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Event-related brain potentials and the processing of cardiac activity

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Abstract

The cortical processing of cardiac afferent input can be studied by means of event-related potentials (ERP), in which characteristic brain waves are seen to accompany rhythmic activity of the heart. In the present paper, results from three studies, investigating the heartbeat-evoked potential are summarized. These studies demonstrated that (a) cardio-afferent input is projected primarily to fronto-cortical areas; (b) typically, this activity is reflected as a broad positive wave form in a range of 300–600 ms after the EKG R-wave; (c) psychological factors such as level of attention and motivation exert influences on the heartbeat-evoked potential which are comparable to effects known from exteroceptive evoked potentials. On the basis of these data we infer that cardioafferent input is for the most part transmitted along visceral fibers and that the cortical processing of cardiac activity is similar to the processing of external stimuli.

Keywords: Evoked potentials; Cardiac activity; Cardiac afferents

1. Introduction

The afferent pathways of most visceral systems are composed of at least as many fibres as there are efferent connections (e.g., Leek, 1972). In some visceral nerves, like the abdominal vagus nerve up to 90% of the fibers are afferent (cf. Andrews, 1986). From animal studies we know that a variety of brain regions is involved in the processing of viscero-afferent information (e.g. hypothalamic and thalamic

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nuclei, amygdalae, hippocampus, cerebellum, somatosensory cortex, prefrontal cortex, and insula; see overview in Montoya, 1994).

Event-related potentials are an important tool for the investigation of information processing with regard to sensory physiology as well as to perceptive and cognitive processes. For instance, evoked-response methodology can yield information regarding afferent fibers and cortical projection areas. Furthermore, the influence of psychological processes such as attention, motivation, and perceptual accuracy can be assessed.

Until recently only very few studies have been concerned with event-related brain activity evoked by internal events. One reason for this lack of empirical results may be methodological peculiarities: If the event that elicits the brain activity is a naturally occurring bodily process, neither stimulus intensity, nor time of occurrence can be predetermined or easily varied. That means, the methodology employed in studies with external stimuli may be only minimally applicable.

Adám (1967) was the first to report results on cortical responses to visceral stimuli. He could demonstrate in humans a cortical α-blocking response to balloon distension of the duodenum. Event-related potentials in response to electrical or mechanical stimulation of the urogenital system in humans have been reported several times (Badr et al. 1982, 1984; Haldeman et al., 1982; Sarica et al., 1986; Vodusek, 1990; Loening-Baucke et al., 1991). The aim of these studies was primarily to investigate nerve conduction processes along afferent fibers in neurological patients. Generally, in these studies the most prominent peak was a negative shift with a latency of about 100 ms and an amplitude ranging from 0.5 to 8 μV. In almost all cases, the maximum of electrical brain activity was observed at centrally located electrodes.

Investigation of the heartbeat as a source of visceroceptive EPs was for the first time reported in 1986 by two groups of researchers. Schandry, Sparrer and Weitkunat (1986) published a study on heartbeat evoked potentials (HEP), where they were able to demonstrate that direction of attention (that directed towards heartbeats vs. that directed toward external events) and cardiac awareness both had an effect on the HEP. The wave form was analysed by principal component analysis yielding most prominent effects at the frontal electrode (Fz) in the time range 250 to 450 ms post-R-wave. Jones, Leonberger, Rouse, Caldwell, and Jones (1986) published an abstract where they reported that subjects who showed a higher cardiac awareness produced HEP amplitudes which were more positive in the time range from 250 to 450 ms than low cardiac awareness subjects. Recently, Riordan, Squires, and Brener (1990) also examined the HEPs of a group of good cardiac perceivers. They found that a positive shift (0.25–1.5 μv) occurred around 120–160 ms post-R-wave. The peak was largest over the right anterior portion of the scalp.

In the following, we shall present results from our laboratory pertaining to three rather fundamental questions: (a) What is the topography and morphology of the HEP? (b) Is it possible to demonstrate a relationship between cardiodynamic function and HEP amplitudes? (c) Is the influence of some psychological factors on the HEP similar to those known from exteroceptive evoked potentials?

2. Topography and morphology of the HEP

We conducted a study (cf. Montoya, Schandry and Müller, 1993) where brain electrical responses to the cortical processing of the heartbeat signal were investigated in a multi-electrode arrangement. Twenty-eight healthy subjects, 11 female and 17 male, aged 20 to 43 years (M = 26.8 years, S.D. = 5.4), participated in this experiment. During the main part of the session, EEG sweeps (time-locked to the R-wave of the EKG) were recorded either while subjects were distracted from internal sensations by being requested to attend to a series of random tones (Standard condition) or with subjects' attention focused on his or her heartbeats (Attention condition). Ten Attention runs alternated with ten Standard runs; each run lasted for 100 heartbeats.

