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International Journal of Psychophysiology 62 (2006) 134 – 140

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

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Cardiac responses induced during thought-based control of a virtual environment

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Received 31 May 2005; received in revised form 6 December 2005; accepted 8 March 2006
Available online 27 April 2006

Abstract

Cardiac responses induced by motor imagery were investigated in 3 subjects in a series of experiments with a synchronous (cue-based) Brain–Computer Interface (BCI). The cue specified right hand vs. leg/foot motor imagery. After a number of BCI training sessions reaching a classification accuracy of at least 80%, the BCI experiments were carried out in an immersive virtual environment (VE), commonly referred as a "CAVE". In this VE, the subjects were able to move along a virtual street by motor imagery alone. The thought-based control of VE resulted in an acceleration of the heart rate in 2 subjects and a heart rate deceleration in the other subject. In control experiments in front of a PC, all 3 subjects displayed a significant heart rate deceleration of the order of about 3–5%. This heart rate decrease during motor imagery in a normal environment is similar to that observed during preparation for a voluntary movement. The heart rate acceleration in the VE is interpreted as effect of an increased mental effort to walk as far as possible in VE.

Keywords: Heart rate deceleration; Motor imagery; Virtual environment; Brain–Computer Interface

1. Introduction

Voluntary, self-paced hand movement is preceded by a slight but stable cardiac deceleration in healthy subjects (Lacey and Lacey, 1980; Obrist et al., 1969; Papakostopoulos et al., 1990). For example, Florian et al. (1998) investigated cardiac responses induced by slow and brisk voluntary self-paced index finger movements of the dominant and non-dominant hand. They found that slow movements induced a monophasic cardiac response, consisting of a deceleration preceding and accompanying movement, whereas brisk movements induced a biphasic cardiac response with a preparatory deceleration followed by a slight post-movement acceleration. This heart rate (HR) deceleration during preparation for a self-paced (voluntary) movement is associated with a negative cortical potential shift known as Bereitschaftspotential (Kornhuber and Deecke, 1965) and an event-related desynchronization (ERD) of sensorimotor rhythms (Pfurtscheller and Aranibar, 1979) and therefore completely attributable to motor cortex activation. This suggests that the neocortical structures involved in preparation for movement impinge upon brainstem cardiovascular nuclei.

However a lot of research focus on motor execution and preparation associated with vegetative mechanisms like cardiovascular or respiratory changes. It has been shown that motor imagery provokes similar, albeit weaker effects (Decety et al., 1991; Jeannerod and Frak, 1999).

There is strong evidence from functional magnetic resonance imaging (fMRI), electroencephalogram (EEG) and magnetoencephalogram (MEG) measurements that motor imagery involves similar cortical structures to those activated during preparation and execution of voluntary movement (Porro et al., 1996; Beisteiner et al., 1995; Neuper and Pfurtscheller, 1999). For example, significant increases in fMRI signal intensity were observed in the primary motor

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doi:10.1016/j.ijpsycho.2006.03.001

cortex (M1), the primary somatosensory cortex (S2) and supplementary motor area (SMA) during both motor performance and imagery (Porro et al., 1996; Roth et al., 1996; Lotze et al., 1999). Accordingly it is not surprising that also vegetative mechanisms would be co-activated with cortical mechanisms underlying motor imagery.

Decety et al. (1991) found that mental imagery of the motor action of running on a treadmill provoked an increase in heart rate, as well as changes in respiratory parameters. In addition, these changes were found to be proportional to the degree of imagined effort. Thus motor imagery corresponds to a subliminal activation of the motor system, where no overt motor output is produced but where corresponding vegetative output, aside voluntary control, becomes apparent. It can therefore be expected that imagination of hand or foot movement also affects the heart rate and depends on the mental effort.

The goal of this paper is to study heart rate changes associated with EEG-based Brain–Computer Interface (BCI) experiments when motor imagery is used as mental strategy (Pfurtscheller et al., 2005). Such a BCI transforms imagery-related EEG changes into an output signal that can provide a new communication channel for completely paralyzed or “locked-in” patients (Wolpaw et al., 2002) but also can control events in the virtual environment (Pfurtscheller et al., 2006; Leeb and Pfurtscheller, 2004). VE provides an excellent testing ground to study the effect of feedback in BCI, for example with the goal to shorten the training time. The present paper reports on heart rate changes when the BCI output signal controls (i) simple cursor movement on a PC monitor or (ii) events in an immersive virtual environment.

