# Influence of music emotional valence on cardio-respiratory coupling

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## Abstract

*The effect of the emotional valence of music on the dynamic interactions between respiration and heart rate is explored. Time-frequency coherence and phase difference analysis by smoothed pseudo Wigner-Ville distribution was used to characterize the cardio-respiratory coupling in 58 healthy subjects listening to short pleasant and unpleasant excerpts. Respiratory rate increased during the listening of acoustic stimuli, being higher during the listening of pleasant (0.33±0.08 Hz) than unpleasant (0.31±0.08 Hz) music, and decreased during silence (0.25±0.07 Hz). Coherence between respiration and heart rate variability was high during all the different conditions (0.98±0.03). A decrease in coherence was observed in the intervals in between two conditions, probably due to the expectation of the next stimulus and an evaluation task required to the subjects. Phase difference analysis showed that the latency between a change in respiration and a correlated change in heart rate was stable and short.*

**Keywords** *Respiratory sinus arrhythmia, time-frequency analysis, coherence analysis, phase difference analysis*

## 1 Introduction

The use of music for therapeutic purposes or, more generally, for improving our well-being is a matter of increasing interest. Music provokes changes in the autonomic modulation of the heart rate and respiration [1, 2], and the interest in the characterization of the influence that different kinds of music have on the activity of the autonomic nervous system is increasing. In a previous work, we analyzed the pattern of response of the respiratory rate and heart rate variability (HRV) indices (instantaneous frequency and power of LF and HF spectral components) during the listening of music characterized by different emotional valence (pleasant and unpleasant music) [2]. We observed that with respect to silence, music provoked significant changes in almost all the analyzed indices, and that pleasant and unpleasant music provoked a different response in the respiratory rate, in the heart rate and in the power of the HF component of the HRV. In this study, we use the same data-set to characterize the changes that pleasant and unpleasant music provokes in the cardiorespiratory coupling. The dynamic interactions between HRV and respiration are quantified by time-frequency coherence and phase difference analysis based on the smoothed pseudo Wigner-Ville (SPWVD) distribution [3, 4].

## 2 Methods

### 2.1 Experimental setting

The experimental setting is detailed in [2]. Briefly, 58 healthy subjects participated in an experiment designed to characterize the effects of acoustic stimuli with different emotional valence. During the experiment, four conditions were employed:

*Pleasant condition* ($P$): Six excerpts of joyful instrumental dance-tunes from the last four centuries were used as pleasant stimuli (all major-minor tonal music, each had a duration of 90 s).

*Unpleasant condition* ($U$): Six unpleasant stimuli were electronically manipulated counterparts of six musical pieces from the last four centuries (all major-minor tonal music with rather minor scales and slow tempo). For any of these stimuli, a new soundfile was created in which the original excerpt was recorded simultaneously with two pitch-shifted versions (one being one semitone above and the other a tritone below the original pitch), and subsequently recorded backwards in order to introduce many dissonant structures. To match the rhytmic structure of these stimuli with the metre of the original pleasant ones, series of Shepard tones were overlaid over the manipulated (unpleasant) musical excerpts. The time interval between Shepard tones was chosen to match the tempo of the pleasant excerpts.

*Sequence of Shepard Tones* ($X$): Shepard tones were presented separately, i.e. without music, as control for the unpleasant stimuli. The purpose was to assess whether Shepard tones alone provoked the same effect as the more complex and dissonant unpleasant excerpts. The particular structure of the sequence creates the auditory illusion of a tone that continually ascends or descends in pitch, yet which ultimately seems to get no higher or lower. The time interval between tones was chosen to match the tempo of pleasant and unpleasant excerpts and six sequences were used.

