

INFLUENCE OF SOUND AND LIGHT ON HEART RATE VARIABILITY

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The effects of acoustic and visual stimuli and their synergistic effects on heart rate variability including gender differences were investigated. Of particular interest was the influence of visual stimulus on heart rate variability during listening to simple sounds of different characters. Twelve male and 12 female university students were selected as subjects. The subjects listened at rest to 7 different figures of sound at loudness levels averaging 60 dB. Beat-to-beat R-R intervals were continuously recorded under the closed-eye condition (CEC) and the open-eye condition (OEC) prior to, during, and immediately after the exposure to acoustic stimuli. Low frequency (LF) power was defined over 0.04-0.15 Hz and high frequency (HF) power over 0.15-0.40 Hz. Cardiac autonomic function was estimated by plotting LF/HF in standard measure against HF in standard measure and by plotting LF/HF (%) against HF (%), accompanied by a demarcated central area. Values of LF/HF tended to be smaller under CEC than under OEC. Values of HF while listening to a 110 Hz sine wave under CEC were significantly greater than values for 880 Hz and 3520 Hz sine waves, or for 110 Hz or 880 Hz sawtooth waves, under OEC. Under CEC, values of HF for 7 figures of sound were greater in females than in males. The value of HF of sine wave for 110 Hz under CEC and OEC was significantly greater than that for white noise under the OEC. The results suggest that the cardiac parasympathetic nervous activity during auditory excitation increases with elimination of visual stimuli and tends to be greater in females than in males.

Key words: Sounds, Light, Autonomic nervous system, Synesthesia, Gender

INTRODUCTION

Physiological responses to environmental stimuli have been investigated intensively (Seals et al., 1992; Hori, 1995; Ohnuki et al., 2000). Studies concerning the effects of different figures of sound on the autonomic function of human beings are important because music has an effect on emotional excitation or emotional sedation and because harmful acoustic stimuli in daily life, e.g. uncomfortable sounds and city noise, are influencing health. Heart rate at rest is regulated through the activity of the cardiac autonomic nervous system (Baust and Marbaise, 1971; Todd et al., 2002). The excitation in the sympathetic nervous system increases heart rate by enhancing the pacemaker while that in the parasympathetic nervous system decreases it by inhibiting the pacemaker (Shepherd and Vatner, 1996). Resting heart rate variability is affected by changes in the emotional state evoked by acoustic and visual stimuli. It is further indicated that the effects of acoustic stimuli can be modified by visual stimuli, and vice versa (McCraty et al., 1996; Jönsson and Sonnby-Borgström, 2002). Few studies have been reported about synergistic effects of acoustic and visual stimuli on cardiac autonomic activity taking into consideration differences between sounds of sine wave, saw-tooth wave and white noise.

Changes in the cardiac autonomic nervous system can be analyzed by power spectral analysis of

heart rate (Brigham, 1974; Akselrod et al., 1981). We have previously reported that gender has some effect on changes in resting heart rate variability caused by listening to different kinds of music (Hori et al., 2005).

The aim of the present study was to examine the effects of different figures of sound on the cardiac autonomic activity by estimating heart rate variability in resting men and women with a special reference to differentiation by gender and to the consequences of visual stimuli (Kuo et al., 1999).

METHODS

Twelve healthy male university students aged 18-22 and 12 healthy female university students aged 18-22 participated in the study. Experiments were performed after obtaining informed consent. The protocol for this study was approved by the Ethical Review Board of the Hyogo College of Medicine.

Subjects, in the fasting state, sat on a chair at rest in a quiet (below 20dB of background noise level) air-conditioned chamber at temperature of 22~23 °C. The subjects, equipped with headphones, closed their eyes for 5 min prior to exposure to sounds, during which time baseline observations were made. Then they listened to sounds on headphones for two min. The different figures of sound were played at intervals of 90 sec.

