calculating lowess curves in the same manner as for the true data.

2.5. Entrainment determination

The entrainment analysis was performed using normalized least mean squares adaptive filters to measure time correlation. This method involves using past values of the music clip as a reference signal to predict the respiration signal (the desired signal). As neither the music nor the respiration signals are stationary in time a linear adaptive filter was used for prediction; the predictor uses the previous 0.3 s (determined heuristically from a range of values between 0.1 and 2 s) of the music clip to predict the respiration signal.[4] The filter coefficients were updated using the normalized least mean squares algorithm (Manolakis et al., 2000). If the music is correlated with the respiration signal in a statistical sense, then the estimator can predict the respiration signal with low mean squared error over intervals with a steady beat, implying that the music signal is influencing the subjects' respiratory response. Tracking is feasible only if the characteristics of the music signal are changing slowly in time relative to the adaptation time of the filter. The mean square error between the estimated respiration signal from the filter and the actual respiration was calculated. If the filtered signal is correlated with the music the mean squared error should be small. To estimate significance the filtering results using the actual clip (the music the subject was listening to at the time) for the reference signal are compared to the results from using the other clips as the reference signal for each respiration recording. All calculations to detect entrainment were performed in MATLAB (2003).

3. Results

3.1. Subjective results

Subjects reported experiencing the targeted mood at a stronger intensity than the other emotions following each induction. The mean rating given by the subjects on each clip to each question appears in Fig. 1, with bars indicating standard error of the mean. The ratings were lower on the sad clips than the fear or happy ones, representing a more mixed reaction to the sad and fear clips than the happy ones. Nevertheless, the questionnaire results indicate that the music clips were effective at eliciting the targeted mood. Analysis of the dial and questionnaire data is presented elsewhere (Johnsen, 2004); this study did not attempt to relate the dial and physiological responses. Few subjects reported familiarity

[2] The mean heart rate in the one s bin immediately preceding the start of the analysis period was used as the baseline; the mean heart rate in each of the following bins was subtracted from this baseline to obtain mean heart rate change. The mean heart rate in each bin was calculated by taking the weighted mean of all RR intervals overlapping the bin after the RR intervals had been converted to heart rate in beats/min. At 1000 Hz, one s bins are 1000 samples long. The first and last sample number of each bin was identified, as well as that of the R wave immediately preceding the bin, all R waves in the bin, and the first R wave after the bin. The mean heart rate in the bin was calculated by taking the average of the heart rate at each of the 1000 samples contained in the bin.

[3] The mean respiration rate change in each bin was calculated in the same manner as the mean heart rate changes (described in footnote 2) except that the bins were enlarged to five s since mean breath length is greater than mean heart beat length.

[4] For this analysis, the music signal was downsampled and converted into a mono signal. The filter had a length of 1500 samples and a sampling rate of 1000 Hz (uses the last 1.5 s of information). This sampling rate ensures that the system concentrates on lower frequency components of the music clip below 500 Hz.

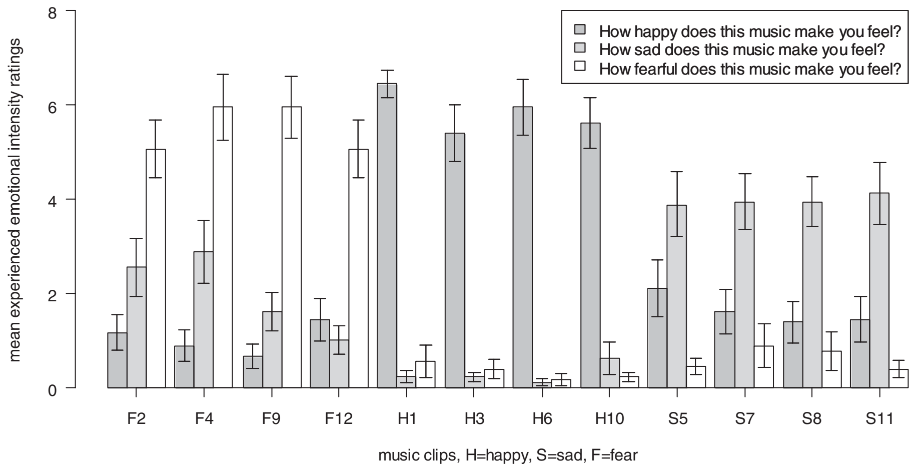

Fig. 1. Mean ratings on each clip; bars indicate the standard error of the mean. The scale ranged from 0 ("none") to 9 ("very much"), $N=18$.

with the music and no subject was able to correctly identify the source of any clip.