*Resting condition* ($R$): In addition to these three stimu-

lus categories, there were also six resting intervals of 90 s duration in which no acoustic stimulus was presented.
All stimuli were matched for volume and tempo, in order to keep the arousal as constant as possible. Each stimulus began with a start-signal-tone, and ended with an end-signal-tone. For the resting condition, after the start-signal-tone, trials were indicated by a new 100 ms, 400 Hz sine wave tone. Stimuli were presented to every subject in the same pseudo-randomized sequence, designed so that each experimental condition followed all other conditions with equal probability. After the end-signal-tone of each trial, participants had to indicate how pleasant or unpleasant they felt at the end of the trial by pressing response buttons. The rating task was followed by a 10 s pause until the next start-signal-tone appeared. Participants were instructed to listen carefully to the auditory stimuli with eyes closed, and to tap the metre of the stimuli with their right index finger. This task was employed to control whether listeners paid attention not only to the pleasant but also to the unpleasant music and to the single tones sequence. No tapping was required during the resting condition.

## 2.2 Data acquisition

Standard 12 leads electrocardiograms were measured using a 32 MREFA amplifier (Twente Medical Systems, Enschede, Netherlands) and digitized with a sampling rate of 1000 Hz. The recorded ECG signal was processed to derive the HRV signal. After the detection of the QRS complexes, the instantaneous heart rate was derived by integral pulse frequency modulation (IPFM) model, which also accounts for the presence of ectopic beats [2, 5], and then evenly resampled at 4 Hz, using spline interpolation. This results in a continuous representation of the heart rate, in which any heart period $(t_{\text{n}} - t_{\text{n-1}})$ results to be approximately assigned to $(t_{\text{n}} + t_{\text{n-1}})/2$. The HRV signal was then obtained by filtering the heart rate with a high-pass filter with a cut-off frequency of $0.03$ Hz.
The respiratory signal was recorded by means of a respiratory belt, a strain gauge transducer with a sampling rate of 1000 Hz, and subsequently resampled at 4 Hz.

## 2.3 Methodology

Auto and cross TF spectra, $S_{\text{xy}}(t,f)$, of HRV signal, $x(t)$, and respiratory signal, $y(t)$, are estimated by SP-WVD, as [3]:

$$S_{\text{xy}}(t,f) = \iint_{-\infty}^{+\infty} \phi_{\text{d-D}}(\tau,\nu) A_{\text{xy}}(\tau,\nu) e^{j2\pi(t\nu-\tau f)} d\nu d\tau \tag{1}$$

$$A_{\text{xy}}(\tau,\nu) = \int_{-\infty}^{\infty} x\left(t+\frac{\tau}{2}\right) y^*\left(t-\frac{\tau}{2}\right) e^{-j2\pi\nu t} dt \tag{2}$$

$$\phi_{\text{d-D}}(\tau,\nu) = \exp\left\{-\pi\left[\left(\frac{\nu}{\nu_0}\right)^2 + \left(\frac{\tau}{\tau_0}\right)^2\right]^{2\lambda}\right\} \tag{3}$$

Time and frequency resolutions are estimated as the full width at half maximum of $\phi_{\text{t-f}}(t,f)_{|f=0}$, $\Delta_{\text{t}}$, and $\phi_{\text{t-f}}(t,f)_{|t=0}$, $\Delta_{\text{f}}$, where $\phi_{\text{t-f}}(t,f)$ is the double Fourier transform of $\phi_{\text{d-D}}(\tau,\nu)$. The kernel parameters were chosen to give a TF resolution $(\Delta_{\text{t}}, \Delta_{\text{f}}) = (10.9\text{s}, 0.039\text{Hz})$. Time-frequency coherence, $\gamma(t,f)$, and TF phase difference spectrum, $\theta(t,f)$, are estimated as [3, 4]:

$$\gamma(t,f) = \frac{|S_{\text{xy}}(t,f)|}{\sqrt{S_{\text{xx}}(t,f) S_{\text{yy}}(t,f)}};\ \ \gamma(t,f) \in [0,1] \tag{4}$$

$$\theta(t,f) = \arctan\left[\frac{\Im\big[S_{\text{xy}}(t,f)\big]}{\Re\big[S_{\text{xy}}(t,f)\big]}\right];\ \theta(t,f) \in [-\pi,\pi] \tag{5}$$

