



## Psycho-physiological responses to expressive piano performance

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### ARTICLE INFO

#### Article history:

Received 15 May 2009

Received in revised form 20 November 2009

Accepted 8 December 2009

Available online 16 December 2009

#### Keywords:

Expressive piano performance

Heart rate

Heart rate variability

Autonomic nerve system

Respiratory measurements

### ABSTRACT

The present study examined selected autonomic and cardio-respiratory responses of nine elite pianists during solo performances of the same single musical piece. The subjects performed the piece with and without self-perceived emotional expression, and with and without free ancillary body movements during expressive performance. Autonomic nervous system and cardio-respiratory parameters were continuously monitored during all experimental conditions. These parameters were heart rate (HR), sweating rate, the root mean square of successive difference (RMSSD) of heart rate variability and respiratory measurements such as oxygen consumption ( $\text{VO}_2$ ), minute ventilation, tidal volume and respiratory rate. Kinematics of the trunk and arms were recorded during all conditions. The subjects also provided subjective rating of the emotions that they experienced during their performances for each experimental condition. Analysis revealed that expressive performance clearly produced higher levels of valence and arousal than the non-expressive condition. This observation is consistent with current embodiment theory. The expressive condition also had significantly higher levels of HR, sweating rate, minute ventilation, and tidal volume, and lower levels of RMSSD and respiratory rate than the non-expressive condition. No difference was found for  $\text{VO}_2$  between these conditions. The expressive condition with ancillary body movements did not significantly differentiate any of the physiological measures except for respiratory rate from those observed without such body movements. These findings suggested that expressive musical performance could modulate the emotion-related autonomic and cardio-respiratory responses that are independent of the effect of physiological load due to expressive ancillary body movements in playing the selected music on the piano.

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### 1. Introduction

Playing the piano is a joyful, enriching and relaxing aspect of the lives of millions of people of all ages and levels of ability. However, this same musical activity can be a highly demanding physical and mental endeavor for serious pianists. Even casual and uninformed observers are frequently struck by the interactions of the mental, emotional and physical energy of successful, gifted pianists. Over the centuries, musicians and lovers of music appear to have developed an intuitive understanding of these interactions. However, until relatively recent times, the scientific community lacked the tools to investigate the

nature of the relationships between emotional aspects of the pianist's musical performance and the accompanying physiological and biomechanical mechanisms that are the vehicles for transforming creative composition into the profound experience of listening to and appreciating high levels of musical performance.

There have been some attempts to investigate physical activity during piano playing. For example, Hoyos et al. (2003) reported that the mean energy cost of 10 pianists was 1.4 kcal/min during 5-min of executing repetitive keystrokes at a moderate tempo. This represented an increase in energy expenditure of 13% when compared with values obtained from the same subjects at rest. Parr (1998) examined heart rate (HR) and cardiac output of 15 expert pianists who performed a bilateral 4-octave scale exercise at a moderate tempo of 100 beats per minute (bpm) and at a near-maximum tempo of 184 bpm. When compared with resting values, they found an increase of 20% in HR and cardiac output at the moderate tempo and an increase of 60% at near-maximum tempo. It is reasonable to assume that these repetitive, utilitarian tasks would have provoked minimal levels of emotional involvement in the subjects. In contrast, Passmore and Durnin (1955) reported an energy cost of 2.5 kcal/min for a single pianist playing a conventional composition. This anecdotal value is approximately 79%

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greater than the mean value reported by Hoyos et al. (2003) for the execution of repetitive keystrokes. However, neither details of their experimental conditions nor physiological measures other than the oxygen consumption ( $VO_2$ ) were presented in their report of the single-subject investigation. Based upon limited objective data it may be hypothesized that observed increases in energy cost may be related to the effect of emotions during performance. However, the manner and extent to which the physiological function of pianists is modulated by expressiveness of performance is yet to be determined.

Previous researchers have investigated the emotional effects of listening to music on psycho-physiological functions (Bernardi et al., 2006; Blood and Zatorre, 2001; Iwanaga et al., 2005; Khalfa et al., 2002; Nater et al., 2006; Sammler et al., 2007). For example, Blood and Zatorre (2001) reported elevated HR and respiration rate in individuals who listened to self-selected music that consistently elicited intensely pleasant emotional responses. The observed increase in HR occurring during the highest valence was about 30 bpm greater than when the same individuals listened to music that they perceived to be non-emotional. The authors also used a positron emission tomography (PET) technique to monitor the central neural network associated with these emotional responses. Activation was observed in the ventral striatum, midbrain, amygdala, orbito-frontal, and medial prefrontal cortex. They concluded that music recruited neural systems of reward and emotion similar to those known to respond specifically to biologically relevant stimuli, such as food and sex, and those that are artificially activated by drugs of abuse. Bernardi et al. (2006) reported that listening to music at a higher tempo induced an arousal effect that was associated with elevated rates of ventilation, HR, and blood pressure (BP). The facilitation in these physiological responses was greater in musically-trained subjects than those without musical training. Khalfa et al. (2002) monitored skin conductance responses, a measure of sympathetic nerve activity, in subjects listening to musical excerpts that could induce different kinds of emotions (fear, happiness, sadness, and peacefulness). They found higher sympathetic activity with fear and happiness than with sadness and peacefulness. Iwanaga et al. (2005) observed that the high-frequency (HF) component of HR variability (HRV), which reflects the activity of parasympathetic nerves, was decreased in subjects who listened to an excitative type of music. Conversely, when the same subjects listened to a sedative type of music the HF component increased. Listening to the same excitative music repetitively caused HR to gradually decrease, and the HF component to gradually increase toward levels observed when subjects were not exposed to music. These changes were considered to be indicative of habituation to the same repetitive musical stimuli.