3.2. Cardiovascular measures

3.2.1. Time-domain measures

The mean and standard deviation of each time-domain heart rate variability measure on each clip is listed in Table 2. Over all clips the mean RR interval length was 896.50 ms (S.D. = 111.73), corresponding to a mean heart rate of 66.9 beats/min. The mean RR interval length varied from 886.37 (S.D. = 116.95) ms on H1 to 909.10 (S.D. = 109.46) ms on F9, a narrow range well within one standard deviation of the overall mean. Mixed model analysis was used to test whether the pattern of changes in the mean RR interval length was similar across subjects. The model returned a highly non-significant estimate ($F(11)=0.7253$, $p=0.7133$), indicating that mean RR interval length did not vary significantly with clip.

The same analyses were performed on the SDNN (standard deviation of the RR interval series), SDSD (standard deviation of the differences between successive RR intervals), and RSA data (respiratory sinus arrhythmia). The mean and standard deviation of SDNN, SDSD, and RSA for each stimulus are included in Table 2. As with the RR interval lengths, the difference between the clips is well within one standard deviation of the mean for all measures. There is a trend towards a higher SDNN on the fear than the other stimuli, but this was not significant in the mixed model, although close to significance ($F(11)=1.8175$, $p=0.0537$). The mean SDSD was similar on all clips; consistently the mixed model did not return a significant clip effect ($F(11)=1.3711$, $p=0.1897$). The mean RSA was also similar on all clips, ranging from 26.37 to 47.98 ms with large standard deviations; the mixed model for RSA was not significant ($F(11)=0.8347$, $p=0.6058$).

Table 2
Mean (standard deviation) of heart rate variability measures by clip

Clip	RR interval length	SDNN	SDSD	RSA
F2	893.83 (119.64)	37.30 (41.86)	39.74 (58.06)	46.44 (75.22)
F4	902.91 (114.51)	45.55 (46.18)	52.51 (70.33)	39.70 (47.74)
F9	909.10 (109.46)	50.30 (46.02)	51.67 (73.83)	47.98 (74.43)
F12	893.27 (104.22)	40.21 (42.07)	42.99 (67.65)	39.16 (43.51)
H1	886.37 (116.95)	40.12 (46.48)	46.49 (76.55)	42.51 (67.55)
H3	893.73 (121.95)	42.23 (41.88)	47.92 (62.08)	43.09 (51.21)
H6	892.17 (117.28)	34.74 (34.09)	35.81 (49.29)	34.68 (50.87)
H10	896.79 (109.75)	40.51 (40.15)	38.52 (62.38)	41.62 (66.03)
S5	897.54 (112.74)	38.37 (34.60)	39.68 (55.43)	35.58 (30.49)
S7	899.00 (119.31)	43.48 (40.28)	42.37 (60.43)	26.37 (20.67)
S8	898.24 (114.53)	41.81 (41.68)	37.20 (60.13)	34.07 (36.10)
S11	895.42 (114.28)	37.36 (37.20)	36.98 (55.70)	30.63 (24.00)

All values in milliseconds, $N=18$.

3.2.2. Activity during mood inductions

The lowess curves calculated for the subjects' mean heart rate changes during the happy (H1, H3, H6, and H10) sad (S5, S7, S8, and S11) and fear clips (F2, F4, F9, F12) appear in pane a of Fig. 2. If the subjects' mean heart rate was constant throughout the induction the curves would remain at the zero line, representing no change in mean heart rate from baseline. The mean heart rate during the happiness inductions did remain near zero for 30 s, followed by a modest acceleration then deceleration back to zero. The mean heart rate during the fear inductions accelerated steadily the first half of the period, then returned to baseline, while during the sadness inductions the mean heart rate initially slowed, followed by a slow return to near baseline. The significance of these trends was assessed using null bands calculated from permutation testing, as described in Materials and methods. The lowess curve for the happiness inductions (pane c of Fig. 2) falls within the bands, indicating that the curve is not distinct from one that might have occurred by chance. The curve for the sadness induction (pane b), by contrast, falls below the bands until about 55 s, indicating a larger heart rate deceleration than would be expected if there is not an interaction between clip type and heart rate. Finally, the curve for the fear induction (pane d) rises above the null bands for about half the clip, indicating greater heart rate acceleration than expected by chance. It is not a contradiction to suggest that significant heart rate differences occurred during the clips while the time domain measures did not find significant differences since the two analyses detect different types of patterns.