The subjects kept their eyes shut throughout the experiment, and listened to 7 different figures of sound, as shown in Table 1. The illumination of the room was set to be an average of 800 lux at the height of the tabletop. Beat-to-beat R-R intervals were continuously recorded using a Polar heart rate monitor 810i™ prior to, during, and immediately after the exposure to sounds. The loudness levels of the sounds averaged 60 dB throughout the experiment. The subjects were given a rest at least for 10 min after the first experiment (Hori et al., 2005). In the subsequent second experiment, they sat on a chair in front of a white wall and kept their eyes open throughout and listened to 7 figures of sound, as shown in Table 1.

Heart rates were calculated as the reciprocal of the R-R interval in sec, multiplied by 60. Power spectrum analysis using a fast Fourier transform was performed. Low-frequency (LF) power and high-frequency (HF) power were defined by the ranges 0.04-0.15 Hz and 0.15-0.40 Hz, respectively. LF and HF powers and the ratio of LF to HF of the R-R intervals were used for statistical comparison. Data were compared using the one-way or two-way analysis of variance (ANOVA) followed by Bonferroni/Dunn post-hoc test. Group differences between the three periods (i.e. prior to, during, and after auditory excitation), differences between different figures of sound and differences between open and closed eye states were compared. Data were expressed as mean \pm SE, and differences confirmed at $p < 0.05$ were considered to be significant.

Table 1. Characteristics of sound stimuli.

Sounds	1	2	3	4	5	6	7
Frequency (Hz)	110	880	3520	110	880	3520	-
Figures of sound	Sin	Sin	Sin	Saw	Saw	Saw	white noise

Conditions before and after listening to sounds were soundless.

Sound at loudness level of 60dB (0.12dyne/cm² at 1000Hz) was used.

Sin: Sine wave, Saw: Sawtooth wave.

RESULTS

The values of LF, LF/HF, and HF for all the subjects under both the closed-eye condition (CEC) and the open-eye condition (OEC), are shown in Fig. 1. There were small differences in the mean values of LF, at all the periods studied. Values of LF/HF under CEC tended to be smaller than those under OEC, and changes in the mean values of LF/HF under OEC tended to be smaller than those under CEC; however, these differences were statistically insignificant. All mean values of HF before and during auditory excitation and after its cessation, under CEC, were greater than those under OEC. Two factors, the sound frequency and the visual stimulus, and their interactions were evaluated by two-way ANOVA. Bonferroni/Dunn post-hoc test also indicated that the mean values of HF before and during exposure to sounds 1, 2, and 3 under CEC were significantly greater (at the 5 % level) than the mean value after sound exposure under the OEC; the mean value of HF for sound 1 under CEC was significantly greater (at the 0.05 level) than those during exposure to sounds 2, 3, 4, 5, and 7 under OEC. The post-hoc test also indicated the mean value of HF for sound 1 under both CEC and OEC was significantly greater than that for white noise under OEC.

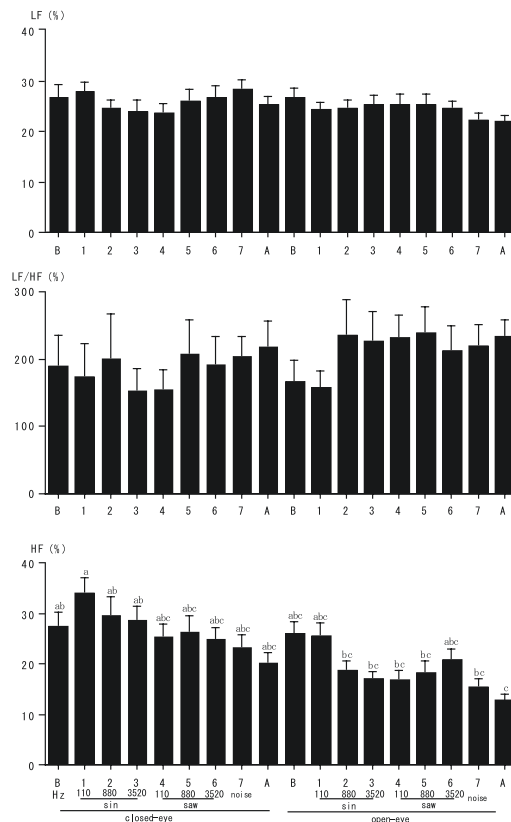


Figure 1. LF (%), ratio of LF/HF (%) and HF (%) in all subjects.