Recent research in the area of embodiment cognition has provided some insights into expressiveness of performance. According to Niedenthal (2007) “The embodiment of emotion, when induced in human participants in manipulations of facial expression and posture in the laboratory, causally effects how emotional information is processed”. For example, Ekman et al (1983) observed emotion-specific activity in the autonomic nervous system of actors and scientists who adopted facial expressions that characterized a series of different emotions. Similarly, Wiswede et al. (2009) manipulated facial expressions of female subjects by requiring them to hold a disposable chopstick horizontally between the teeth as a smile condition, and to hold the chopstick vertically with the upper lip as a no-smile condition. The authors also monitored autonomic nervous system activity when no chopstick was used for the control condition. The authors reported changes in electrophysiological parameters during the performance of a choice-reaction task under the three facial conditions examined. Michalak et al. (2009) compared selected biomechanical characteristics of gait in patients who were clinically depressed and sad with those of matched never-depressed subjects. They reported that patients suffering from depression walked slower, with more slumped postures, exhibited reduced arm swing and head movements, together with greater medio-lateral sway, when compared with non-depressed

subjects. The authors concluded that, “Embodiment theories suggest a reciprocal relationship between bodily expression and the way in which emotions are processed”. When applied to piano playing it must be assumed that physical expressiveness in the form of ancillary body movements may in fact influence the emotional state of the pianist, rather than emotional state inducing ancillary movements of the body. That is, the precise control of keystrokes for highly tuned sound production during expressive performance may demand higher levels of emotional arousal, attention or concentration, and muscular activity. During expressive piano performance, pianists appear to use ancillary actions of the arms, legs, trunk, and head, and thus the level of muscular activity is likely to be increased when compared to solitary practice. All of these technique modifications may lead to changes in autonomic nerve activity as well as cardiac and respiratory functions. Thus, based on available research, it is reasonable to assume that cognitive effort, including attention and expectation, appears to play a role in the physiological responses to musical emotions.

Due to the complex and intricate differences between the many and varied pieces of piano music available to the performer, the task of evaluating the psycho-physiological effects of artistic expression on the individual pianist would be daunting. As a first step, we used a sample of highly trained pianists and compared selected variables of autonomic nervous system and cardio-respiratory functions during the performance of the same single musical piece, with and without the emotional expression perceived by the subjects themselves, and with and without ancillary movements. Kinematic parameters of selected segments of the body were monitored during the time that performers played the selected piece of music under the various conditions examined. On the basis of current embodiment theory it was hypothesized that expressiveness in the form of ancillary body movements would influence emotions, which in turn, would be associated with an increase in sympathetic nerve activity and a decrease in parasympathetic nerve activity, and thereby raise HR. It was also hypothesized that emotional respiratory variables such as minute ventilation, tidal volume, and respiratory rate would also be modulated, and that  $VO_2$  would be increased as a result of increased muscular activity due to ancillary movements of the body during expressive performance. An understanding of these parameters may provide a foundation upon which the psycho-physiological study of music could be built.

## 2. Methods

### 2.1. Subjects

Nine active, Japanese, classic pianists (7 females and 2 males) whose ages ranged from 19 to 26 years (mean  $\pm$  SD = 24.0  $\pm$  4.5 years) served as the subjects for this investigation. Five of the subjects were professional performers, and the remaining four were graduate students who were majoring in piano performance at the School of Music at two universities in the Kansai (middle-west) region of Japan. These latter students were aspiring to be professional pianists. All subjects had at least 17 years of piano training experiences and had been awarded prizes at major domestic and/or international classic piano competitions. All subjects were healthy non-smokers, without any medical problems or medications that could have influenced their cardio-respiratory responses.

Selection of the subjects was made as follows. First, a group of 20 highly skilled pianists residing in the Kansai region was identified from lists of participants who had appeared in recent major domestic and international competitions. A letter describing the general nature of our proposed psycho-physiological study was sent to each member of the group in order to solicit interest in participating in the investigation. Fifteen pianists who expressed interest were then interviewed telephonically and voluntarily provided information about their piano education backgrounds and performance careers.

Those who were actively performing, had more than 15 years of piano training, and had no history of cardiovascular or neurological problems, were then given additional information about the purpose of the study, and the experimental tasks to be performed during the experiment. In addition, they were asked if they believed that they would be able to play the experimental music (see below) with and without expressing their emotions. Ten candidates who appeared to meet all these criteria volunteered to participate in the study. About a month before the experiment, each of the ten volunteers came to the laboratory and performed the experimental music using the lab piano. In particular, they were asked to report whether they could successfully play the piece in the laboratory using their usual expressive manner, and also perform the same piece without expressing their emotions during the performance. With only a single exception, the prospective subjects adamantly indicated that they could comply with these requests. The individual who indicated that she was not confident that she could comply was not included as a subject in the investigation. Written informed consent was then obtained from each subject, and the Osaka University Ethics Committee approved all procedures.

### 2.2. Music used for the investigation

The music selected for the study was the well-tempered Clavier, Vol. I, No.1 prelude written by J. S. Bach in the 18th century, which is one of the most popular classical pieces for individuals learning to play the piano. The complete score of this music is provided (see [Appendix A](#)). This piece can be performed predominately by hand and finger movements, and it allows performers to maintain a constant playing tempo (60 bpm) and relatively constant loudness (mezzo-forte). All subjects reported that they had practiced this piece sometime in their early training, so that with an additional one or two days of practice prior to the experiment they were able to perform it without viewing the score. In a previous study we employed a 10-point scale to objectify the effects of different types of music upon listeners (Nakahara et al., 2009). This same scale was used to evaluate the affective valence (pleasant and happy = 10, and unpleasant and unhappy = 1) and arousal (stimulating and exhilarated = 10, and calming and relaxed = 1) for the piece of music used in the present investigation. A group of music-major students ( $N = 34$ ) and a group of non-music-major students ( $N = 29$ ) consistently rated this music with high valence (pleasant and happy: average  $\pm$  SD =  $8.3 \pm 1.6$  point) and with relatively low arousal (calm:  $2.3 \pm 1.5$  point).

### 2.3. Experimental conditions

Four experimental conditions were examined for each subject. These were, (1) playing the selected music while incorporating the free ancillary body movements that he or she would habitually use for artistic expression in a live concert performance (the “expressive/free” condition), (2) playing the same music artistically and expressively, as in condition #1, but the subjects were instructed to voluntarily minimize ancillary body movements of the head, trunk, and upper arms (the “expressive” condition), (3) playing the same music as a finger exercise without expressing emotions and without ancillary body movements (the “non-expressive” condition), and (4) seated in a motionless position on the piano bench for 3 min with the hands resting on the piano keys (the “rest” condition). The test order of these experimental tasks was randomly assigned to each subject. The inhibition of emotional feelings during the non-expressive condition was achieved by each subject in a voluntary manner.