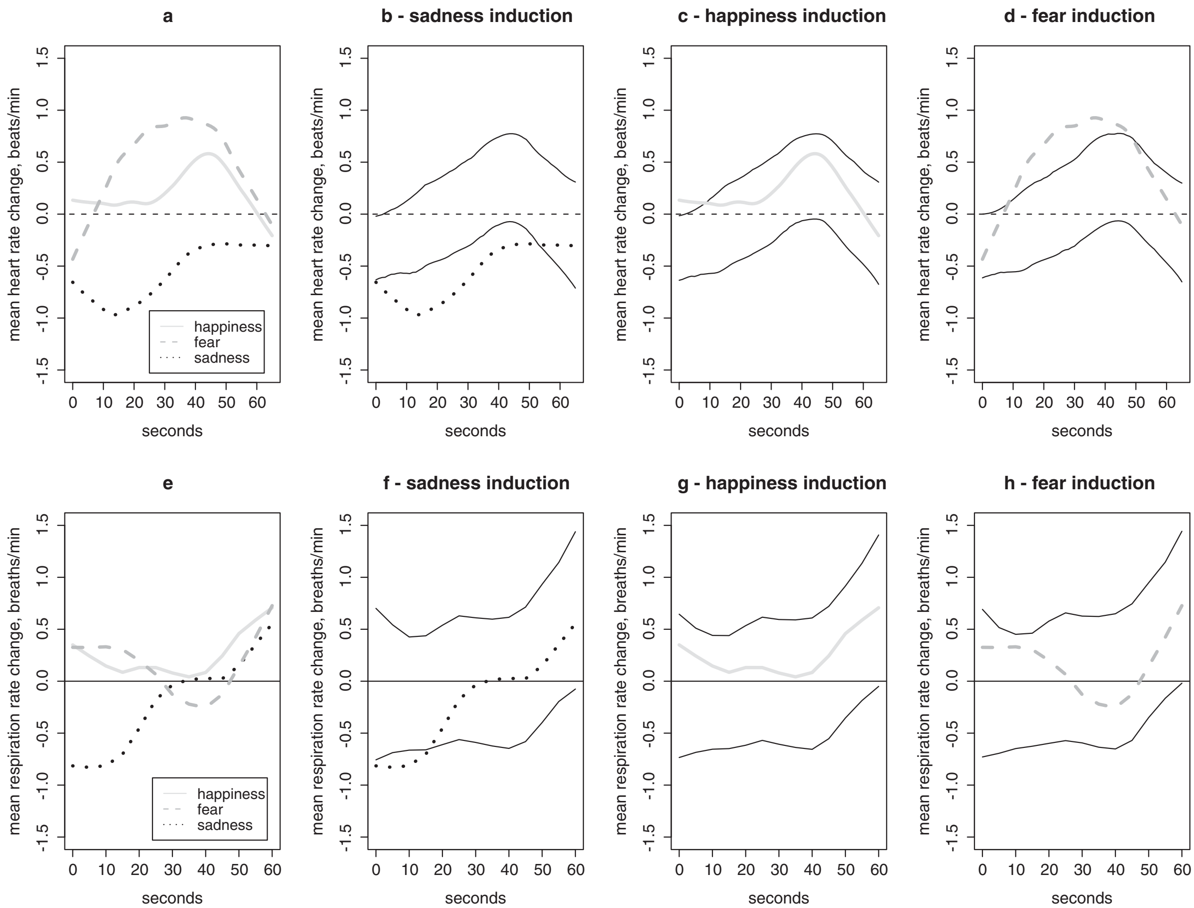

Fig. 2. Lowess curves and null bands depicting the mean heart rate changes (panes a, b, c, d, $N=18$) and mean respiration rate changes (panes e, f, g, h, $N=13$) during the mood inductions. Mean heart rate changes are in beats/min, mean respiration rate change in breaths/min. Thin lines on plots b, c, d and f, g, h show the location of the null bands.