2. Materials and methods

The study was performed on 3 able-bodied student volunteers aged 23–30 years. All subjects were right handed, without a history of neurological disease and gave informal consent to participate in the study. The subjects took part in a series of BCI experiments over some months with the goal of achieving control over their brain activity for mental control of a virtual environment (VE) (Pfurtscheller et al., 2006). Two mental strategies were used in BCI training: imagination of right hand vs. left hand or imagination of right hand vs. foot/leg movements. In this work only the results of foot/leg versus right hand imagery are reported. In the majority of the experiments, in addition to 3 bipolar EEG channels, the electrocardiogram (ECG) was also acquired from the thorax, sampled at 250 Hz, stored and used for off-line processing. The BCI system consisted of a biosignal amplifier (g.tec, Guger Technologies OEG, Graz, Austria), a data acquisition card (National Instruments Corporation, Austin, USA) and a standard PC running Windows XP (Microsoft Corporation, Redmond, USA). The recording and real-time processing is handled via rtsBCI (http://sourceforge.net/projects/biosig/), based on MATLAB 6.5 (MathWorks, Inc., Natick, USA) in combination with Simulink 5.0, Real-Time Workshop 5.0 and the open source package BIOSIG (http://biosig.sf.net/).

2.1. Experimental paradigm

Each subject took part in 4 to 6 BCI training sessions with feedback in Graz. Thereafter, 2 sessions were performed in London in a multi-projection-based stereo and head-tracked VE system commonly known as a “CAVE” (Cruz-Neira et al., 1993) and finally, one control session was made in Graz again. The particular VE system used was a ReaCTor (SEOS Ltd., West Sussex, UK) which surrounds the user with three back-projected active stereo screens (3 walls) and a front-projected screen on the floor. Left- and right-eye images are alternately displayed at 45 Hz each, and synchronized with CrystalEye™ stereo glasses. A special feature of any VE system is that the images on the adjacent walls are seamlessly joined together, so that participants do not see the physical corners but the continuous virtual world that is projected with active stereo (Slater et al., 2002). The used VE was a virtual main street with various shops on both sides and populated with some virtual characters that walked along the street, whereby the characters were programmed to avoid collisions with the participant. The task of the subjects was to go to the end of the street, whereby imagination of foot movements resulted in a motion and imagination of hand movements in a stop. The VE contained no audio track and the information of the tracking system was disregarded, so that the subject was always walking straight. In the VE experiment the subject sat in a relaxed position in a chair inside the CAVE whereas in the control experiment the subject sat in front of the desktop computer. Each session was composed of 2 to 8 runs and lasted approximately 1 h. In each run, the subject had to imagine movements in response to an auditory cue-stimulus, given either as single beep or as double beeps (20 foot and 20 right-hand cues). In the sessions performed in Graz an additional visual cue-stimulus, in the form of an arrow pointing downwards or to the right, respectively was presented on a computer monitor, to support the learning process. Each trial lasted about 8 s, with 3 s before the cue-stimulus appearance. The subject was instructed to imagine the indicated movement over the next 4 s while feedback (FB) was given during that time. The time between the trials was randomized in the range from 0.5 to 2 s. During the experiments in Graz FB in the form of a moving bar is given to inform the participant about the accuracy of the classification during each imagery task (i.e. classification of right hand imagery was represented by the bar moving to the right and classification of foot movement imagery by the bar moving downward). In the VE experiments correct classification of feet motor imagery was accompanied by moving forward with constant speed in the projected virtual street and the motion was stopped on correct classification of hand motor imagery. Incorrect classification of foot motor imagery resulted as well in halting, and incorrect classification of hand motor imagery in backward motion (Leeb and Pfurtscheller, 2004).

The data of both VE sessions in London and one final control sessions in Graz with imagination of right hand vs. foot/leg movement are reported in this paper. The EEG trials were used for the discrimination of the 2 mental states of motor imagery.