### 2.4. Experimental apparatus

The experimental set-up consisted of a three-lead electrocardiogram (ECG, DS-2150, Fukuda Denshi Co., Japan), a sound-level meter (NL-20, Rion Co., Japan), an automatic respiratory gas analyzing system (AE-280 S, Minato Med Sci. Co., Japan), sweat rate meter (SKD-100,

SKINOS CO., Japan), two 8-channel light-emitting diode (LED) position detection sensor cameras and amplifiers (C-5049, Hamamatsu photonics Co., Japan), and a Yamaha U1 upright piano ([Fig. 1](#)). A microphone for the sound-level meter was hung from the ceiling at a height of 1 m above the keyboard surface of the piano. The amplitude of the music was obtained from the sampled peak sound data.

### 2.5. Procedures

The acoustics and temperature of the laboratory used for data collection were controlled in a similar fashion to a traditional recording studio. Two weeks prior to data collection each subject came to the laboratory, at which time the required tasks and experimental procedures were carefully described, and the subject was given the opportunity to ask questions about various aspects of the study. The subject was then given the opportunity to practice all four experimental conditions on the piano in the laboratory. This was continued until the subject felt confident and comfortable performing each required task. The aforementioned procedures were utilized in an attempt to minimize anxiety associated with the experimental equipment and with the presence of the experimenters. Subsequently, the subject was given instructions about preparations for the day assigned for data collection. These included avoidance of strenuous exercise and the maintenance of normal diet for the preceding 24 h, and refraining from ingesting food, alcohol and caffeine for at least 2 h preceding the experiment. The subjects were also asked to practice playing the music at home until they were able to play without viewing the score, and to be confident that they could play the piece while suppressing their emotional involvement and avoiding ancillary body motions. A few days prior to the data collection session each subject reaffirmed that he or she was able to successfully play the music from memory under the specified conditions. Subjects reported that it took a few days of practice (range = a half day to 2 days) to meet these requirements with confidence.

After arriving at the laboratory on the day of data collection the subject “warmed up” during the final opportunity to rehearse the experimental musical piece under each of the required experimental conditions. Subsequently disposable ECG electrodes (Ag/AgCL) were attached to the chest to monitor HR. LEDs used to monitor arm and trunk kinematics were then mounted on the skin over the spinous processes of the seventh cervical vertebra (vertebra prominens) and the fifth lumbar vertebra, and the centers of the right coracoid process of the scapula and the greater trochanter (lateral side of the femur). A capsule that was used to measure sweat rate was then attached with adhesive tape to the surface of the left planta pedis (sole of the foot), and finally the subject was fitted with a mask that covered the nose and mouth during respiratory gas analysis.

The subject was then requested to maintain a seated, resting position in front of the piano for approximately 15 min in order to achieve a stable and calm cardiovascular status. The average HR during the last 1 min of this resting period was recorded and subsequently used as his or her resting baseline HR. Between each of the testing conditions, the subject was allowed to relax until the average 10-s HR fell within the range of  $\pm 2$  bpm of the baseline HR. Typically, these adaptive rest periods ranged from 5 to 8 min in length. Respiratory parameters were monitored using a gas analysis system interfaced with a laboratory personal computer. Minute ventilation, tidal volume, respiratory rate,  $VO_2$ , and end-tidal carbon dioxide pressure were continuously monitored on a breath-by-breath basis during the experimental period, and the data were continuously stored in the computer. During the subsequent data analysis, median values of these respiratory parameters were computed for each experimental condition for each subject. The median value was selected as a descriptive statistic, rather than the mean, because the data commonly indicated a relatively large breath-to-breath variability in the parameters examined.

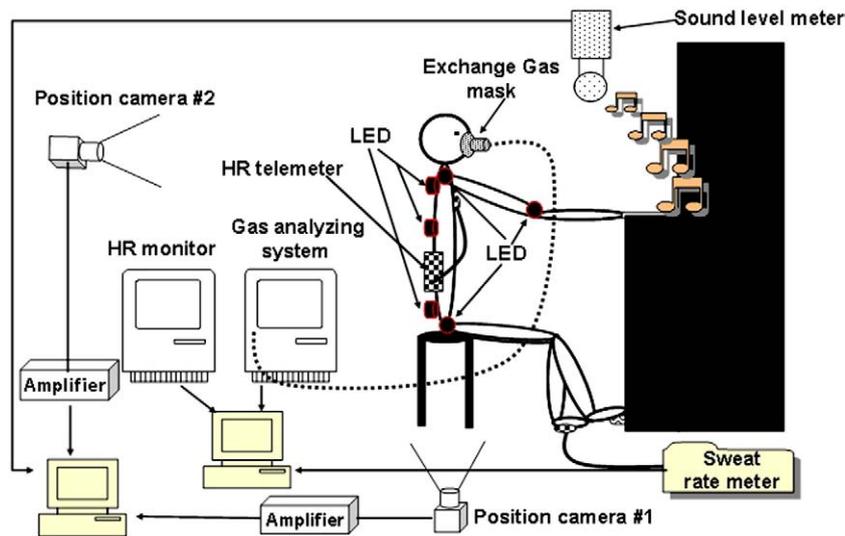


Fig. 1. The experimental set-up.