The degree of TF filtering given by the kernel was sufficient to provide coherence estimates which range between 0 and 1 in the entire TF domain. The region where coherence estimates are statistically significant is defined as:

$$\Omega \equiv \left\{(t,f) \in (\mathbb{R}^+ \times B)\ \big| \{\gamma(t,f) > \gamma_{\text{TH}}(t,f)\right\}; \tag{6}$$

where $B \in [0.15, 0.5]$ Hz is the respiratory band, and $\gamma_{\text{TH}}(t,f)$ is a threshold function which depends on the TF resolution of the distributions used to estimate the TF coherence [3].
To estimate the time course of coherence and phase differences, specific time-varying spectral bands are localized. Coherence is estimated in a spectral band centered around the instantaneous frequency of a spectral peak in the cross time-frequency spectrum, $f_{\text{xy}}(t)$:

$$\Omega^{(\gamma)} \equiv \left\{(t,f) \in (\mathbb{R}^+ \times B)\ \big|\ f = f_{\text{xy}}(t) \pm \frac{\Delta_{\text{f}}}{2}\right\} \tag{7}$$

$$f_{\text{xy}}(t) = \arg\max_{f\in B} |S_{\text{xy}}(t,f)| \tag{8}$$

Note that $f_{\text{xy}}(t)$ is strictly related to the respiratory rate. Phase difference is estimated in a spectral band centered around $f_{\text{xy}}(t)$ and where coherence is significant:

$$\Omega^{(\theta)} \equiv \left\{\Omega^{(\gamma)} \cap \Omega\right\} \circ R(t,f); \tag{9}$$

In this expression, $R(t,f)$ is a rectangle of sides $2\text{s} \times \frac{\Delta_{\text{f}}}{2}$ Hz and $\circ$ denotes the opening (processing technique which involves erosion and dilation). The opening excludes from $\{\Omega^{(\gamma)} \cap \Omega\}$ the portions of TF domain which are smaller than $R(t,f)$, thus adding robustness to the final estimates.
Coherence $\gamma(t)$, phase difference $\theta(t)$ and time delay $\mathcal{D}(t)$ indices are estimated as [4]:

$$\gamma(t) = \frac{1}{\Delta_{\text{f}}} \int_{\Omega^{(\gamma)}} \gamma(t,f) df \tag{10}$$

$$\theta(t) = \left[\int_{\Omega^{(\theta)}} \theta(t,f) df\right] \Big/ \left[\int_{\Omega^{(\theta)}} df\right] \tag{11}$$