Details can be found elsewhere (Leeb et al., 2005b). The error rate based on single trial classification before and during the motor imagery process is calculated and displayed in form of a diagram (see Fig. 2). Fifty percent error means no discrimination while 0% indicates perfect discrimination between the two motor imagery tasks.

2.2. Electrocardiogram processing

The first step in ECG processing is to detect the QRS (ventricular contraction) complexes in the ECG signal (see Fig. 1A). 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 a modified Pan–Tompkins algorithm (Pan and Tompkins, 1985) implemented in the g.BSanalyze software package (g.tec—Guger Technologies OEG, Graz, Austria). Thereafter a visual inspection of the detected QRS complexes was performed to guarantee high data quality.

2.3. Calculation of imagery-induced HR changes

From the RR-interval time series the instantaneous heart rate (IHR) was calculated by linear interpolation between

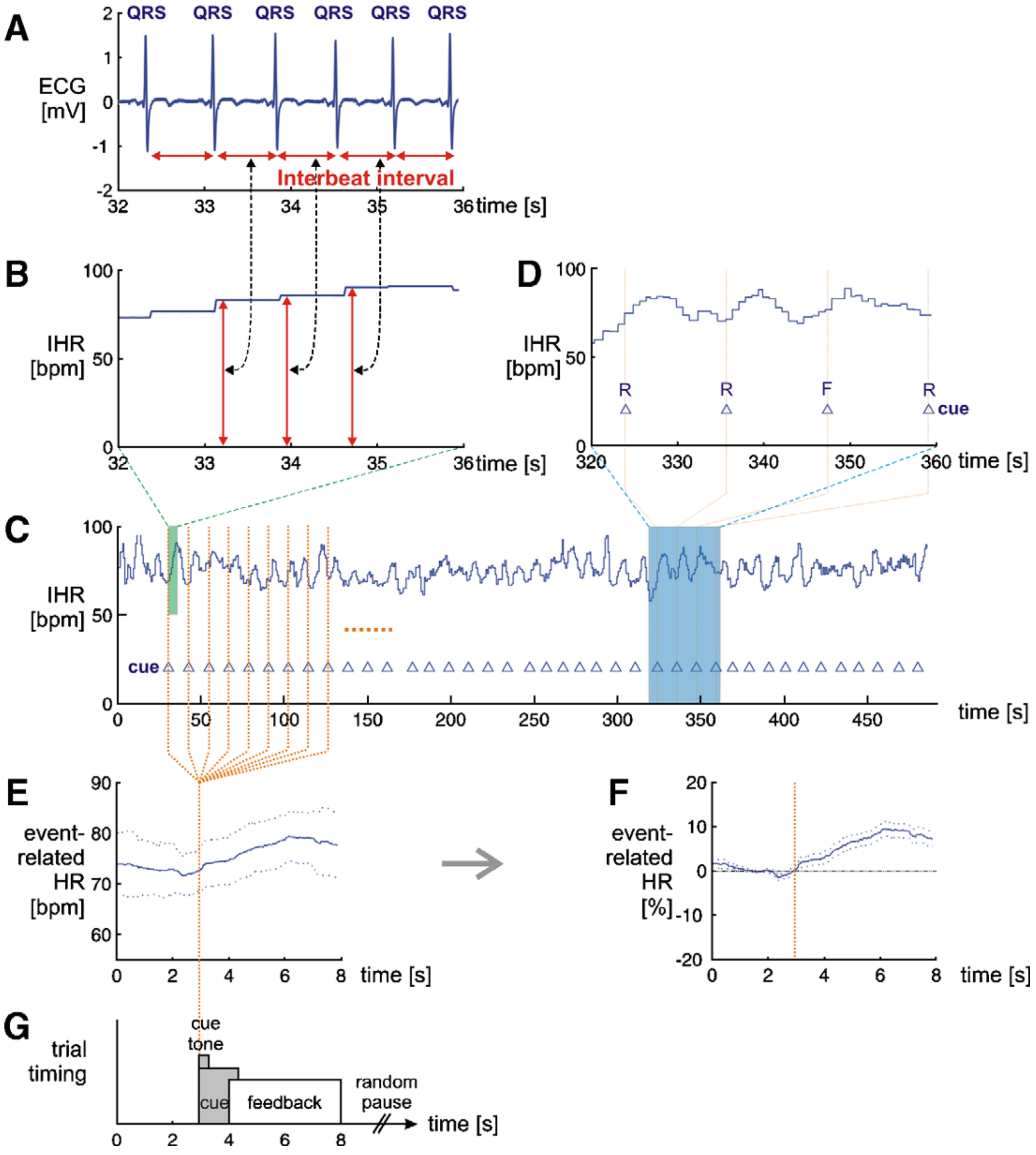

Fig. 1. Scheme for calculating event-related heart rate changes (data from subject S2, VE condition). (A) Original ECG signal with marked QRS complexes. (B) Interbeat interval between the QRS complexes and calculation of instantaneous heart rate (IHR). (C) IHR time course in beats-per-minute (bpm) of one run, with indicated cue-stimuli (start of the motor imagery). (D) Zoomed version of (C), additionally the type of cue, either right hand imagination R or feet imagination F is exemplarily indicated. (E) Average of event-related heart rate changes with 3 s before and 5 s after the cue-stimulus presentation. Mean HR is plotted in solid and standard deviation (SD) in dotted. (F) Relative event-related HR change in percent compared to the mean HR in a 1-s reference interval between second 1 and 2 (normalized HR change). (G) Timing of the one trial. At second 3 the cue-stimulus appears and between second 4 and 8 feedback is given to the subject. After each trial a pause of random duration between 0.5 and 3 seconds occurs.

consecutive RR-interval samples and resampling with 4 Hz (de Boer et al., 1985) (see Fig. 1B–D). After the selection of 8-s instantaneous HR trials with 3 s prior to the cue-stimulus, averaging was performed across the 40 trials of each run (see Fig. 1E). Finally the relative event-related HR change in percent compared to the mean HR in a 1-s reference interval between second 1 and 2 (normalized HR change) is calculated (see Fig. 1F). The result shows an event-related HR time