During each of the 4 experimental conditions, ECG data were continuously monitored with the three-lead electrocardiogram, sweat rate was monitored with the sweat rate meter, and the level of radiated sound of the piano was monitored with the sound-level meter. All data were recorded on a personal computer via an A/D converter at a sampling rate of 1 kHz. After the completion of all data collection ECG data were expressed in bpm for each R-R interval. The R-R interval data were then interpolated to obtain an equally sampled time series. Using “Advanced HRV Analysis” software (Niskanen et al., 2004), the value of the root mean square of the standard deviation (RMSSD) of HR for every successive 10-s period was used as an estimate of the transient vagal tone level for each subject during each of the experimental conditions (Owen and Steptoe, 2003). The sweat rate data were initially recorded as time-dependent voltage signals, but were subsequently converted into the volume of water per square centimeter of skin surface per min ( $\mu\text{g}/\text{cm}^2/\text{min}$ ) using a calibration value obtained prior to the experiment. The sweat rate was used to estimate the level of transient sympathetic tone. Similarly, the sound signal data that were recorded as a voltage were converted into the amplitude of sound pressure.

Movement of the trunk in the frontal and sagittal planes, and the arm in the sagittal plane were recorded during the data collection period using two position sensor camera-amplifier units for the position sensor system (see position cameras #1 and #2 in Fig. 1). The cameras were placed 1.5 m from the dorsal side and 3.5 m from the right side from the subject, respectively. The kinematic signals from the motion analysis systems were sampled at a rate of 150 Hz, and stored on a SONY personal computer. For purposes of synchronization, respiratory and sound amplitude data were simultaneously stored with the kinematic data in the same computer. The kinematic data were digitally smoothed at a cut-off frequency of 10 Hz using a second-order Butterworth digital filter. Frontal and sagittal plane angles were then generated using an inner product method. The total angular excursions of the trunk (in the sagittal and frontal planes), and upper arm (sagittal plane only) during the entire playing period were then computed for each experimental condition for each subject.

## 2.6. Subjective evaluation

Using the 10-point subjective rating scale described above, the level of arousal and valence induced by the musical performance was assessed for each subject at the conclusion of performing under each of the experimental conditions. The subject was also asked to report if

he or she perceived emotional responses while performing under each of the experimental conditions, and to identify the portion or measures where the highest pleasant emotions were perceived. Finally, the subject was asked to assess his or her ability to excluded emotional arousal during each of the non-expressive conditions.

## 2.7. Data analysis and statistics

One-way ANOVA with repeated measures design was used to identify statistical difference between data generated under each of the experimental conditions on each of the dependent variables. If the sphericity assumption was violated, then Greenhouse–Geisser degrees of freedom corrections were applied. Post-hoc analyses were conducted using Tukey’s procedure. Statistical significance was accepted at  $P < 0.05$ .

## 3. Results

### 3.1. Psychological load effect (comparison between the expressive and non-expressive conditions)

#### 3.1.1. Subjective measures

For the expressive conditions, the mean values of valence were fairly high and mean arousal ratings were relatively low (Table 1). These observations indicate that subjects experienced high levels of pleasure/happiness together with calm feelings when they performed the selected piece of music under the expressive conditions. The non-expressive condition, on the other hand, had a rating of valence that corresponded to slightly unpleasant/unhappy effects on the performers, which were accompanied by a low arousal level. ANOVA revealed significant difference in these emotional measures between the two conditions (see “expressive vs. non-expressive” in Table 1). The highest level of pleasant feeling was commonly reported to have been experienced during the 28th and 29th measures after the onset of the music (see Fig. 2, and also Appendix A). Some also reported the highest level of pleasant feeling at the 21st and 22nd bars.

#### 3.1.2. Sound pressure level and body movements

The levels of sound pressure generated by the performers did not differ between the expressive and non-expressive conditions (Table 1). There was also no difference in total angular excursion of the trunk and arm under the conditions examined (Table 1).

**Table 1**  
The mean values for Subjective evaluations, HR, HRV, sweat rate, respiratory variables and body movement.

	Rest	Non-exp	Exp	Exp/free	F-values from the ANOVAS	
					Non-exp vs. exp	Exp vs. exp/free
Arousal level	—	1.6 ± 0.7	3.7 ± 1.7	3.8 ± 1.3	10.39*	0.31
Valence level	—	3.4 ± 1.6	8.8 ± 1.0	9.0 ± 0.9	78.77***	2.29
SPL (dB)	52.3 ± 1.2	77.3 ± 0.9	78.1 ± 1.5	78.0 ± 1.5	2.00	0.35
Excursion (rad)						
Trunk in the frontal plane	13.7 ± 5.5	16.4 ± 6.6	17.3 ± 4.9	23.9 ± 13.6	1.21	5.06
Trunk in the sagittal plane	8.9 ± 1.1	14.9 ± 7.6	15.9 ± 7.3	19.4 ± 8.6	1.81	6.54*
Arm in the sagittal plane	10.3 ± 1.9	19.0 ± 6.9	19.5 ± 6.8	24.3 ± 8.0	0.15	8.07*
HR (bpm)	77.1 ± 7.7	82.7 ± 6.7	90.1 ± 9.4	91.4 ± 9.4	15.4**	1.36
RMSSD (ms)	28.5 ± 7.4	23.2 ± 7.9	18.6 ± 6.7	20.3 ± 5.1	7.52*	0.28
Sweat rate (µg/cm <sup>2</sup> /min)	49.4 ± 15.7	50.6 ± 15.8	63.3 ± 23.3	62.3 ± 21.0	7.63*	0.44
VO <sub>2</sub> (ml/min)	203.8 ± 49.5	245.8 ± 54.4	254.8 ± 60.0	270.4 ± 66.2	1.07	0.08
PETCO <sub>2</sub> (mm Hg)	37.5 ± 4.3	37.0 ± 4.3	36.7 ± 4.3	36.3 ± 4.7	0.83	0.05
Minute ventilation (l/min)	7.1 ± 1.2	8.5 ± 1.9	9.6 ± 2.5	9.9 ± 4.6	5.45*	0.16
Tidal volume (ml/min)	528.5 ± 178.5	438.1 ± 81.0	581.8 ± 177.8	735.2 ± 406.0	13.24**	3.49
Respiratory rate (n/min)	15.4 ± 2.3	19.8 ± 3.9	17.4 ± 5.4	15.3 ± 5.9	10.54*	15.01**

Non-exp: non-expressive, Exp: expressive.

The values are the mean and standard deviations for all subjects.

\* $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*  $P < 0.001$ .