Electrical brain activity was recorded at 19 scalp locations (Fz, F3, F4, F7, F8, Fp1, Fp2, Cz, C3, C4, T3, T4, Pz, P3, P4, T5, T6, O1 and O2). An electrooculogram (EOG) was also registered. One additional electrode was placed on the tip of the nose (serving as reference signal for the elimination of EKG-artifact[1]) and two EKG electrodes were attached at the chest. EEG reference leads were linked mastoids, whereas a ground electrode was placed on the forehead.

The peak of the R-wave served as the trigger for the recordings of all derivations in both conditions. (It should be noted that this does not imply that the R-wave is seen as the 'stimulus' in heartbeat perception, but rather that it is only used technically as the element of the cardiac cycle, during which time locking of the EEG sweeps is carried out). One sweep lasted 800 ms, starting at 100 ms before and ending 700 ms after the R-wave. One thousand sweeps of physiological data were recorded corresponding to one thousand heartbeats for each condition.

The grand averages for the Standard condition are shown in Fig. 1 for the 19 electrode locations.

In the early latency range of 150 to 300 ms a small negative wave form appeared at fronto-central positions[2]. However, the predominant characteristic of the HEP was a positively going wave form in the latency range 250 to 600 ms at most electrodes. At frontal electrodes, this positivity reached a maximum of 2 microV in amplitude.

The distribution of HEP-voltages over the scalp for two different epochs is displayed in Fig. 2.

The HEP activity is predominantly apparent in the frontal region. This allows some considerations about the neuroanatomical structures being involved in transmission of the heartbeat signal. If frontal regions are more involved in the processing of the heartbeat than central or posterior areas, this supports the idea that heartbeat sensations might be transmitted via visceral (sympathetic or

[1] The influence of EKG on the scalp electrodes was reduced by a method, described in detail in Weitkunat and Schandry (1995; pp. 116–118).

[2] In most of the tracings a peak around 0 ms is visible; this is a consequence of incomplete EKG-artifact reduction.