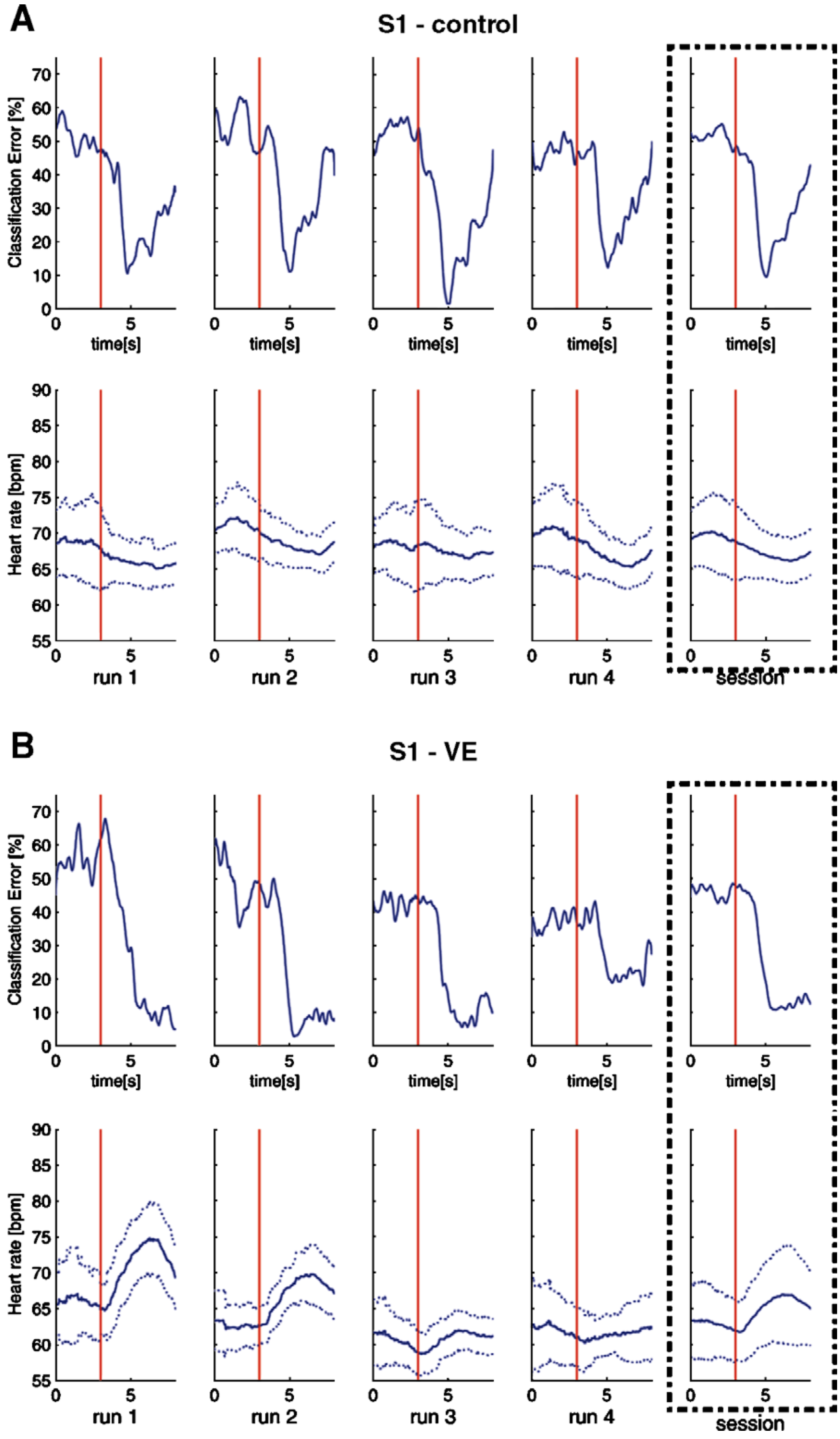

Fig. 2. Results of one control session composed of 4 runs (subject S1) are displayed in the upper panel (A). Time courses of the classification error in percentage are plotted in the top row. The vertical lines indicate the time point of the cue presentation. The bottom row displays the HR time courses in beats per minute (bpm). The thick line represents the mean over the trials and the two thin lines represent the corresponding inter-trial SD. The last column on the right side (framed) is the outcome of one session, which equals the