$$\mathcal{D}(t) = \frac{\theta(t)}{2\pi f_{\text{xy}}(t)} \tag{12}$$

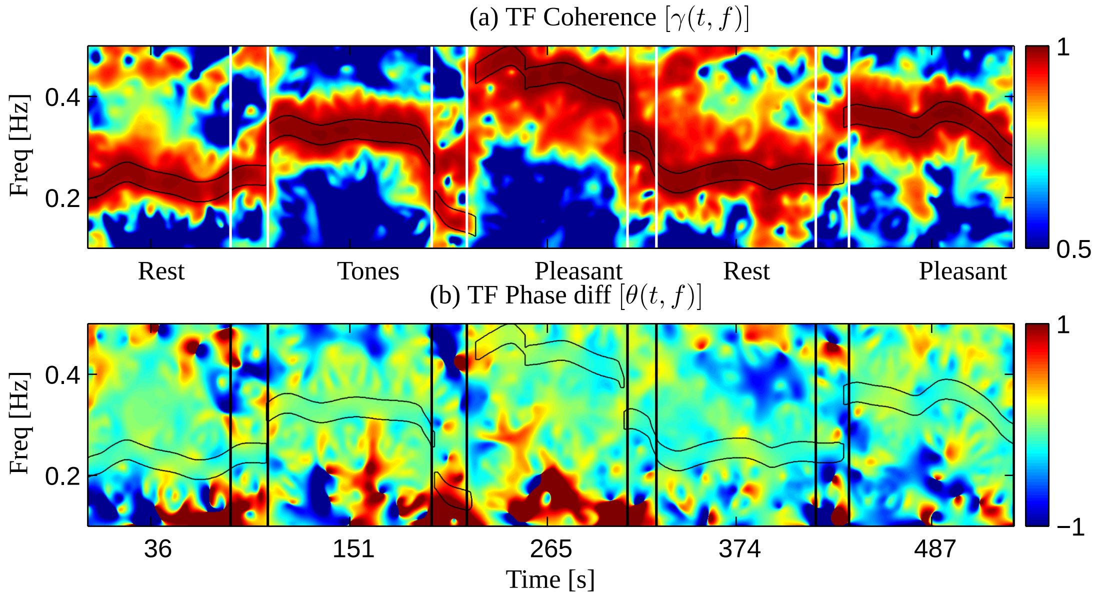


Figure 1: Example of (a) TF coherence, and (b) TF phase difference representations during the listening of 5 conditions. Black contours encircle $\Omega^{(\gamma)}$ in (a), and $\Omega^{(\theta)}$ in (b).

# 3 Results

A representative example of TF coherence and phase difference representations is shown in Fig. 1. From visual inspection of $\gamma(t, f)$ and $\theta(t, f)$ it is clear that some specific spectral bands are needed to extract robust and accurate estimates. These time-varying spectral bands, $\Omega^{(\gamma)}$ in (a), and $\Omega^{(\theta)}$ in (b), are encircled by black contour. The instantaneous frequency $f_{xy}(t)$, which is strictly related to the respiratory rate, was characterized by a remarkably high inter-condition variability, i.e. $f_{xy}(t)$ changed abruptly at the beginning of a new condition, and also by intra-condition variability, i.e. $f_{xy}(t)$ changed during each condition. Despite these changes, $\gamma(t, f)$ was always high insight $\Omega^{(\gamma)}$, and $\theta(t, f)$ was always close to zero insight $\Omega^{(\theta)}$.

The median time course of the indices during each condition is shown in Fig. 2. These results were obtained as the median between 348 realizations (each condition was repeated 6 times for every subject). It is shown that every condition provoked changes in indices $f_{xy}(t)$ and $\gamma(t)$ that were characterized by two phases: a short period of about 20 s in which changes are fast, and a later longer period in which indices were almost stable. Table 1 shows the median value (med) and interquartile range (iq), estimated among the realizations, of the temporal median of each index during the later period, $t \in [20, 90]$ s. Musical stimuli provoked an increase in $f_{xy}(t)$, which was more evident during the listening to pleasant music (med±iq = 0.33±0.08 Hz) than during listening of unpleasant stimuli (0.31±0.08 Hz) or tones (0.30±0.07 Hz), while silence decreased $f_{xy}(t)$ (0.25±0.07 Hz). The differences between these indices, whose median time courses were clearly separated, show that music strongly affects the respiratory rate [2]. The time course of coherence, shown in panel (b), was similar during all the conditions. It decreased during the intervals in between two conditions and increased afterward regardless of the condition (med±iq = 0.98±0.02). Phase difference and time delay, shown in panels (c) and (d), did not change during the different conditions, neither in the intervals in between two conditions. The inter-stimuli variability of the phase difference was characterized by an interquartile range of about 0.5 rad. This low variability (iq<8% of the total range $2\pi$) shows that there is a strict coordination between respiration and heart rate.

