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Centrally controlled heart rate changes during mental practice in immersive virtual environment: A case study with a tetraplegic

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Abstract

A tetraplegic patient was able to induce midcentral localized beta oscillations in the electroencephalogram (EEG) after extensive mental practice of foot motor imagery. This beta oscillation was used to simulate a wheel chair movement in a virtual environment (VE). The analysis of electrocardiogram (ECG) data revealed that the induced beta oscillations were accompanied by a characteristic heart rate (HR) change in form of a preparatory HR acceleration followed by a short-lasting deceleration in the order of 10–20 bpm (beats-per-minute). This provides evidence that mental practice of motor performance is accompanied not only by activation of cortical structures but also by central commands into the cardiovascular system with its nuclei in the brain stem.

Keywords: Heart rate acceleration; Motor imagery; Virtual environment; Brain–computer interface

1. Introduction

Two types of changes in heart rate (HR) can be differentiated, an event-related HR deceleration known as orienting response and an event-related HR acceleration known as defence response (for a recent review cf. Sokolov et al., 2002). With respect to information processing two types of HR deceleration responses can be distinguished: an early response related to stimulus anticipation and registration (Lacey and Lacey, 1980; Van der Molen et al., 1989; Bohlin and Kjellberg, 1979) and a second type related to motor preparation. While Bohlin and Kjellberg (1979) favoured the view that expectancy is responsible for the HR deceleration, the work of Brunia (1984), Damen and Brunia (1987) and Papakostopoulos et al. (1990) provide strong evidence that motor preparation is the dominant factor in HR deceleration. Two recent publications are of interest with respect to HR deceleration. During a strong cognitive task, translation of words, the HR displayed a significant deceleration (Pfurtscheller et al., 2007). Imagination of hand or foot movement revealed also HR deceleration (Pfurtscheller et al., 2006a) and similar effects have been reported in the period just preceding different response conditions (Brunia and Damen, 1985) and prior to internally (self)-paced finger movements (Florian et al., 1998).

Beside deceleration also HR acceleration is a frequent response to activation of cortical structures. HR acceleration was not only reported during cognitive processing (e.g. Danilova et al., 1994), but also during mental simulation of movement (Decety et al., 1991; Oishi et al., 2000) and during motor imagery sessions (Papadelis et al., 2007).

In this paper we report on HR data recorded during simulated wheel chair control in an immersive VE. A tetraplegic patient had to “move” a wheel chair in a virtual street by using thought. In particular, movement through the virtual street was controlled by mentally induced electroencephalogram (EEG) bursts.

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2. Methods

2.1. Subject

The patient enrolled in the study is a 30-year old male, who sustained a traumatic spinal cord injury in 1998. He has complete motor and sensory paralysis below the level of the seventh cervical spinal vertebra and an incomplete lesion below cervical level four. Due to the location of this lesion it is likely that only the vagal heart innervation remained completely intact. During an intensive biofeedback training period he learned to induce beta burst at 17 Hz during foot motor imagery (Pfurtscheller et al., 2000).

2.2. EEG- and ECG-recording

One single EEG channel was recorded bipolarly 2.5 cm anterior and posterior to the electrode position Cz over the foot representation area (ground electrode was placed on the forehead). The EEG was amplified and band-pass filtered between 0.5 and 30 Hz with a biosignal amplifier (Guger technologies OEG, Graz, Austria). The electrocardiogram (ECG) was recorded bipolarly from the thorax (corresponding to an Einthoven II recording) with the same amplifier and filtered between 0.5 and 100 Hz. A 50 Hz notch filter was applied before the biosignals were digitized with a sampling rate of 250 Hz. The real-time processing was performed under Simulink (MathWorks, Inc., Natick, USA) using rtsBCI (Scherer, 2004–2007).

A single logarithmic band power feature was estimated from the ongoing EEG after digitally band-pass filtering (15–19 Hz, Butterworth filter of order 5), squaring, averaging (moving average) the samples over the past second and log-transforming. A simple threshold was used in the online experiments to distinguish between foot movement imagination (control or intentional state) and rest (non-control or non-intentional state). Whenever the band power exceeded the threshold a foot motor imagery was detected and the signal was used to control the VE (for details see Leeb et al., 2007).

2.3. Virtual environment and experimental paradigm

The tetraplegic patient was placed with his wheel chair in the middle of a multi-projection based stereo and head-tracked VE system of the type commonly known as a "CAVE" (Cave Automatic Virtual Environment, Cruz-Neira et al., 1993). The actual system used was a Trimension ReaCTor (SEOS Ltd. West Sussex, UK) that has a three back-projected vertical screens (3 m×2.2 m) and a floor screen (from a ceiling mounted projector) (3 m×3 m) controlled by a Silicon Graphics Onyx 2. The VE depicted a virtual street populated with 15 virtual characters (avatars), which were lined up along the street (see Fig. 1).