averaged result over the 4 runs and 160 trials, respectively. The results of one VE experiment of the same subject (S1) are shown in the lower panel (B).

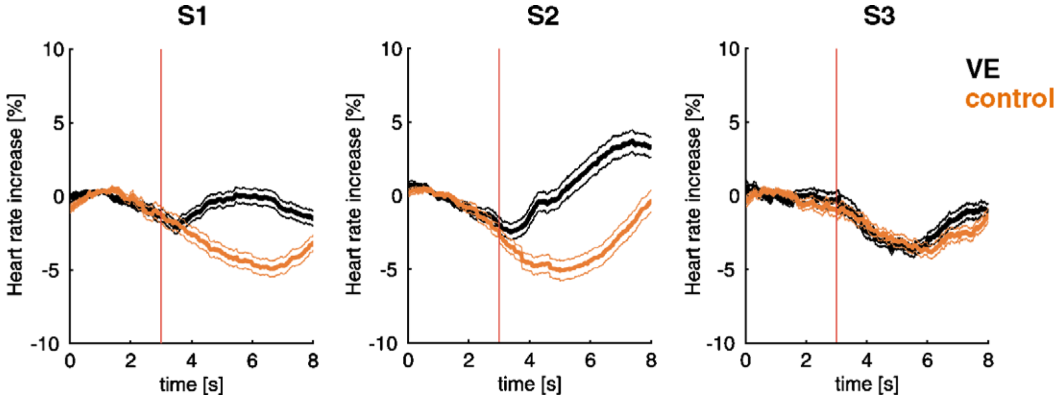

Fig. 3. Normalized HR time courses (mean ± SE) for VE (plotted in black) and control (PC, plotted in orange) condition. For calculation 160 trials are used in the control condition and 280/240 (S1 and S2/S3) trials (exclusive of the first run) in the VE condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

course together with the sample-by-sample inter-trial standard deviation (SD).