### 3.1.3. Estimates of autonomic nerve activity

Fig. 2 shows changes in the 10-s means of HR, and RMSSD for the expressive and non-expressive conditions for all subjects during the last 1-min of the preparatory period and the subsequent period of

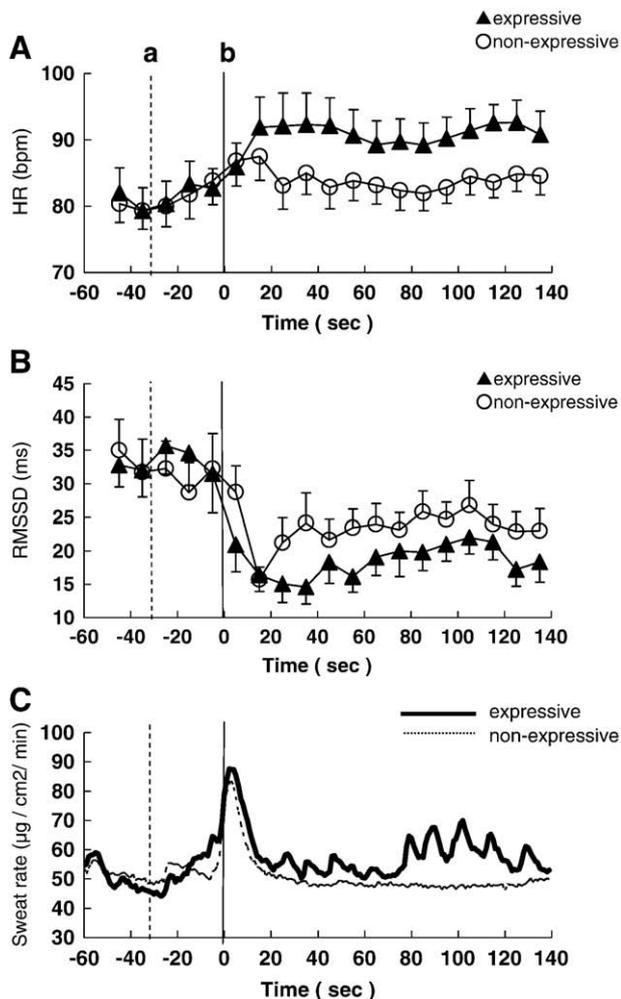
performance. The mean values for the performance period and the results of ANOVA tests for each variable under the conditions examined are presented in Table 1.

HR increased slightly before the onset of performance, and continued to increase for the initial 20-s period of performance in both the expressive and non-expressive conditions. The observed increase in HR was greater and sustained at a higher level during the expressive performance than during the non-expressive performance. The expressive/non-expressive difference in the mean value of HR for all subjects was statistically significant (see “expressive vs. non-expressive” in Table 1).

During the expressive condition, the maximum value of HR occurred at approximately 110–120 s from the beginning of the performance for all subjects. This period of time corresponded to the 28th and 29th bars in the score, and is also coincident with the highest level of perceived emotional response (see the results of “subjective evaluation” above).

RMSSD, an index of parasympathetic nerve activity, decreased rapidly from the onset of performance in both the expressive and non-expressive conditions (Fig. 2B). This decrease was greater for expressive performance than for non-expressive performance, and consequently withdrawal of the vagal tone must also be greater. The lower RMSSD value for the expressive condition, when compared with the non-expressive condition, was maintained throughout the performance period. The difference in the mean values of the RMSSD was statistically significant (Table 1).

Changes in the 1-s mean sweat rate for all subjects are shown in Fig. 2C. For the expressive condition the sweat rate, an index of sympathetic nerve activity, increased slightly following the signal given to subjects 30 s before the beginning of performance (the pre-performance period). Interestingly, immediately after the onset of performance, a strong pulse-like change occurred for both the expressive and non-expressive conditions. Following this response, sweating dropped to a level similar to that of the pre-performance period for both conditions. During the middle of the performance period, sweat production was generally low, but its level was constantly greater for the expressive condition than for the non-expressive condition. During the expressive condition, there were numerous pulse-like bursts of sweating during the latter half of the performance period. This phenomenon did not occur during the non-expressive condition. The highest peak during this period occurred during the time between 110 and 120 s from the onset of performance, and once again corresponded to the period of the performers' highest reported emotions. The mean value of sweat rate for the entire performance period during the expressive performance was significantly higher than for the non-expressive performance (Table 1).



**Fig. 2.** Time histories of mean HR (A), RMSSD (B) and sweating rate (C) during the entire experimental period for the expressive and the non-expressive conditions. The data are the mean values for all subjects. Vertical bars represent the SE values. a: a call for the 30 s before the performance onset, and b: onset of the performance.

### 3.1.4. Respiratory measures

The time histories of mean minute ventilation, tidal volume, and respiratory rate for all subjects are shown in Fig. 3A, B, and C, respectively. The mean values of  $VO_2$ , end-tidal carbon dioxide pressure, minute ventilation, tidal volume, and respiratory rate for all subjects during the performance period are presented in Table 1. ANOVA revealed no significant differences between the expressive and non-expressive conditions for  $VO_2$  and end-tidal carbon dioxide pressure (Table 1).

Minute ventilation started to increase during the pre-performance period in both conditions. Following the start of performance it continued to increase for a short period of time. During the latter half of the performance period minute ventilation reached markedly higher levels in the expressive condition than in the non-expressive condition (Fig. 3A).

Tidal volume increased to some degree during the initial 20 s of expressive performance, subsequently there was a marked increase during the latter half of the performance period (Fig. 3B). In contrast, tidal volume for the non-expressive condition remained relatively constant throughout the performance period. The mean value of this variable along with minute ventilation for the entire expressive performance period was significantly larger than that for the non-expressive performance (Table 1).

Respiratory rate increased during the pre-performance period for both the expressive and non-expressive conditions (Fig. 3C). This increase was more pronounced for the non-expressive condition than for the expressive condition. During the latter half of the performance period respiratory rate clearly decreased for the expressive condition, but not

for the non-expressive condition. The mean value of respiratory rate for the entire performance period was therefore significantly less for the expressive condition than the non-expressive condition (Table 1).