Columns and vertical bars indicate mean values and standard errors, respectively. LF: low frequency; HF: high frequency.

Hz: frequency of sounds; sin: oscillator sounds produced in the form of a sine wave; saw: oscillator sounds produced in the form of a sawtooth wave; noise: white noise; B: before auditory excitation; A: after cessation of auditory excitation. The superscript letters indicate the results of one-way ANOVA followed by multiple comparison of Bonferroni/Dunn (when values share the same letters a, ab, abc they are not significantly different ($p > 0.05$) otherwise they are significantly different ($p < 0.05$)).

The values of LF, LF/HF and HF prior to, during, and immediately after listening to 7 different figures of sound in male and female subjects are shown in Fig. 2. Changes in the mean values of LF prior to, during, and after auditory excitation were small in both male and female subjects. However, changes in mean values of LF/HF were considerably greater than those of LF. Mean values of LF/HF during auditory excitation tended to be greater in male subjects than in female subjects under CEC, and mean values of LF/HF tended to be greater under OEC than under CEC. Under CEC, all the mean values of HF prior to, during, and after cessation of auditory excitation were greater in female subjects than in male subjects. Two way ANOVA and post-hoc test indicated that the mean values of HF were significantly greater in female subjects than in male subjects under CEC. All the mean values of HF during auditory excitation except for sound 6 in male subjects were greater under CEC than under OEC.

Gender differences of HF under OEC were smaller than those under CEC. Mean values of HF after auditory excitation in both male and female subjects were smaller than those before listening under both CEC and OEC. One-way ANOVA and the post-hoc test confirmed that the mean value of HF for sound 1 in female subjects under CEC was significantly greater than after cessation of auditory excitation in both male and female subjects under OEC.

The differences between male and female subjects with regard to cardiac autonomic responses induced by listening to different figures of sound under OEC and CEC were examined in more detail. LF/HF was plotted in standard measure (the ratio of the difference between the mean values of each item and the mean value of the reference level before auditory excitation, under OEC in all subjects, to its standard deviation) against HF in standard measure (Fig. 3).

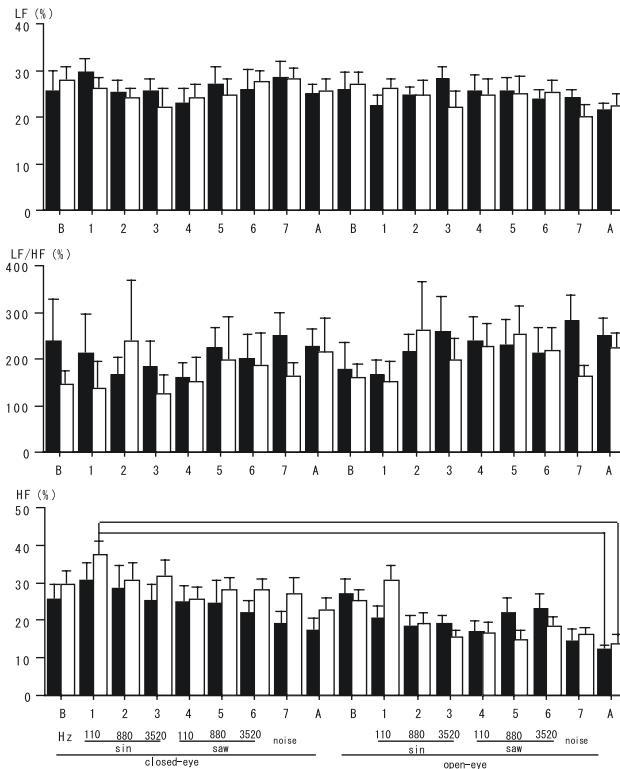


Figure 2. LF (%), ratio of LF/HF (%) and HF (%) in male and female subject. Columns and vertical bars indicate mean values and standard errors, respectively. Abbreviation are as indicated in Fig. 1. Data indicate results of one-way ANOVA followed by multiple comparison of Bonferroni/Dunn. Horizontal lines indicate significant difference ($p < 0.05$).