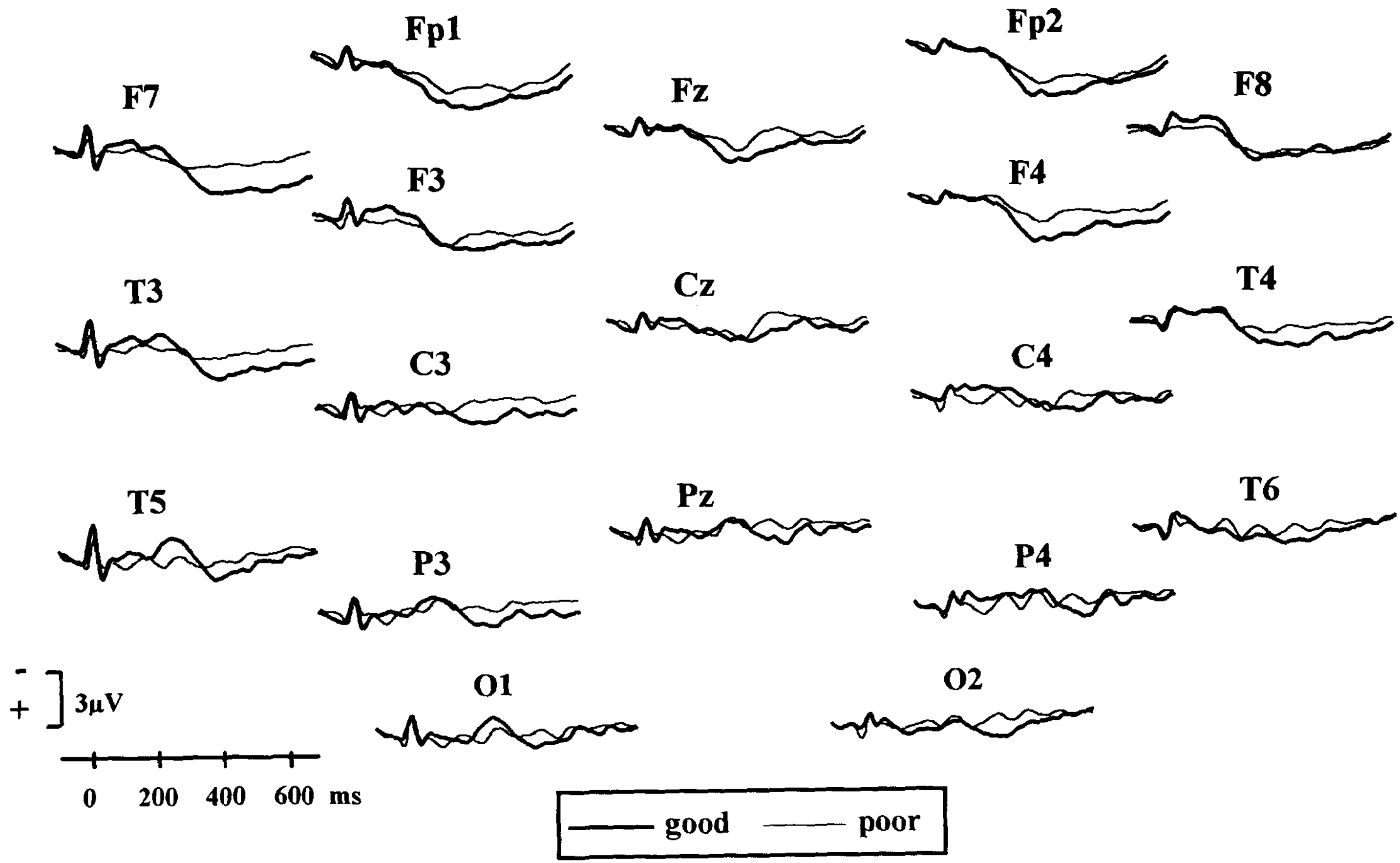

Fig. 1. Corrected grand averages during the Standard condition for good and poor perceivers. Time base point 0 is coincident with the onset of the EKG R-wave.

parasympathetic) afferents rather than by somatosensory pathways, since the latter project to another area, namely the gyrus postcentralis. Several authors have pointed to the importance of the premotor and the orbital areas of the frontal lobe for processing viscero-afferent information. These areas receive, for instance, projections of visceral afferent pathways via the hypothalamus and the thalamus (Fuster, 1980; Netter, 1987; Nauta and Feirtag, 1986; Nieuwenhuys et al., 1988). Another important frontal region is the insula (covered by the frontal lobes). Cechetto and Saper (1987) showed that afferent impulses from the baroreceptors project to this area in the rat. It has also been demonstrated that a stimulation of this area yields a variety of visceral reactions. Neafsey (1990, p. 148) has summarized the role of the prefrontal area in the following way '...the prefrontal cortex, at least in part,... represents the heart, stomach, lungs, liver, kidney, etc. via its control or its processing of visceral afferent information...'.