### 3.2. Physical load effect (the expressive-free and expressive conditions)

The effect of ancillary body movements was investigated by comparing the kinematics of both the trunk and the arms during the expressive-free condition and the expressive condition.

#### 3.2.1. Body movements, sound pressure level, and subjective measures

Both of the expressive-free and expressive conditions had a similar mean value of arousal and valence levels (Table 1). This indicated that the subjects could successfully perform the task by retaining similar emotional levels with or without ancillary body movements. The mean sagittal-excision values of the trunk and arm for the expressive/free condition were about 35% larger than those for the expressive condition, and this difference was statistically significant (see the “expressive vs. expressive/free” in Table 1). The mean value of the movement of the trunk in the frontal plane for the expressive/free condition was nominally larger than the mean value for the expressive condition, but the difference was not statistically significant ( $p = 0.055$ ). The mean values of sound pressure levels were quite similar for the two conditions (Table 1).

#### 3.2.2. Autonomic nerve activity and cardio-respiratory measures

Fig. 4A shows the time course of 10-s means of HR for all subjects during the expressive/free and expressive conditions, and Fig. 4B and C show the corresponding mean minute ventilation, and tidal volume. Some increase in these variables was observed before and immediately after the performance onset for the expressive/free condition. During most of the performance period, however, the mean HR and minute ventilation values were similar for both the expressive/free and expressive conditions. The tidal volume, on the other hand, had larger mean values during the latter half of the performance period (Fig. 4C). On the other hand, there was no significant difference between the two conditions for the average tidal volume of the entire performance period (Fig. 4C). The lack of statistical significance may be attributed to the large inter-subject variability (see Table 1). When averaging the tidal volume across the entire performance period, the difference between the two conditions did not reach the level of significance due to the larger inter-subject variability (see Table 1). Respiratory rate was significantly less for the expressive/free condition than for the expressive condition (Table 1). The other measures of autonomic nerve activity and cardio-respiratory had similar mean values for the two conditions (Table 1).

## 4. Discussion

### 4.1. Psychological effects of expressive performance

It was hypothesized that there would be greater emotional effects on the activity of the autonomic nerve system and on cardio-respiratory function during expressive performance than during non-expressive performance. Data analysis revealed that the descriptive indicators of autonomic nerve activity (HR and its variability, and sweat rate), and respiratory function (minute ventilation, tidal volume, and respiratory rate) were significantly influenced by the effects of expressiveness during performance. Conversely, descriptive indicators of metabolic cost (oxygen consumption and end-tidal carbon dioxide tension) were not significantly different under the two conditions. In addition, the magnitude of movements of the trunk and arms was similar during the expressive and non-expressive conditions.

Analysis of RMSSD and sweat rate data indicated that expressive performance was associated with a lower level of parasympathetic activity and a higher level of sympathetic activity than non-expressive performance. Therefore, both sympathetic and parasympathetic functional changes must play a significant role when a pianist chooses to

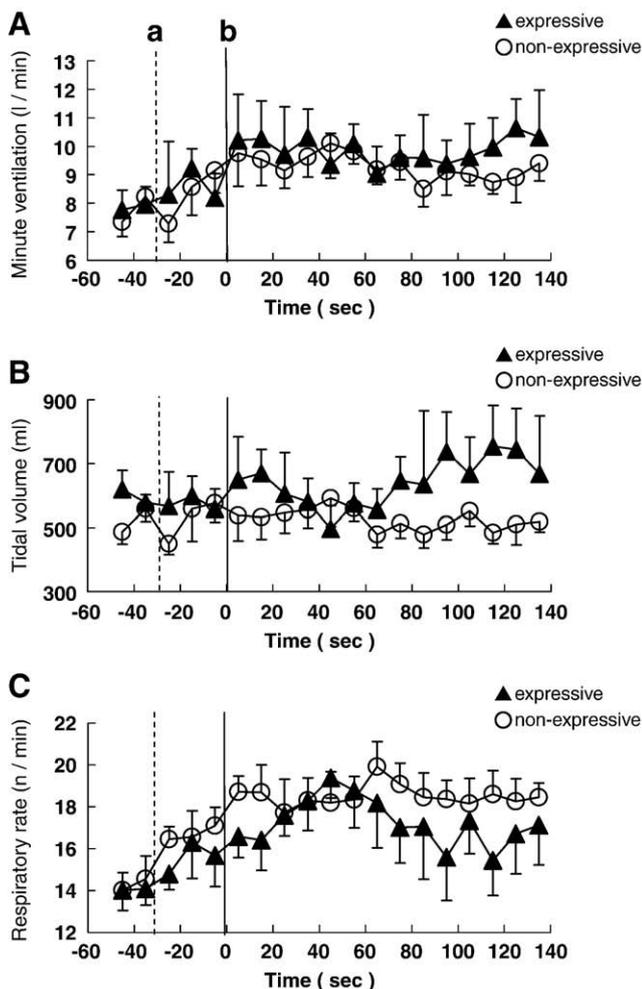


Fig. 3. Time histories of mean minute ventilation (A), tidal volume (B), and respiratory rate (C) during the entire experimental period for the expressive and the non-expressive conditions. The data are the mean values for all subjects. Vertical bars represent the SE values. a: a call for the 30 s before the performance onset, and b: onset of the performance.