3.3. Respiratory measures

3.3.1. Time-domain measures

The mean and standard deviation of each respiratory measure for each clip is listed in Table 3. Averaging over all clips the mean breath length was 3447.03 (S.D. = 380.06) ms, corresponding to 17.41 breaths/min; mean SDNNresp 472.99 (S.D. = 291.21) ms, mean SDSDresp 603.92 (S.D.=390.18) ms, mean inspiration length 1514.44 (S.D. = 340.41) ms, mean expiration length 1930.69 (S.D. = 367.52) ms, and mean inspiration duty cycle 0.44078 (S.D. = 0.08108).

The mean breath lengths listed in Table 3 vary with clip type: the mean breath length is shortest on the happy clips (H1, H3, H6, and H10), longest on the sad clips (S5, S7, S8,

Table 3
Mean (standard deviation) of respiration measures by clip

Clip	Breath length	SDNNresp	SDSDresp	Inspiration time	Expiration time	Inspiration duty cycle
F2	3394.99 (324.42)	362.47 (125.16)	495.88 (221.85)	1519.61 (272.36)	1771.09 (317.34)	0.4645 (0.0784)
F4	3513.97 (394.74)	541.42 (293.54)	712.42 (466.75)	1516.71 (304.27)	1864.82 (291.52)	0.4490 (0.0770)
F9	3421.65 (312.94)	493.88 (281.11)	572.81 (289.34)	1434.12 (333.04)	1884.28 (403.84)	0.4361 (0.0982)
F12	3372.15 (387.01)	433.99 (407.68)	526.94 (510.12)	1545.81 (385.76)	1973.49 (337.54)	0.4362 (0.0792)
H1	3300.25 (330.18)	479.18 (290.96)	710.91 (498.16)	1447.52 (277.34)	2136.94 (347.16)	0.4066 (0.0658)
H3	3331.28 (283.00)	299.42 (124.18)	379.57 (133.55)	1629.52 (628.78)	1743.10 (328.27)	0.4694 (0.1144)
H6	3377.32 (376.98)	474.48 (260.62)	606.91 (427.03)	1605.48 (241.71)	1989.89 (386.97)	0.4478 (0.0713)
H10	3343.31 (308.35)	487.37 (194.80)	578.21 (322.11)	1472.96 (288.56)	2065.48 (306.95)	0.4174 (0.0628)
S5	3596.33 (386.98)	505.69 (322.87)	613.18 (369.33)	1484.06 (288.81)	1932.83 (384.34)	0.4351 (0.0794)
S7	3585.15 (339.25)	513.70 (255.59)	724.13 (416.66)	1508.93 (302.75)	1839.89 (311.25)	0.4533 (0.0772)
S8	3547.89 (388.94)	507.82 (243.48)	643.34 (273.21)	1519.97 (286.07)	2057.48 (443.31)	0.4322 (0.0556)
S11	3567.82 (613.89)	544.96 (492.99)	636.75 (522.96)	1481.08 (412.64)	1900.88 (440.14)	0.4411 (0.1087)

All values in milliseconds, $N=13$.

and S11), and intermediate on the fear clips (F2, F4, F9, F12). The mixed model of mean breath length returned a significant clip effect estimate ($F(11)=2.77$, $p=0.0031$), indicating that mean breath length varies significantly with clip. Further estimates (Table 4) were performed to determine the source of the variation. These estimates indicate that the mean breath length was significantly ($p<0.0001$) longer during the sadness than the happiness induction, and significantly ($p=0.0014$) longer during the sadness than the fearful induction. There was not a significant difference ($p=0.070$) in mean breath lengths during the happiness and fearful inductions.

An interaction of clip type and mean expiration length is suggested by the figures in Table 3. The differences were further examined by plotting the mean expiration length on each clip for each subject individually, indicating that for most subjects the mean expiration length was longer on the sad than the fear or happy clips (not shown). The mixed model of mean expiration length returned a significant effect of clip type ($F(11)=2.445$, $p=0.0087$). The estimates (Table 5) indicate that the pattern of significant mean expiration length differences matches that of total breath length differences: expiration length was significantly ($p<0.0001$) longer during the sadness than the happiness inductions, and significantly ($p=0.0048$) longer during the sadness than the fearful inductions. There was not a significant difference ($p=0.094$) between mean expiration length during the happiness and fearful inductions.