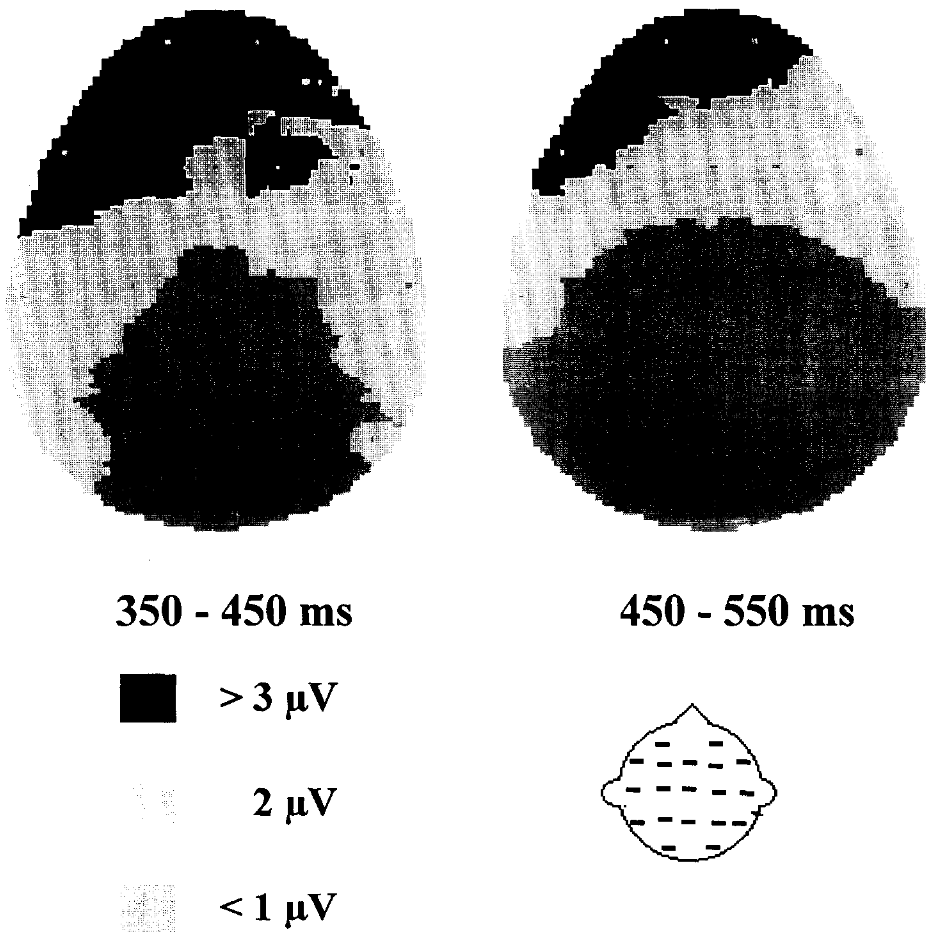

Fig. 2. Distribution of HEP voltages over the scalp for the time epochs 350–450 ms and 450–550 ms. The frontal position is up.

3. Cardiodynamic function and the heartbeat evoked potential (HEP)

From the work on exteroceptive evoked potentials (EP) it is well known that stimulus intensity has a direct relation to certain components of the EP. For instance, it has been shown for the somatosensory EP that increased stimulus intensity enhances the amplitude of the N1 component (Smout et al., 1992; Hansen, Ertekin, and Larsson, 1990; Frieling, Enck, and Weinbeck, 1989; Sarica and Karacan, 1986). For the perception of heartbeats one may assume that certain mechanical events during the cardiac cycle serve as the stimulus in the HEP. Such an event should have to do with the transfer of energy between the ejected blood mass and pressosensitive vascular tissue.

In the above mentioned study by Montoya, Schandry, and Müller (1993), we collected data on cardiodynamic function together with HEP recordings. At the end of the HEP registration, a 1-min recording of cardiovascular activity (at rest) was carried out using impedance cardiography. The following parameters of cardiodynamic function were obtained on the basis of the impedance recording: (a) Stroke volume (SV) was calculated according to the Kubicek's formula (c.f., Sherwood et al., 1990); (b) myocardial contractility (Heather index, HI) was defined as dZ/dt_{max} divided by the time interval between the EKG-Q-wave and the occurrence of dZ/dt_{max}; (c) Momentum was estimated as the quotient of stroke volume and left ventricular ejection time (LVET) (see Schandry, Bestler, & Montoya, 1993); (d) Energy was obtained as $SV/(LVET)^2$. Pearson's product-moment correlation coefficients were calculated across subjects between the HEP mean amplitudes of adjacent 100 ms time windows and the different cardiac parameters at rest. In general, correlations were highest in the 450 to 550 ms post-R-wave window.

Table 1
Correlation (Pearsons's r) between the mean amplitude of the heartbeat evoked potential in the time window 450-550 ms and parameters of cardiac function for selected electrodes

Electrode	450-550 ms			
	Stroke volume	Momentum	Heather-Index	Energy
Fz	0.35*	0.65***	0.14	0.65***
F3	0.31	0.57**	0.06	0.57**
F4	0.39*	0.60**	0.23	0.56**
F7	0.01	0.38*	−0.14	0.50**
F8	0.54**	0.71***	0.29	0.61**
Cz	0.41*	0.65***	0.22	0.60**
C3	0.26	0.55**	0.05	0.56**
C4	0.31	0.57**	0.08	0.56**
Pz	0.29	0.50**	0.09	0.48**
P3	0.22	0.49**	0.07	0.50**
P4	0.29	0.48**	0.08	0.46**

*p < 0.05, **p < 0.01, ***p < 0.001.

Correlation coefficients reached their highest values for Energy and Momentum (see Table 1). Only the data for frontal, central and parietal electrodes are shown; at the other locations the coefficients were mostly non-significant.

Correlation coefficients as high as 0.6 to 0.7 were obtained for frontal and central electrodes[3]. That means that 40 to 50% of the variance in the amplitude of the HEP in this time range can be explained by the mechanical strength of myocardial action. To our knowledge, only very rarely have correlations of such dimensions been observed for the relationship between stimulus intensity and EP amplitude.