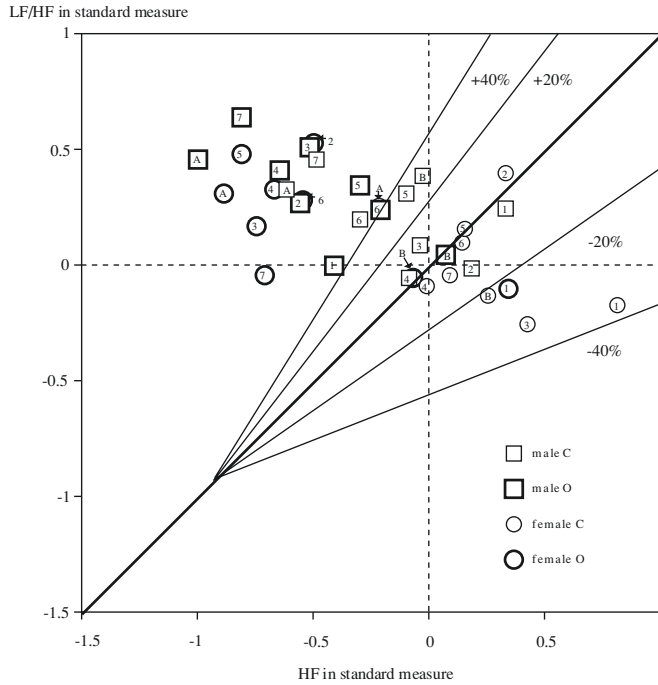


Figure 3. Correlations between LF/HF (%) and HF (%) in male and female subjects. Mean values of LF/HF in standard measure are plotted against those of HF using values of all subjects before auditory excitation under OEC, as a reference. B: Before auditory excitation; A: after cessation of auditory excitation; O: open-eye; C: closed-eye; \square : male C; \blacksquare : male O; \circ : female C; \bullet : female O.
 — Standard line.
 — Isodeviation lines.
 - - - - - Lines indicate zeros of LF/HF (%) and HF (%) in standard measure.

HF in standard measure, x , is calculated by using the actual mean values of HF with the mean (\overline{HF}) and standard deviation (σ_{HF}) of the control measurements (under the open-eye, soundless condition, just prior to auditory excitation):

$$x = \frac{HF - \overline{HF}}{\sigma_{HF}} \quad (1)$$

The equation used in the calculation of LF/HF in standard measure (y) is formula (1) in which LF/HF is used in the place of HF. In this figure, the real line passing the origin is called the standard line and every point on the standard line should be represented by the standard value of LF/HF vs. the value of HF. The standard value of LF/HF (LF/HFs), in a certain group having a HF value of x , in standard measure, is expressed as:

$$LF / HF_s = \sigma_{LF / HF} \cdot x + \overline{LF / HF} \quad (2)$$

where $\sigma_{LF/HF}$ and $\overline{LF/HF}$ are the standard deviation and the mean value of LF/HF for the reference, respectively.