No relationships between mean inspiration length, SDNNresp, SDSDresp, or inspiratory duty cycle and mood induction type were found. The range of mean inspiration lengths for individual subjects tended to be narrow, with similar values on all clips. The mixed model of mean inspiration time ($F(11)=0.3717$, $p=0.9647$) did not show a significant effect of clip type. Despite the relatively constant mean SDNNresp and SDSDresp (Table 3) across the inductions, the values for each individual subject varied a great deal between the clips (not shown). The pattern of variation varied for each subject however, so the mean was relatively constant. Mixed models of SDSDresp ($F(11)=0.9436$, $p=0.5017$) and SDNNresp ($F(11)=0.9442$, $p=0.5011$) did not find significant clip effects. The mean inspiration duty cycle for the individual clips was very similar, ranging from 0.4066 to 0.4694 (Table 3), well within one standard deviation of the overall mean of 0.44078 (S.D.= 0.08108) and the mixed model ($F(11)=0.9100$, $p=0.5331$) did not find a significant interaction of clip type and mean inspiration duty cycle.

Table 4
Mixed model estimates for mean breath length

Label	Estimate	Standard error	*t* value	*df*	Pr>|*t*|
F−H	356.54	195.07	1.83	119	0.0701
F−S	−636.41	194.56	−3.27	119	0.0014
H−S	−992.95	189.34	−5.24	119	<0.0001

Table 5
Mixed model estimates for expiration length

Label	Estimate	Standard error	*t* value	*df*	Pr>|*t*|
F−H	385.06	227.95	1.689	119	0.0938
F−S	−653.59	227.39	−2.874	119	0.0048
H−S	−1038.65	221.31	−4.693	119	<0.0001

3.3.2. Activity during mood inductions

Lowess curves for the subjects' mean respiration rate changes during the happy, sad, and fear clips appear in Fig. 2, pane e. The curve representing the changes during the fear and happiness inductions are similar, although the fear induction includes a decreased respiration rate followed by an increase during the last half of the clip. The curve for the sadness induction differs, showing an initial respiration rate decrease. As before, the significance of these trends was assessed using null bands calculated from permutation testing, which appear in panes f, g, and h of Fig. 2. The null bands are relatively wide, encompassing nearly all of the true lowess curves, suggesting that differences in the pattern of respiration rate changes during the mood inductions are not significant. This conclusion does not suggest that conclusions drawn from the time-domain measures are incorrect; the two analyses capture different aspects of variability.

3.4. Entrainment

The correct music clip tended to predict the respiration signal for the corresponding case more accurately (in terms of mean squared error) than the other music clips used in this study. The prediction is most accurate during periods where the music has a fairly steady rhythm. Further analysis is necessary to determine which components of the music the subject may be responding to and the speed of the physiological response. The results are illustrated in Fig. 3, which shows the respiration and error signals for one subject. In this figure the dark line is the estimation error that results when the clip the subject was listening to is used to train the filter, while the lighter lines show the estimation error when other clips were used. The error is much less when the clip the subject was listening to is used to train the adaptive filter, showing that for this subject during these clips there is a relationship between the music signal and the respiration signal. The mean squared error between the respiration signal and the filtered estimate of the respiration signal for each subject and clip appear in Table 6 and are plotted in Fig. 4.

The mean squared errors vary both by subject (Table 6) and clip (Fig. 4). Comparing the columns of Table 6 it can be seen that the errors tend to be smaller on all clips for some subjects (e.g. b, c, h, i, k), indicating that their respiration matched the music more closely. Also, several clips did not predict any subjects' respiration signal well (e.g. S8 and H6), probably due to these clips' lack of a strong rhythm and/or frequent rhythm changes. Clips with the steadiest beats (e.g. H10, S11) had the lowest error for most subjects, suggesting that clips with a standard rhythm tend to result in more entrainment, or perhaps