The task of the participant was to "move" the wheel chair from avatar to avatar until the end of the virtual street was reached. This translation of the virtual wheel chair along the street was accomplished by imagining that he was moving his paralyzed feet. He moved forward only while foot motor imagery was being detected in the EEG signal. In addition he was required to stop in just front of every avatar before actually reaching it. After a while, at his own choice, the subject could imagine another foot movement and start to virtually walk again, until the end of the street was reached. The avatars were placed on the same positions in all runs of the experiment and the participant started from the same point. In the case of 15 correct stops in one run, the performance was 100% (for details see Leeb et al., 2007). Six runs were carried out on one day.

2.4. Calculation of heart rate (HR) changes

The first step in ECG processing is to detect the QRS (ventricular contraction) complexes in the ECG signal. The QRS complexes determine the distance in time from one heart contraction to the next one (RR-interval). The QRS complexes were detected automatically based on an algorithm using a filter bank to decompose the ECG signal into various subbands (for details see Afonso et al., 1999). From the RR-intervals the instantaneous heart rate (IHR) was calculated between consecutive RR-interval samples. After selection of IHR trials with 5 s prior and 5 s after each detected EEG band power maximum, averaging was performed across the trials of each run. For the statistical evaluation of HR changes in relation to the band power maximum ("0" on x-axis in Fig. 2C) the HR was determined in each IHR trial at times "0", 3 s before and 3 s thereafter and a Wilcoxon-test was performed. The time point 3 s after the band power maximum corresponds approximately to the maximum of the post-imagery HR deceleration (see Fig. 2C).

3. Results

3.1. Performance measure and EEG changes

The results of the experiments are summarized in Table 1. Altogether the tetraplegic subject spent about 30 min in the VE

Fig. 1. Picture of the virtual street with the avatars and the tetraplegic subject in the wheel chair.