Given a value of LF/HF in standard measure (y), the actual value of LF/HF is expressed as:

$$LF / HF = \sigma_{LF / HF} \cdot y + \overline{LF / HF} \quad (3)$$

The distance of the vertical line between the point (x, y) and the standard line indicates the absolute difference of LF/HF from the standard LF/HF, in standard measure. The degree of excess or diminution of LF/HF may be expressed as a percentage deviation of the actual value of LF/HF from the standard (LF/HFs). This ratio, r, is calculated as follows:

$$r = \frac{\text{LF / HF} - \text{LF / HF}_s}{\text{LF / HF}_s} \quad (4)$$

By calculation and transformation, equation (5) can be obtained from equations (2), (3) and (4):

$$\begin{aligned} y &= \frac{\text{LF/HF} - \overline{\text{LF/HF}}}{\sigma_{\text{LF/HF}}} \\ &= \frac{1}{\sigma_{\text{LF/HF}}} [(1+r)\text{LF/HF}_s - \overline{\text{LF/HF}}] \\ &= (1+r)x + \frac{\overline{\text{LF/HF}}}{\sigma_{\text{LF/HF}}} r \end{aligned} \quad (5)$$

In Fig. 3, the solid straight lines indicate the deviation lines (+40%, +20%, -20%, -40%) of LF/HF and the dotted lines indicate the zeros of LF/HF and HF in standard measure.

Most plots of male subjects tended to be located in the upper-left region while those of female subjects tended to be located in the lower-right region, indicating larger values of LF/HF and smaller values of HF in males compared with those in females. Plots belonging to subjects under OEC were located to the upper-left of plots belonging to those under CEC, in both male and female subjects. This figure also shows that changes in HF in standard measure were greater than those in LF/HF in standard measure. This demonstrates a trend of negative correlation between values of LF/HF in standard measure and those of HF in standard measure.

To estimate the effects of acoustic and visual stimuli on heart rate variability in a simple and convenient way, the mean values of LF/HF (%) for male and female groups under both OEC and CEC were plotted against those of HF (%), in Fig. 4. In this figure, the central square area (C area) was set so as to include about one fourth of the points of all subjects before listening to sounds under OEC.

DISCUSSION

Changes in heart rate variability and in the state of the cardiac autonomic nervous system are relatively small in persons at rest when the environmental stimuli were not changed, although significant changes are observed even in healthy persons during and after exercise (Terziotti et al., 2001; Mouroto et al., 2004). However, significant changes are found in patients with heart disease, thyroid disorders or diabetes even in the resting state (Weise et al., 1988; Macor et al., 1996; Krittayaphong et al., 1997).

In healthy persons, heart rate increases slightly during inspiration and decreases slightly during expiration (Huikuri et al., 1990; Kollai and Mizsei, 1990; Bloomfield et al., 2001). No significant changes in respiratory rate have been observed before, during and after auditory excitation (Oishi et al., 1999; Hori et al., 2005).

It is known that considerable changes in heart rate variability are usually observed in accordance with emotional excitement or emotional sedation caused by listening to sounds (Nattiez, 1987; Umemura and Honda, 1998; Valentine and Evans, 2001). Different orders of acoustic stimuli could cause some effects on emotional changes evoked by listening to different figures of sounds.