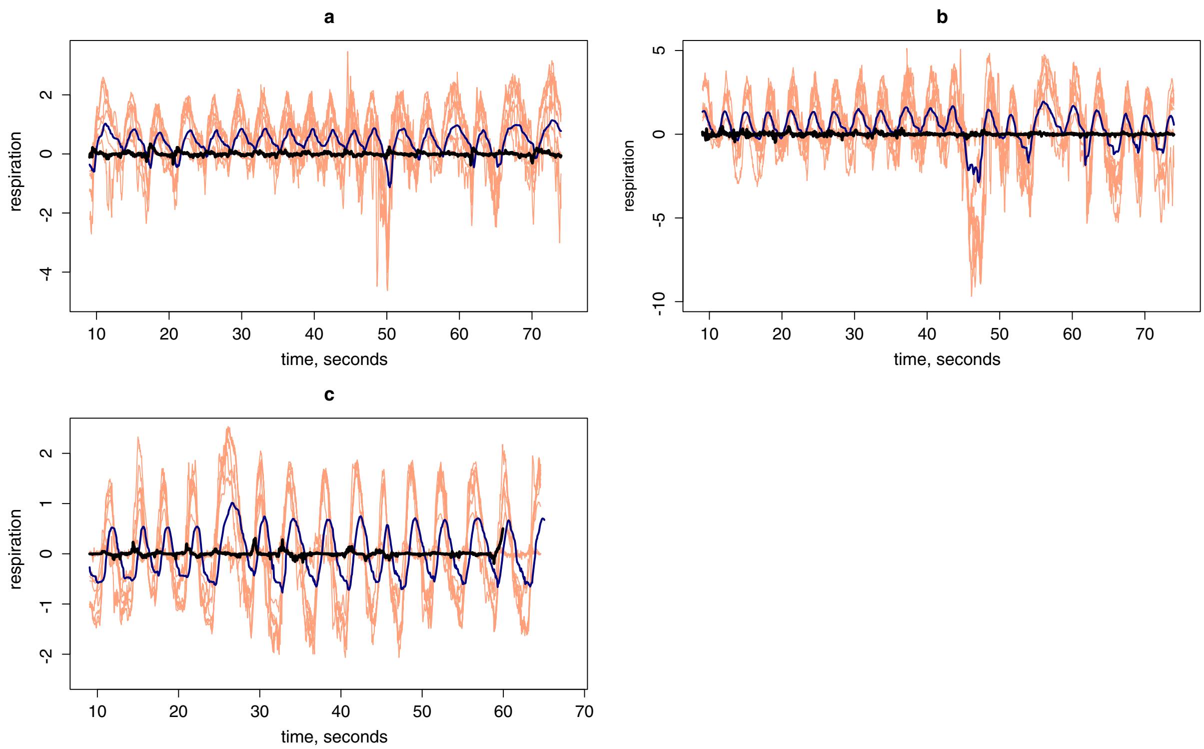

Fig. 3. Representative signals to illustrate the results of the entrainment analysis. These three plots show the respiration for one subject during three different stimuli: F9 (pane a), H10 (pane b), and S11 (pane c). In each plot the blue line is respiration, the black line is signal error for the matching clip (F9 for pane a, H10 for pane b, S11 on pane c), and the orange lines are the signal error when the other clips were used as predictors. The error when the clip the subject was listening to (black line) was used as the predictor is generally less than the error to the other clips, indicating higher correlation between the matching clip and the respiration signal than the other clips. [For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.]

that these clips are better for predicting quasiperiodic signals (such as respiration) in general.

4. Discussion

Based on subjects' reports, the musical mood induction used in this experiment was successful. The subjects reported experiencing moods while listening to the music; in many cases strong emotions. The subjects' median emotional intensity ratings indicate distinct emotional experiences: the median rating was 6 for the fear and happiness inductions and 4 for the sadness induction on a scale of 0 ("none") to 9 ("very much"). No differences were found on any of the traditional cardiovascular measures examined, but evidence was found that the heart rate decelerated during the sadness induction and accelerated during the fear inductions. Differences in total breath length and total expiration length were found in the expected direction (slower respiration during the sadness than the fear or happiness inductions) on the time-domain measures but not when changes during the clips were examined.

Previous research and theories of the mechanisms of emotional experience suggest that measurable physiological