4. The influence of psychological factors on the HEP

4.1 Attention

Evoked potentials triggered by external stimuli are sensitive to the manipulation of attention (Shevrin and Rennick, 1967; Groves and Eason, 1969; Callaway and Halliday, 1982; Salamy et al., 1984; Stelmack and Michaud-Achorn, 1985). Focusing attention on a stimulus has been demonstrated to enhance the N1 component of the EP. In the above mentioned study by Montoya et al. (1993) two different conditions were introduced: Heartbeats had to be ignored (here, subjects counted randomly presented tones) or heartbeats had to be concentrated on, i.e. they had to be counted. Focusing attention on the heartbeats generally resulted in a negative shift of the HEP (in our case, this means a depression of the positivity). This effect of attention was found to be significant for the central locations in the latency range 350 to 550 ms.

4.2 Motivation

When the incentive value of the stimulus is increased, a positive shift may be observed for certain components of the EP. Begleiter et al. (1983), for example, found higher positivity (in the P300 range) in response to stimuli associated with the chance of winning or losing a dollar as compared with neutral stimuli. We conducted a HEP study (cf. Weitkunat & Schandry, 1990) where motivation to perform well in heartbeat perception tasks was manipulated by giving subjects (7 female, 12 male) the chance to win money upon good performance in this task. During ten phases (each lasting for 200 heartbeats), the subjects were requested to silently count their heartbeats. While one group was not given any incentive during the last five phases (group NoMot), the other was informed that any counting result better than the best individual previous result would be rewarded with 5 DM (group Mot). In order to control for habitual heartbeat perception ability, subjects were preselected on the basis of an initial heartbeat perception task and were assigned either to the group of 'good' or of 'poor' heartbeat perceivers.

[3] We also calculated correlations between EKG epochs and the corresponding HEP epochs. All correlation coefficients were below 0.3 and did not reach significance.

The HEP wave forms recorded from good heartbeat perceivers performing under incentive conditions displayed a broad positive component (that was not present in the NoMot condition) with a maximum at approximately 400 ms post R-wave; this effect was most pronounced at the Fz electrode site (see Fig. 3).

We interpret this effect as being related to motivational rather than perceptual processes. This distinction is supported by the performance during the initial heartbeat perception test: Accuracy was not different between motivation and no-motivation conditions in either group. This finding of a motivation-related positive complex further supports the concept of integrating HEP and traditional (exteroceptive) evoked potentials. As with exteroceptive evoked potentials, the HEP exhibits a P3-like component under conditions of heightened motivation.