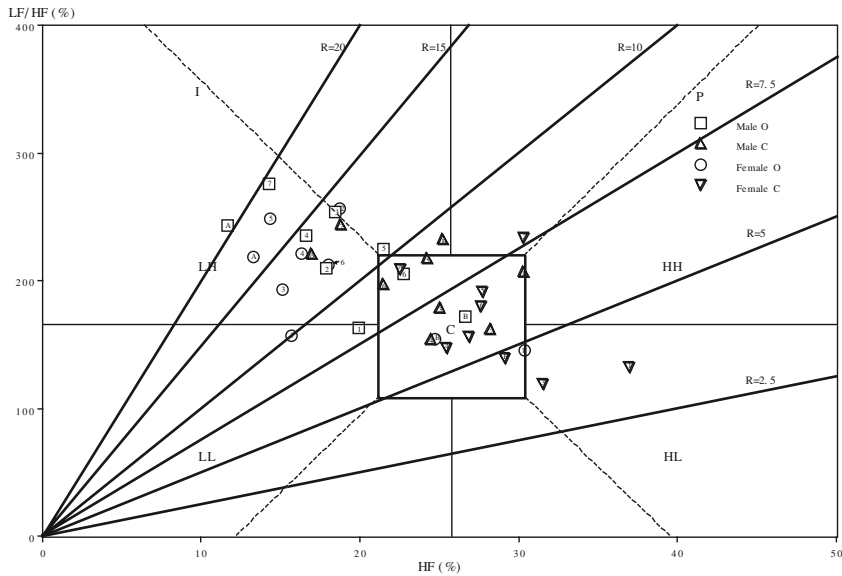


Figure 4. Correlations between LF/HF (%), HF (%), and values of parameter R. Mean values of LF/HF (%) are plotted against those of HF (%). Values in all subjects before listening to sounds under the OEC were used as a reference.

Figures in squares, triangles, circles, and inverted triangles indicate the different figures of sounds (Table 1).

R: parameter R, the ratio of values of LF/HF to those of HF;

B: before auditory excitation; A: after cessation of auditory excitation; O: open-eye;

C: closed-eye; \square : male O; \triangle : male C; \circ : female O; ∇ : female C.

— Lines of constant R

— Lines indicating mean values of LF/HF (%) and HF (%) of all subjects before auditory excitation.

----- P: Line passing through the points
 $(\overline{HF} - 0.319\sigma_{HF}, \overline{LF/HF} - 0.319\sigma_{LF/HF})$,
 $(\overline{HF} + 0.319\sigma_{HF}, \overline{LF/HF} + 0.319\sigma_{LF/HF})$

----- I: Line passing through the points
 $(\overline{HF} - 0.319\sigma_{HF}, \overline{LF/HF} + 0.319\sigma_{LF/HF})$,
 $(\overline{HF} + 0.319\sigma_{HF}, \overline{LF/HF} - 0.319\sigma_{LF/HF})$.

C area: enclosed by two vertical lines and two horizontal lines passing through four points corresponding to the means ± 0.319 standard deviations

LL area: Low HF, low LF/HF. LH area: Low HF, high LF/HF.

HL area: High HF, low LF/HF. HH area: High HF, high LF/HF.

Emotional excitation or emotional sedation caused by listening to sound of 60 dB is supposed to be small in the present experiment. Therefore, it is expected that almost all of the subjects practically recovered from changes in emotional state due to acoustic stimuli within 90 sec after cessation of auditory excitation (Hori et al., 2005). However, further investigation is required to determine to what extent different order of acoustic stimuli affects or interacts with the heart rate variability caused by listening to sounds.

Heart rate variability is affected by changes in the activity of the cardiac sympathetic nerves and parasympathetic nerves; therefore, non-invasive assessment of the state of the cardiac autonomic nervous system can be made by the analysis of heart rate variability (Akselrod et al., 1981; Eckberg 1997; Aubert et al., 2001). All sounds used in the present experiment had approximately the same loudness (60 dB). Each sawtooth sound wave was composed of a wave with the primary frequency,

which determined the pitch of the sound, and a harmonic vibration, which gave the sound its quality or timbre. Each sinusoidal sound wave consisted of only a pure tone at the primary (fundamental) frequency with no harmonic vibrations.

The value of HF during listening to sound of sine wave at 110 Hz under CEC and OEC was significantly greater than that of white noise under OEC. Under CEC, differences in values of HF during listening to sounds are supposed to be caused by acoustic stimuli only. Considerably greater mean values of HF resulting from a sine wave stimulus over a sawtooth wave stimulus under CEC were observed. These differences may have arisen from the difference in the components of these sounds, the pure tone of the sine wave versus the overtones included in the sawtooth wave and white noise including many sounds of different frequencies.