Table 6
Mean squared error estimates for each clip

Clip/subject	a	b	c	d	e	f	g	h	i	j	k
H1	0.78	0.21	0.27	1.67	3.20	1.29	2.61	0.56	0.16	1.36	0.10
F2	8.95	0.09	0.07	1.01	NA	6.00	7.44	1.31	0.31	NA	0.21
H3	4.99	0.03	0.19	1.66	7.06	4.20	6.65	0.64	0.30	11.53	0.13
F4	11.68	0.03	0.26	1.75	8.10	3.21	9.41	0.86	0.09	2.84	0.09
S5	0.19	0.01	0.03	1.67	2.58	1.04	6.97	0.39	0.27	0.14	0.086
H6	15.55	9.58	2.39	11.17	7.43	4.90	13.72	5.91	2.81	16.11	0.15
S7	8.29	2.50	0.77	5.76	6.80	4.88	9.96	4.06	1.58	3.96	1.68
S8	12.69	14.96	2.93	12.57	7.13	8.54	16.19	10.69	2.81	7.99	9.19
F9	1.05	1.16	0.36	0.98	2.23	1.73	7.61	0.68	0.54	2.39	1.26
H10	0.24	0.001	0.13	0.09	0.99	0.20	1.54	0.07	0.02	0.30	0.006
S11	0.026	0.05	0.02	0.08	0.23	0.10	1.99	0.03	0.04	0.71	0.01
F12	1.82	0.19	0.11	3.82	3.64	0.97	14.86	0.32	0.39	5.16	0.07

The mean squared errors were estimated over the 65-s period starting 9 s after the onset trigger. Missing data indicated by NA.

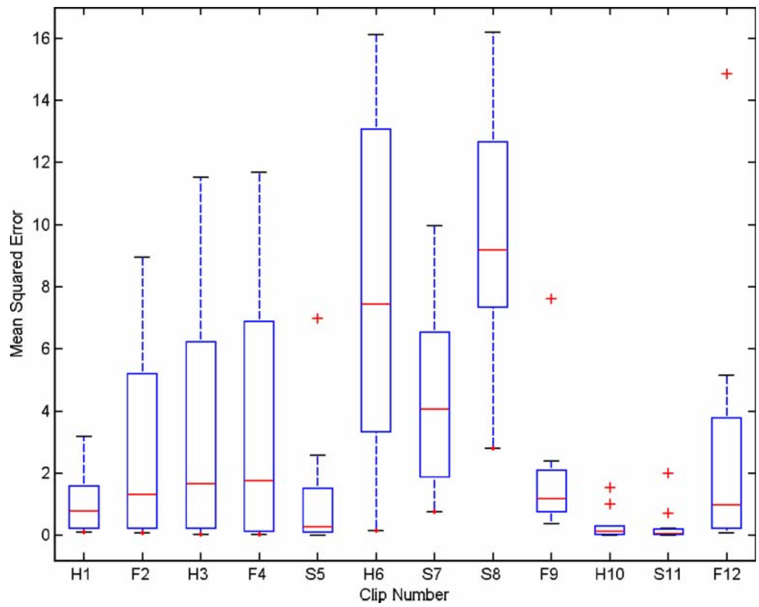

Fig. 4. Boxplots of the mean squared error estimates for each clip.

changes accompany the experience of strong emotion, and that music is capable of inducing such strong emotion. We found modest evidence that the physiological changes occurred consistently with the mood inductions. Distinct differences in measures of respiratory and cardiovascular activity occurred between the mood inductions. Both the mean total breath length and expiration length had significant interactions with clip type: mean breath and inspiration lengths were longest for the sad induction, intermediate during fear, and shortest during the happiness induction. Despite this significant interaction it is not clear that the differences we found in respiratory activity were due to the induced emotion because the music used for the different emotion inductions varied greatly in dominant rhythm.

The music used to induce happiness had quick, toe-tapping rhythms and melodies, in stark contrast to the sadness-inducing music, dominated by long chords and much slower tempos. We chose the stimuli because they were the most consistently shown to induce emotion in the pilot study; no effort was made to match rhythms or tempos. This is consistent with the protocol used in previous musical mood induction experiments (e.g. Krumhansl, 1997; Mayer et al., 1995; Nyklícek et al., 1997). It is not surprising that our pilot study resulted in pieces with different tempos: musical theory and research suggests that tempo is a critical determinant of the mood associated with music. Mode and tempo are often cited as the characteristics most influential for emotional expressiveness in music (Dalla Bella et al., 2001; Peretz et al., 1998). According to a review by Gabrielsson and Lindstrom (2001), fast tempos have been associated with expressions of activity/excitement, happiness/joy/pleasantness, potency, surprise, anger, and fear. Slow tempos are associated with expressions of calmness/serenity, dignity/solemnity, sadness, tenderness, boredom, and disgust. Further emphasizing the relationship between tempo and mood, Gottselig (2000) found that the ability of subjects to correctly identify the emotion expressed by music was related to their temporal auditory perception.