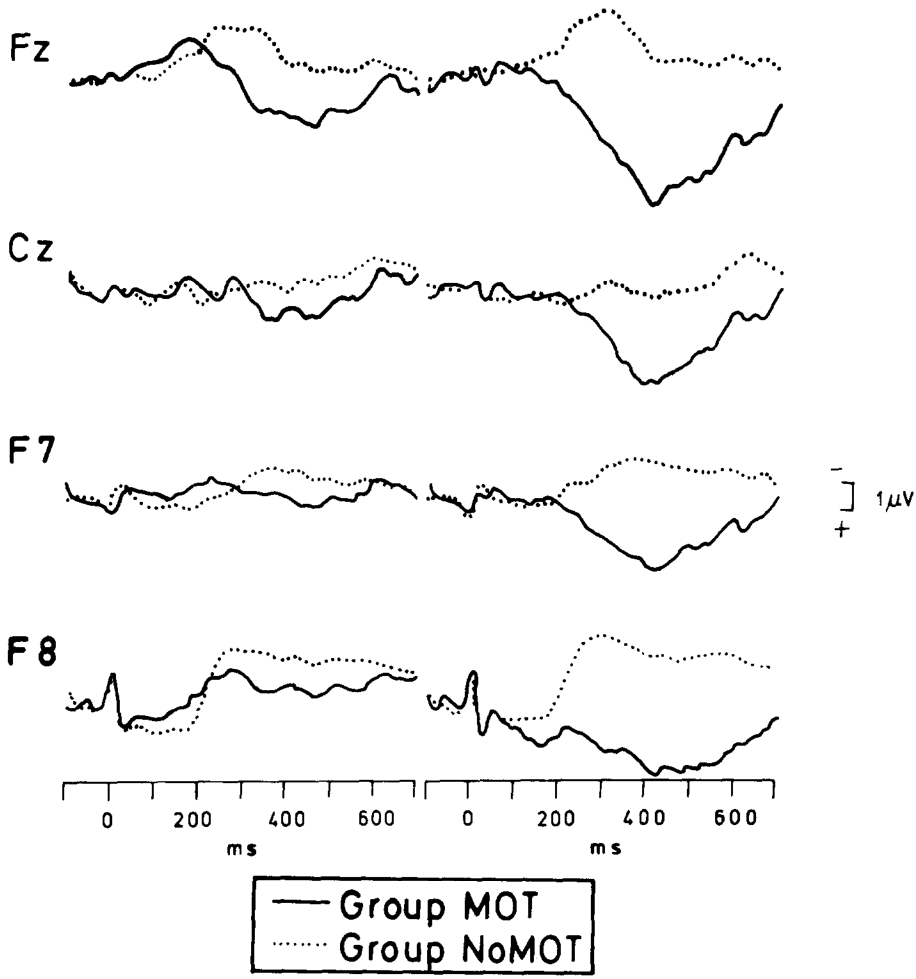

Fig. 3. Corrected HEP waveforms for group MOT during the phase without motivation (Phase A) and during the phase with motivation (Phase B) for good heartbeat perceivers. Time base point 0 is coincident with the onset of the EKG R-wave.

4.3 Cardioceptice sensitivity and the HEP

Studies using external stimuli of weak intensity have shown that evoked potential amplitudes derived from detected stimuli are higher than those from missed stimuli (e.g. Wilkinson and Seales, 1978). Performance in heartbeat perception tasks may be increased by adequate training procedures. Thus, one might expect that successful heartbeat perception training should result in enhanced HEP components.

In a study by Schandry and Weitkunat (1990), a training procedure was employed that provided immediate feedback on the occurrence of heartbeats: During an initial 45 min training procedure, subjects were requested to press a button upon the perception of a heartbeat. If a response was executed within a time-window of 100 to 500 ms post R-wave, positive feedback was given acoustically. In addition, during one third of the experiment, heartbeats were fed back by an external tone signal in order to foster perceptual learning. While in one group of 20 subjects these tone signals were of constant loudness throughout all acoustic feedback trials (group 'constant tone'), intensity of these feedback tones was gradually diminished to zero in the group 'fading tone' (22 subjects). Thus, the first approach was characterized by maximal external information on the internal process. The second procedure was designed to compel subjects to gradually switch to the use of interoceptive information in order to respond correctly to diminishing 'feedback' signals. Efficacy of the procedure was tested by measuring the reduction in variability of response latencies of the motor reactions. Both groups improved in this measure, with the 'constant-tone' group providing significantly better results than the 'fading-tone' group.

Before and after heartbeat perception training, subjects were requested to silently count their heartbeats ('ATT-PRE' and 'ATT-POST', respectively) while 200 HEP sweeps were recorded during each such condition.

An ANOVA performed on HEP wave forms yielded clear HEP differences between ATT-PRE and ATT-POST for the 'constant tone' group. (This group was most successful during perception training.) Here, training resulted in a negative shift (about 1–2 microV) of the wave form in the latency range of 250 to 400 ms at Fz, Cz, F7 and F8. This increased HEP negativity after successful heartbeat perception training is interpreted in terms of a refined 'stimulus set' (cf. Broadbent, 1971) related to more accurate detection of the target stimulus.

5. Discussion

Several considerations follow from the studies that were summarized in the above.

(1) Afferent input from the cardiovascular system, occurring during rhythmical heart action, is accompanied by specific electrical activity of the brain. This activity is most pronounced at frontal areas, which points to the involvement of visceral fibers in the cardio-afferent signal transport to higher brain centres. Additionally, this brain electrical activity reveals a strong and positive relation to the energy that is transferred between the ejected blood mass and pressosensitive tissue (presumably

being the source of the 'stimulus' in heartbeat perception). (2) As the data from poor heartbeat perceivers show, the presence of this brain electrical activity is independent of the conscious perception of the heartbeat signal. This means that the regularly occurring heartbeats are constantly monitored by certain cortical areas. (3) Psychological factors like attention, motivation and perceptual sensitivity exert a comparable influence on the heartbeat evoked potential as is known from EPs in response to external stimuli.

From our results it may be inferred that the CNS processes which are related to the perception of bodily processes are to a great extent equivalent and comparable to those related to the perception of external events. Especially, we conclude that the neurobiological basis for interoception is as well developed and as efficient as that for exteroceptive perception.

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