The sound of the sawtooth wave with a lower pitch has more harmonic vibrations (overtones) than does one with a higher pitch because the maximum sound frequency audible to humans is 20,000 Hz. Among the sawtooth waves, those at 110 Hz had the most overtones while those at 3520 Hz had the fewest. The audible threshold of the human ear varies with the frequency of sound. Among the three different fundamental tones used in the present experiment, sounds at 110 Hz exhibit the smallest sensitivity and those at 3520 Hz the greatest, at a loudness level of 60 dB (Ganong, 2003).

As shown in Fig. 1, all the mean values of HF prior to, during and after auditory excitation under CEC, in all subjects, were greater than those under OEC. In particular, the mean value of HF during auditory excitation by the 110 Hz sine wave under CEC was significantly greater (at the 5 % level) than the mean values for certain sounds during and after cessation of auditory excitation under OEC. This difference may have been caused by the synergistic effects of the lowest frequency, the pure tone, the smallest sensitivity to sound at 110 Hz, and the lack of visual stimulus. The mean values of HF before auditory excitation and while listening to an 880 Hz or 3520 Hz sine wave under CEC were also significantly greater than mean value after cessation under OEC.

Under CEC, female subjects showed greater mean values of HF than male subjects (Fig. 3). Difference between mean value of HF for sound 1 under CEC and that after cessation of auditory excitation under OEC was statistically significant (at 5% level) in female subjects and this difference in male subjects was not statistically significant (Fig.2). These results suggest that the values of HF, corresponding to parasympathetic nervous activity, increase with the disappearance of visual stimulus, especially in female subjects.

Figure 3 shows that changes in HF caused by listening to sounds in standard measure were greater than those in LF/HF, mainly sympathetic nervous activity, and that trends of negative correlation existed between the values of HF and LF/HF. This meant that changes in the direction of the activities of both nervous systems were reversed. These results indicate that auditory excitation evokes greater changes in parasympathetic nervous activity than in sympathetic nervous activity, and that increases in the former tend to be accompanied by decreases in the latter.

The cardiac autonomic nervous system, the sympathetic nervous system and the parasympathetic nervous system, tonically influence the cardiac pacemaker. The sympathetic nervous system enhances automaticity of the pacemaker whereas the parasympathetic system inhibits it, and changes in heart rate usually involve reciprocal action of sympathetic and parasympathetic nerves (Bern and Levy, 2000).

Changes in automaticity of the pacemaker caused by increased activity of the parasympathetic nerves are rapid due to quick activation of special acetylcholine-regulated K^+ channels in the cardiac cells, and decay of the cardiac response is quick due to rapid hydrolyzation of acetylcholine. The cardiac response to increased sympathetic nervous activity is much slower than the response to increased parasympathetic nervous activity due to a delayed release of noradrenaline and to mediation via a slow second messenger system. Thus changes in the activity of the parasympathetic nervous system can alter heart rate much more rapidly exerting the beat-by-beat control of heart rate compared with the cardiac sympathetic nervous system (Bern and Levy, 2000). It is reported that women had higher values of HF, whereas men had higher values of LF/HF (Kuo et al, 1999) and this gender

difference could be caused by higher plasma concentrations of estrogen in women (Liu et al., 2003). Under CEC in the present experiment, female subjects exhibited greater mean values of HF (Fig. 2) and smaller values of the parameter R with the exception of sound 2 during auditory excitation (Fig. 4). Two-way ANOVA and the post-hoc test also indicated that the females showed significantly greater mean values of HF than males under CEC (Fig.2)]

These results coincide with the results that female subjects usually showed greater mean values of HF and smaller mean values of LF/HF than male subjects when subjects sat in a chair at rest with the closed eyes and listened to 8 kind of music (Hori et al., 2005). Data obtained in the present experiment may indicate that females at rest can control their heart rate more rapidly in response to acoustic stimuli in the absence of visual stimulus than males can.

Decreases in the mean values of HF after auditory excitation in both CEC and OEC suggest that the cessation of acoustic stimuli induces a decrease in the activity of the cardiac parasympathetic nerve, regardless of visual stimuli.

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