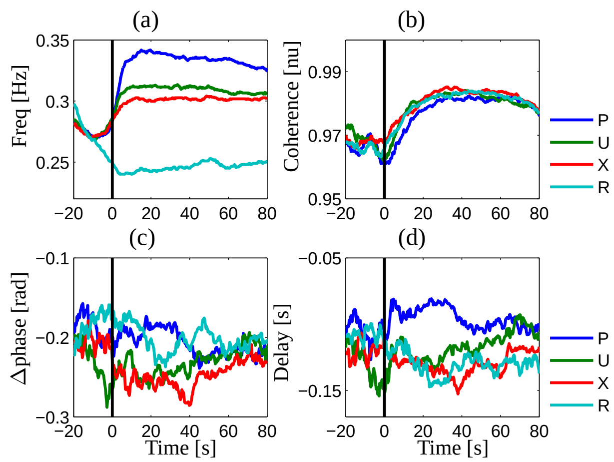


Figure 2: Median trends of the indices of synchronizations. (a): Instantaneous frequency of the cross SPWVD, $f_{xy}(t)$. (b): Band coherence $\gamma(t)$. (c): Phase differences $\theta(t)$. (d): Time delay $\mathcal{D}(t)$. Conditions are: pleasant ($P$), unpleasant ($U$), sequence of tones ($X$) and rest ($R$).

## 3.1 Discussion

It is well known that an oscillation synchronous with the respiratory rate is present in the heart rate. This phenomenon is called respiratory sinus arrhythmia, and it has both clinical and physiological relevance [6, 7]. In this study, we characterized the dynamic interactions between the heart rate variability and the respiratory signal by cross time-frequency analysis. This methodology is based on the SPWVD and has been shown to be particularly suited for the analysis of non-stationary signals [3, 4]. In this study, we were able to continuously quantify the strength and the degree of synchronization of the cardio-respiratory coupling, while heart rate and respiratory frequency were changing fast.

The results show that the HF component of the HRV signal was highly coupled to the respiratory activity. The local coupling, quantified by coherence estimates, was high even when the respiratory rate changed quickly, as at the beginning of any condition, and when the power of the HF component of the HRV was low, as during the listening to pleasant music [2]. A lower coherence level, observed during the interval in between two conditions, cannot be explained as an effect of the music, since the same pattern was observed also during resting condition. A decrease of the strength of the local coupling after and before each condition is likely due to the increase in the power of the LF component observed during these short periods [2]. One can speculate that during the interval in between two consecutive stimuli, the task of rating the previous musical stimulus and the expectation of the next one could both increase the sympathetic and reduce the parasympathetic activity. This may imply a reduction of the coupling around the respiratory frequency.

Given that phase difference estimates were negative, and given that respiration and heart rate are in phase (an increase of the respiratory signal, i.e. an inspiration, is associated to an increase in the heart rate), the results confirmed that respiration leads the HF component of the HRV signal. Respiration was persistently reflected in the heart rate with a short delay, of about 0.1 s, which is not affected by the different conditions. However, it is worth noting that phase difference and time delay strongly depend on the methodology used to represent the HRV signal [4], specifically on the temporal instant at which any heart period is assigned. With respect to a classical representation of the heart rate, in which the heart period $(t_n - t_{n-1})$ is located at $t_n$, our representation anticipates the heart rate of about half heart period. This should be taken into account when the characteristic time delay of the respiratory sinus arrhythmia is estimated by cross spectral analysis [7].

In conclusion, we observed that respiratory rate was higher during the listening of pleasant than unpleasant music, and decreased during silence. Coherence between respiration and HRV decreased in the intervals in between two conditions, probably due to the expectation of the next stimulus and an evaluation task required to the subjects. Phase difference analysis showed that the latency between a change in respiration and a correlated change in HR was stable and short.

| | $f_{xy}(t)$ [Hz] | $\gamma(t)$ [nu] | $\theta(t)$ [rad] | $\mathcal{D}(t)$ [s] |
|---|---|---|---|---|
| P | 0.33± 0.08 | 0.98±0.03 | -0.21±0.50 | -0.10±0.25 |
| U | 0.31± 0.08 | 0.98±0.02 | -0.22±0.53 | -0.11±0.27 |
| X | 0.30± 0.07 | 0.98±0.02 | -0.24±0.45 | -0.13±0.25 |
| R | 0.25± 0.07 | 0.98±0.03 | -0.21±0.52 | -0.13±0.34 |

Table 1: Global results during $t \in [20-90]$ s. Results are given as the median±interquartile range of the temporal median of the time course of each index


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