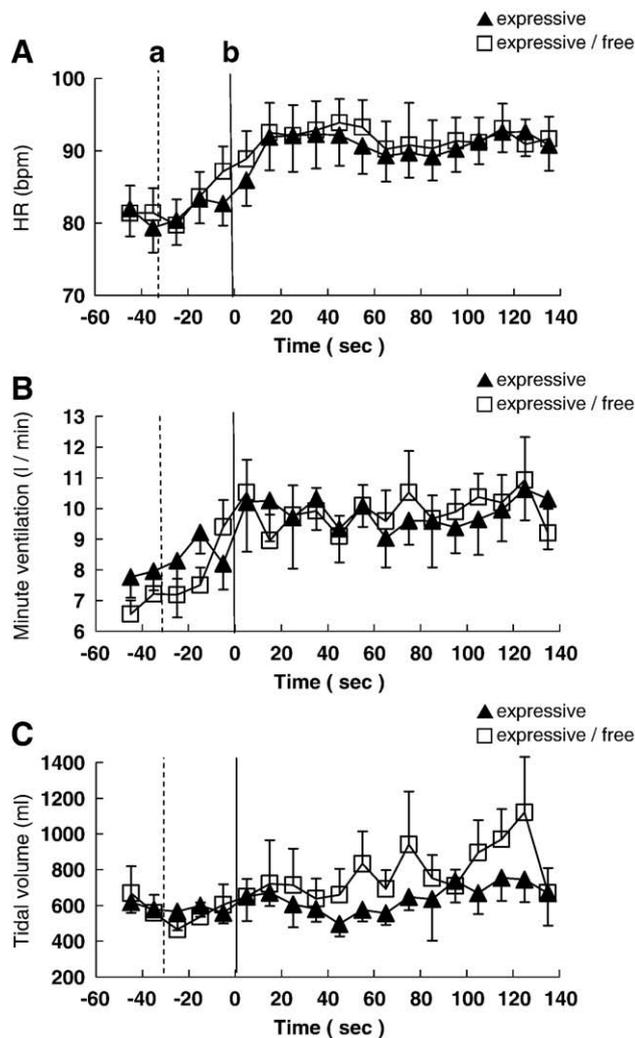


Fig. 4. Time histories of mean HR (A), minute ventilation (B), and tidal volume (C) during the entire experimental period for the expressive/free and the expressive conditions. The data are the mean values for all subjects. Vertical bars represent the SE values. a: a call for the 30 s before the performance onset, and b: onset of the performance.

incorporate expressiveness in his or her performance. This reciprocal modulation in autonomic nerve function appears to be a cause of the higher level of HR with expressive performance when compared with the non-expressive condition, because metabolic cost was very similar under the two conditions. The withdrawal of the vagal tone in response to musical perception, together with an increased level of valence, has also been reported by Iwanaga et al. (2005). Similarly, Khalifa et al. (2002) reported that music providing listeners with happiness and pleasant feelings induced relatively high skin conductance responses and thus greater sympathetic activation. Undoubtedly, central neural command associated with emotions is involved in the autonomic changes that accompany the processing of pleasurable feelings induced by music. Blood and Zatorre (2001) drew attention to the roles of the ventral striatum, midbrain, amygdala, orbitofrontal cortex, and ventral medial prefrontal cortex. These brain areas are known to be active in response to other euphoria-inducing stimuli, such as food, sex, and abused drugs. These authors proposed that music could play an important role in stimulating endogenous reward systems. It is most likely that these neural substrates were related to the higher HR and associated autonomic nerve activity observed during expressive performance in the present investigation.

Comparisons of indicators of respiratory function during non-expressive performance and the resting condition indicated that the motor activity of piano playing brought about increased minute

ventilation, which was due mainly to an increased rate of respiration rather than augmented tidal volume. Conversely, the rate of respiration underwent a notable drop during expressive performance. This was accompanied by increased tidal volume in advance of heightened emotional feelings of the performers, most likely reflecting the volitional nature of the manipulation of respiration for emotion induction (Ley 1994; Bloch et al., 1991). To date, the effect of expressive effort on respiratory variables has received little attention from investigators of the effects of emotions induced during musical performance. The present study appears to be the first attempt to investigate the effect of emotion on selected respiratory variables in a sample of skilled performers playing the same piece of music. Only a few investigations have focused on the control of respiration during musical performance. Reports of previous investigators indicated that minute ventilation increased with an increase in the self-perceived level of arousal (Boiten et al., 1994). These observations are consistent with the findings of the present study. In contrast, the results of studies that examined emotional effects on respiratory rate while listening to music indicated that the respiratory rate increased with an increase in rated valence and arousal (Baumgartner et al., 2006; Etzel et al., 2006; Krumhansl, 1997; Gomez and Danuser 2004). Based on available evidence it appears that respiratory response to emotions may differ for active musical performers and passive listeners. It may be postulated that the decrease in respiratory rate observed during musical performance must have provided the highly trained pianists with an advantageous effect on the expression of emotions or valence induction associated with playing the current music. Denot-Ledunois et al. (1998) have reported that children who engage in a game that requires focus of attention exhibit a notable lower respiratory rate than when they engage in a non-attentive play condition. The authors indicated that the children unconsciously held their breath during their participation in a game that required focus of attention. It can be postulated that the subjects in the present investigation may have lowered respiratory rate in response to the intense concentration required during the demanding conditions involved in expressive musical performance. Whether this phenomenon occurs during the performance of other types of music involving strong emotions needs to be investigated in a future study.

#### 4.2. Physical effects of expressive performance

The Bach's prelude selected for the present investigation is played in arpeggio, that is, notes are played in sequence, rather than overlapping with other notes. Consequently, the music can be played by utilizing movements that are restricted to the distal portions of the upper extremities. However, amplified body movements are commonly observed when skilled pianists play this music with expression. We assessed the extent of ancillary physical movements involved in each task by monitoring accumulated excursions of the trunk and upper arm during the entire performance under each of the conditions examined. Although the subjects were instructed to reduce upper body movements as much as possible during the expressive condition, we observed that the actually trunk and upper-arm movements were 70–90% greater than those observed during the resting state. These movements were periodic in nature, and clearly synchronized with the rhythm of the music. This observation is consistent with reports that rhythm-related body movements of singers are not easily suppressed, even after being instructed to avoid such movements (Sundberg et al., 1995). It is also known that expressive behaviors vary from one performer to the next, and can be linked to the performer's unique interpretation of a particular song (Clarke and Davidson, 1998). Similarly, the trunk movements observed in the present study clearly varied from one subject to the next. Inter-subject variability is immediately apparent from the relatively large magnitude of the SD of trunk excursion. Despite the apparent inability of the subjects to completely suppress body movements, they clearly exhibited significantly larger fore-aft trunk and

upper arm movement during the expressive/free condition than during the expressive condition.