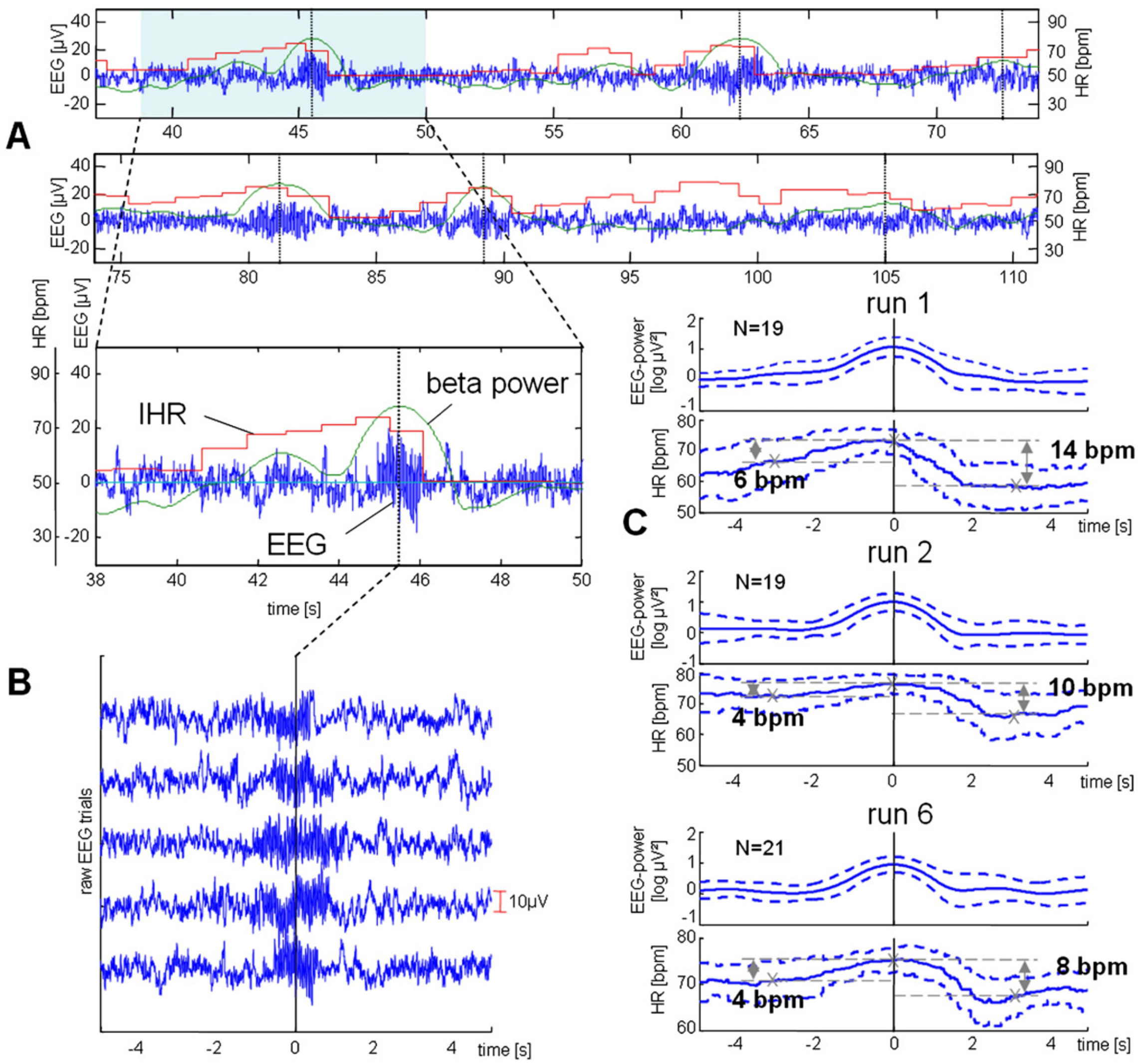

Fig. 2. (A) Raw EEG (in blue), instantaneous heart rate (IHR, in red) and time course of the logarithmic band power (15–19 Hz, in green). Remarkably the HR increase starts some seconds before the band power enhancement. (B) Examples of raw EEG trials selected by the beta band power maximum at "$t=0$". (C) Examples of motor imagery-induced beta bursts and averaged logarithmic band power epochs (mean ± SD) together with synchronous averaged IHR epochs (mean ± SD). The HR increases and decreases (in bpm) 3 s before and after the band power maximum are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with self-paced EEG-based control, and in 3 runs he achieved a performance of 100%. This means that he was able to generate at free will (internally-paced) a specific pattern of brain oscillations (beta bursts with frequencies of 17 Hz; examples in Fig. 2B) through foot motor imagery and to thereby control the movement of the wheel chair in the VE.

3.2. HR changes induced by motor imagery in VE

The HR varied from 64.1 bpm (run 1) to 92 bpm (run 3) (see Table 1). While the IHR was relatively high and stable in the runs 3, 4 and 5, it displayed a characteristic pattern during motor imagery only in the runs 1, 2 and 6 (see Fig. 2C). This pattern was composed of a slow HR acceleration, followed by a fast deceleration and a slow return to the mean HR. This HR pattern appeared to be parallel to the EEG beta bursts (for examples, see Fig. 2B and C). In other words, foot motor imagery was accompanied not only by a midcentral localized beta burst but also by a biphasic HR change starting with an acceleration. The statistical analyses revealed a significant ($p < 0.005$) HR increase of 11.1% (run 1), 6.1% (run 2) and 6.5% (run 6) in the last 3 s before the band power maximum (beta burst) and a significant ($p < 0.001$) HR decrease in all 3

Table 1
Summarized data of the 6 runs

Run	1	2	3	4	5	6	Average
Performance [%]	100.0%	93.3%	100.0%	100.0%	73.3%	73.3%	90.0%
Mean HR [bpm]	64.1	72.2	92.0	87.4	76.0	70.5	77.0
Time [s]	360.8	327.2	218.7	180.8	203.7	255.0	257.7

The performance (in %), the mean HR rate (in beats-per-minute, bpm) and the total time needed for the run (in seconds) are indicated.

runs (21.1%, 14.5% and 11.8%) in the first 3 s after the burst maximum.

4. Discussion

In the present study we investigated HR changes during self-paced foot motor imagery in one tetraplegic subject sitting in a wheel chair within a virtual environment, with the goal to move forward in the virtual street using thought (Leeb et al., 2007). The analysis of the data revealed a preparatory HR acceleration terminated by a HR deceleration during mental practice.

Special emphasis should be paid to the fact that preparation of a specific movement and imagination of the same movement involve similar cortical networks (Porro et al., 1996; Lotze et al., 1999) and are accompanied in general by a HR deceleration (Brunia and Damen 1985; Brunia 1984; Papakostopoulos et al., 1990; Florian et al., 1998). In training sessions with an EEG-based brain–computer interface and hand versus foot motor imagery the common HR response was a deceleration (see Fig. 2 in Pfurtscheller et al., 2006a). During EEG-based control of “walking” in VE, the same mental strategy can induce, however, HR acceleration (see Fig. 3 in Pfurtscheller et al., 2006a). This provides evidence that the increased mental effort and emotional processing (“walking” in immersive VE) are driving forces behind the HR acceleration. One reason for the observed preparatory HR increase could be that our tetraplegic patient was highly motivated and therefore directed increased attention to “walk” in the immersive environment. Another reason could be the fact that because of the level of the cerebral lesion only the vagal heart innervation originating in medullary brain stem nuclei was intact. It must be noted, however, that an increased mental effort does not always result in a HR increase. So for example increased word difficulty in translation from one to another language was accompanied by an increased HR deceleration (Pfurtscheller et al., 2007). It should be also mentioned that in contrast to the important work of Brunia (1984) and others, no cue-stimulus was used and therefore no anticipatory HR deceleration could be expected.

A similar coupling between brain and autonomic activity also starting with a HR acceleration was found in preterm infants. This weak but significant HR acceleration, followed by a deceleration in the order of 2–5 bpm, was observed time-locked to EEG bursts (Pfurtscheller et al., 2005).

The reported HR changes in the order of 10–20 bpm during effortful mental activity provides evidence for the first time that the performance of a brain–computer interface (Wolpaw et al., 2002) could perhaps be improved when both, the EEG and the HR are analysed and used for control. It could even be possible to realise a “brain switch” (Pfurtscheller et al., 2006b) by effortful mental activity and HR analysis and classification only.

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