3. Results

Fig. 2 displays examples of induced HR changes and the corresponding EEG classification error for different runs obtained in one representative subject. The upper panel (A) of Fig. 2 shows the results of the control experiment composed of 4 runs and the lower panel (B) of one VE experiment. The classification error (top row) varies between 5% and 20% and indicates that most of the trials were correctly classified during motor imagery, that is, the subjects performed the mental tasks satisfactorily. The inspection of the error curves in Fig. 2 gives evidence that in the control experiments (Fig. 2A) the imagery process was more phasic or short-lasting compared to the VE experiments (Fig. 2B). The VE and control experiments have in common that the heart rate starts to decelerate already slightly before the presentation of the cue-stimulus. The HR time courses during the control experiment (Fig. 2A, bottom row) display a HR decrease in all runs in parallel with the motor imagery process. In the VE experiment (Fig. 2B) the HR displays a variable increase in the individual runs. The framed diagrams on the right sides of Fig. 2A and B display the averages over the runs (session) including 160 trials (4 × 40).

During the VE experiment the HR time courses demonstrate not only a great variability over the individual runs, but display two characteristic features. First, a HR acceleration is present in all runs and second, the HR increase is most pronounced in the first run in the VE and becomes smaller in the following runs.

The normalized HR time courses obtained in all subjects and both conditions (control and VE) are summarized in Fig. 3. In the case of the VE experiments the first run was not used for calculation to avoid adaptation in the CAVE condition (see for example the large HR acceleration in the first CAVE run in subject S1, Fig. 2B) In each diagram, the mean percentage HR (± SE) change is indicated. In the control condition, all subjects displayed a significant HR decrease in the order of 3–5%. One of the subjects also displayed a HR decrease in the VE condition. The two other subjects displayed a HR increase starting with the cue presentation at second 3.

Additionally we analyzed the behavior of single IHR trials associated with the two most important tasks in VE experiment to learn more about the phenomenon of HR acceleration in VE experiments: moving forward during correct classification of foot/leg motor imagery and moving backward during false classification of hand motor imagery. In the former case the FB

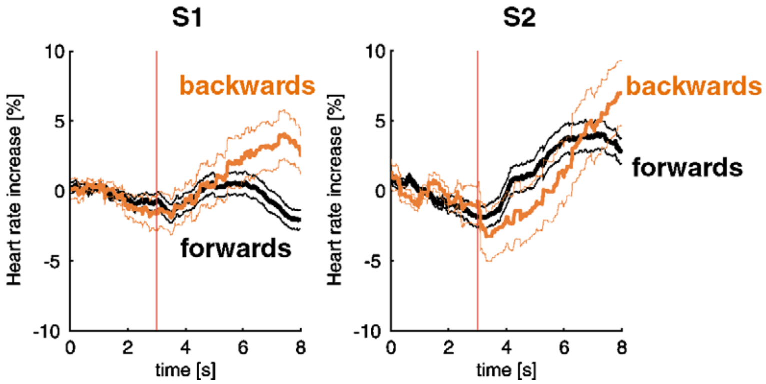

Fig. 4. Normalized HR time courses (mean ± SE) calculated for correct classified foot MI trials (126 in S1 and 129 in S2, plotted in black) and false classified hand MI trials (35 in S1 and 28 in S2, plotted in orange). Correct classification resulted in forward moving and false classification in backward moving. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was positive, in the latter case it was negative. The results of these analyses are presented in Fig. 4. It can be seen that the HR changes display a similar pattern in both subjects. The positive FB is accompanied by a slightly short-lasting and weaker HR acceleration, when compared to the negative FB. The differences between both HR responses are not significant, but demonstrate clearly different time courses in the two FB conditions.

4. Discussion

The results of the presented studies provided two novel findings: (i) motor imagery in BCI sessions can be accompanied either by a HR increase or a HR decrease (ii) correct (positive FB) and incorrect (negative FB) classification of the brain state during motor imagery can result in different pattern of the HR changes.