Contrary to our expectation, for the cardio-respiratory variables examined, a significant difference was found only in the respiratory rate, which was decreased rather than increased during expressive performance. As for the mean energy cost of increased muscular activity required for the ancillary movements, the expressive/free condition demanded 15.6 ml/min (6%) greater oxygen consumption than the expressive condition. However, the difference was not statistically significant, which may be attributed to fairly large inter-subject variability. The observed difference in the mean values of oxygen consumption amounts to only 0.1 kcal/min, and thus the physiological effect of ancillary body movements during expressive piano performance may actually vary from one subject to the next.

The mean respiratory rate was less for the expressive/free condition than for the expressive condition. The former condition also tended to have increased tidal volume, which was most evident during the latter half of the performance period (See Fig. 4C). It seems probable that greater body movement facilitates respiratory function, increasing tidal flow during each breathing cycle. This will be accompanied by a corresponding decrease in respiration rate.

The findings overall suggest that ancillary body movements such as trunk sway, and the rhythmic hand movements made by highly skilled pianists do not appear to be directly related to expression and the creation of sounds, but may be used to communicate emotional intentions with the audiences and other musicians. It may also be speculated that kinesthetic mechanisms might provide an additional source of feedback that assists with the maintenance of consistent tempo. In other words, it is conceivable that the rhythmic oscillations of the body may somehow function as a kinesthetic “metronome”. The latter concept is well beyond the scope of the present investigation.

Some limitations of the present study should not be ignored. First, in an effort to bring out the physiological response to motor action associated with habitual piano performance, we did not provide the subjects with any instructions concerning breathing. Consequently, some differences in breathing rate and tidal volume were observed between the conditions. RMSSD, used in this study for the assessment of cardiac vagal outflow, has been shown to be less affected by the respiratory modulation than the high frequency spectral power computed from spectral analysis of HRV (Penttilä et al., 2001). Nevertheless, uncontrolled respiratory rate and depth might have influenced the estimation of cardiac vagal activity. Another limitation of the present study may be the retrospective nature of the subjective measures of valence and arousal. Between each of the conditions, the subjects were allowed to relax in order to return to the cardiovascular steady state and neutral emotional state. However, it is possible that the magnitude of those effects may have been underestimated by memory bias. Finally, the small size of our sample ( $N=9$ ) undoubtedly introduced the probability of type II errors.

#### 4.3. Implications of the present findings

In the results section of the present study, we indicated that the emotional effort of musical performance induced high pleasurable feelings and the top-down regulated psychophysiological responses, independent of metabolic demand. Emotion modulation is commonly employed in the psychotherapeutic use of music to directly evoke emotions, to recall emotional memories, and to learn more flexible emotional responses. Musical perception-induced feelings of intense pleasure correlate with the activation of the reward, motivation, and arousal brain regions and activate emotion-related autonomic responses (Blood and Zatorre, 2001). In particular, musical performance integrating a patient's corporeal expression of emotion and emotional experience has been shown to be more effective in alleviating unpleasant emotional states such as anxiety and depression, than simply listening to the same music. Similarly, Ekman et al.

(1983) reported that producing the emotion-prototypic patterns of facial muscle action resulted in autonomic nervous activity of large magnitude and this activity was more clear-cut than those produced by reliving emotional feelings. According to embodiment theory, emotions and physiological responses are consequences of physical actions. Therefore, appropriate physical actions could potentially have a positive effect on the emotions in the mental health setting. For example, creating music and incorporating whole-body choreographed movements that are associated with joy, confidence and other positive emotions may be used to supplement existing modes of therapy. This concept could be the focus of future research in the area.

The recent discovery of mirror neurons provided another perspective concerning the significance of ancillary body movements during expressive musical performance. Mirror neurons were originally discovered in the visuo-motor areas of the macaque brain by Giacomo Rizzolatti and his colleagues at the University of Parma, Italy (Rizzolatti and Craighero, 2004). These neurons discharge both during the performance of a physical action, and during the observation of another individual performing a similar action (Gallese et al., 1996). Thus, the neurons of the observer mirror the behavior of the other individual, as if the observer was performing the activity. Based on the findings of brain imaging studies it has been suggested that there is a homologous system in humans (Gazzola and Keysers, 2009; Iacoboni et al., 1999). An auditory mirror system, sharing action and hearing, has also been found in animals (Kohler et al. 2002) and humans (Gazzola et al., 2006) Using facial expression of emotions, Jabbi et al. (2007) have further shown that the frontal operculum is active when a person experiences an emotion and also when he or she observes another person experiencing a similar emotion. Their findings suggest that this cortical region together with the visuo-auditory-motor cortical areas contribute to empathy by mapping the bodily feelings of others onto the internal bodily state of the observer. Taken together, an ancillary movement during expressive musical performance may contribute to sharing musically generated emotions as well as physically generated emotions with the audience.

Application of embodiment theory to the results of the present investigation may have implications for music pedagogy. Munoz (2007) concluded that, “To perceive, feel, or understand music, it is crucial to perceive, feel, and understand our body”. She further proposed that, “The basic strategies to teach students how to feel, enjoy, produce, and convince with expressive gestures are usually to initiate them in imitation of gestures in order to develop their own inspiration in their future movements”. To this end she advocates that students should study video recordings of their performances and employ mirror visualization of performances, and to incorporate free and conscious bodily expressions during their practice and performance sessions. These proposals are entirely consistent with the findings of the present investigation. Finally, although only trained musicians were examined in the present study, we believe that the potential effects of musical performance can be extended to the general population. This hypothesis needs to be tested in the future study.

#### Appendix A

The score of the experimental music (the well-tempered Clavier, Vol. I, No.1 written by J.S. Bach) between the 18th to 35th bars, and the bar(s) where the subjects experienced highest pleasant feeling (the horizontal lines). Diminish harmony and the resolution following diminish harmony are known to give the most clear emotional effects. Those measures correspond to the area of bars 21st and 28th. The number above the horizontal lines indicates the number of subjects who reported highest pleasant feeling. All subjects reported highest pleasant feeling at the 28th and 29th bars. Two of nine subjects also reported that a high pleasant feeling was also experienced at the 21st and 22nd.

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## Appendix A.

## References

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