The short-term cyclic correlation analyses suggest that subjects' respiration became partly entrained to the music beats on many clips, indicating that the interaction of clip type and physiological measures may be due to differences in the tempo of the music used to induce each emotion rather than emotional experience itself. We do not believe that the subjects were consciously attempting to match their breathing to the music's tempo; manipulating the rating dial and preparing for the post-clip questionnaires should have dominated the subjects' attention (subjects were not asked about their respiration, however). Instead, it is likely that the subjects unconsciously matched their breathing to dominant tempos. Past observations have identified a tendency of subjects to breathe with musical rhythms (Diserens, 1923); our finding of a relationship between respiration and the tempo of music is consistent with the more recent findings of Haas et al. (1986). It would be interesting for future studies to examine music similarity and features (such as timbre) to check for frequency-based responses to the clips (Park, 2000), or evaluate the clips with acoustic similarity measures (Berenzweig et al., 2003). It is also possible that the differences in heart rate found between the fear and sadness inductions were due to the driving of respiration by the music tempos, since respiratory changes can cause heart rate variability changes (reviewed in Boiten, 1996; Grossman, 1983). This finding, that subjects respond to aspects of the stimuli in addition to any induced mood, is not unique to music stimuli, but occurs with many types of stimuli.

The low magnitude of cardiovascular and respiratory differences between the mood inductions is surprising given the intensity of emotional experience reported by the subjects. There are several possible explanations for this finding. One possible explanation is that the subjects exaggerated their experienced mood intensity ratings. Previous work has shown that the efficacy of musical mood induction procedures is heavily dependent on subject instructions (Hermans et al., 1996; Lenton and Martin, 1991). Lenton and Martin (1991) compared the ability of music and "subliminal" music (silence) to induce moods under two sets of instructions (telling the subjects that they will be asked to rate their mood versus performing unspecified future "tasks") and found that instructions containing references to mood were necessary and sufficient for successful mood induction measurements. The instructions provided to the subjects in this study did not include guidance on how to change their mood as is sometimes done during musical mood induction (Clark, 1983; Clark and Teasdale, 1985; Sutherland et al., 1982), but did include directions to rate the "strength of the emotions you are feeling" continuously, implying that the subjects should feel emotion in response to the music. It is possible that the subjects responded to the questionnaire based more on the mood that they perceived the music expressing than the mood they actually felt. If this occurred and subjects only experienced minor emotions the physiological correlates may be too subtle to detect with our methodology.

Another possible explanation is that the subjects chosen for this experiment had muted cardiovascular responses due to age. The average age of the subjects was 50, the oldest 74. Many measures of cardiovascular activity are reduced in variability in older people (Antelmi et al., 2004; Stein et al., 1997; Umetani et al., 1998). As a result, repeating the experiment with younger subjects may produce larger-magnitude findings of emotion-related cardiovascular change, although this would raise questions of the necessity of cardiovascular and respiratory responses for emotional experience.

It is also possible that significant differences were not found in the time-domain measures of cardiovascular activity due to the small number of participants and stimuli length in this experiment. Similar previous studies (Krumhansl, 1997; Nyklícek et al., 1997), which did report significant time-domain measure differences, included more than twice the number of participants and longer recordings than this study. The effect size reported in those studies was very small, so a larger sample size than used here may be needed to obtain significant results. This study did find evidence of changes in mean heart rate during the mood inductions consistent with the differences in time-domain measures reported in those previous studies, however, so the results are not contradictory.

The findings of this study add to the understanding of physiological reactions to emotions induced by music. Time-domain cardiovascular differences were not found, in contrast to previous research (Krumhansl, 1997; Nyklícek et al., 1997), although evidence for differences in heart rate within the clips between the inductions was identified. The entrainment of respiration to the music in this study, where conscious coordination should have been minimized by instruction and concurrent tasks, adds emphasis to previous reports that respiration can be driven by music (Diserens, 1923; Haas et al., 1986). The ability of many music tempos to drive respiration complicates the use of music for mood induction, and may make it impossible to separate physiological reactions to tempo from those due to the experienced mood. It remains to be seen whether entrainment is necessary for subjective reports of emotional experience, but clearly entrainment must be considered in studies utilizing musical mood induction and physiological measurements.

Acknowledgements

The data reported here derive from Erica Johnsen's (2004) doctoral dissertation.

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