The HR deceleration found in the control condition of all subjects is expected because similar neural structures in motor and premotor areas are activated during motor imagery and motor execution (Porro et al., 1996; Lotze et al., 1999) and furthermore self-paced hand movement is preceded by a HR deceleration (Papakostopoulos et al., 1990; Florian et al., 1998). A logical consequence of the activation of motor and premotor areas is not only the negative cortical potential shift (Kornhuber and Deecke, 1965), the desynchronization of sensorimotor rhythms (Pfurtscheller and Lopes da Silva, 1999) and the increase of the corticospinal excitability (Fadiga et al., 1999; Bonnet et al., 1997) but also the HR deceleration.

More surprisingly was the result of the HR acceleration in 2 subjects observed in the VE experiments. This HR response was, however, not uniform. Especially, subject S1 provoked the most prominent HR acceleration in the first run in the CAVE with a clear decline in the following runs (example see Fig. 2B). This initial HR acceleration might be the result of the unusual situation. The subject was required to sit on a chair in the middle of the CAVE, placed inside a VE and had to make special effort to achieve good performance of VE control.

The questionnaire presented after the VE experiments revealed an interesting detail. Both subjects S1 and S2 had an internal competition about how far they could walk in the virtual street (Friedman et al., 2004). For the performance control in the VE experiment a cumulative artificial mileage (CAM) was introduced (details see (Leeb et al., 2005a)) whereby the largest CAM was achieved by subjects S1 and S2. Therefore it can be hypothesized, that the observed HR acceleration in VE experiments was a consequence of the “competition” and revealed to the increased mental effort. Respectively it might be of interest to reflect to the work of Decety et al. (1991) who reported a covariation of heart rate response and degree of imagined effort. Correct classification of foot motor imagery and walking forward was accompanied by a positive FB, and false classification of hand motor imagery and walking backward by a negative FB. When the mental effort is the driving force behind acceleration, moving backwards in the “competition” was extremely frustrating and acting as a reinforcement to change the classification result and to walk forward. The result provides provisional evidence (Fig. 4) that backward moving (negative FB) resulted in a stronger and longer-lasting HR increase as forward walking.

In all control and 2 VR experiments HR deceleration prior to the cue-stimulation was found (see Fig. 3). One explanation for the deceleration could be the anticipatory HR response, reported by Jennings et al. (1990, 1991). The term “anticipatory HR deceleration” used by Jennings et al. (1990) is misleading, however, because in the 1-s period between warning signal and reaction stimulus different processes take place. These processes are not only related to stimulus anticipation but also to motor preparation and decision making. Similarly processes related to anticipation of the cue-stimulus, preparation for motor imagery and preparation for decision making (hand vs. foot imagery) took place in our experiments. Further research is needed to clarify whether stimulus anticipation or motor preparation is the dominant element for HR decelerations. Nevertheless the absence of acceleratory recovery (Jennings et al., 1991, 1990) after cue presentation and response initiation (motor imagery) in the control experiments suggests that motor preparation is more likely responsible for the HR deceleration prior to cue presentation.

Another alternative explanation for the HR deceleration prior to cue-stimulation could be due to recovery from acceleration in the previous trial. This is, however, unlikely, because the anticipated deceleration was about the same for control and VE conditions in subjects S1 and S2. It has also to be mentioned that HR time courses can be computed either instantaneous (as in our case) or delayed (de Boer et al., 1985), whereby the difference between both methods corresponds to one interbeat interval. Also a bias due to the methodology used can be ruled out because the deceleration starts more as 2 interbeat intervals (see Fig. 3, subjects S1 and S2) before cue-onset).

The study suggests that neocortical structures involved in motor imagery impinge upon brain stem cardiovascular nuclei and modify the heart rate. In general, motor imagery is associated with a HR deceleration, however a HR acceleration is also possible. It is hypothesized that HR acceleration in the immersive virtual environments is related to the degree of imagined efforts.

Acknowledgement

The work was funded by the European PRESENCIA project (IST-2001-37927). The authors are grateful to C. Keinrath for assistance in data recordings, S. Wriessnegger for English corrections and G. Supp and D. Zimmermann for taking part in the experiments.

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