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NEURAL CORRELATES OF USER-INITIATED MOTOR SUCCESS AND FAILURE – A BRAIN–COMPUTER INTERFACE PERSPECTIVE

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Abstract—Any motor action is, by nature, potentially accompanied by human errors. In order to facilitate development of error-tailored Brain–Computer Interface (BCI) correction systems, we focused on internal, human-initiated errors, and investigated EEG correlates of user outcome successes and errors during a continuous 3D virtual tennis game against a computer player. We used a multisensory, 3D, highly immersive environment. Missing and repelling the tennis ball were considered, as 'error' (miss) and 'success' (repel). Unlike most previous studies, where the environment "encouraged" the participant to perform a mistake, here errors happened naturally, resulting from motor-perceptual-cognitive processes of incorrect estimation of the ball kinematics, and can be regarded as user internal, self-initiated errors. Results show distinct and well-defined Event-Related Potentials (ERPs), embedded in the ongoing EEG, that differ across conditions by waveforms, scalp signal distribution maps, source estimation results (sLORETA) and time–frequency patterns, establishing a series of typical features that allow valid discrimination between user internal outcome success and error. The significant delay in latency between positive peaks of error- and success-related ERPs, suggests a cross-talk between top-down and bottom-up processing, represented by an outcome recognition process, in the context of the game world. Success-related ERPs had a central scalp distribution, while error-related ERPs were centro-parietal. The unique characteristics and sharp differences between EEG correlates of error/success provide the crucial components for an improved BCI system. The features of the EEG waveform can be used to detect user action outcome, to be fed into the BCI correction system.

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Key words: Event-Related Potentials (ERP), motor-errors, motor-success, Error-Related Potentials (ErrP), virtual reality, Brain–Computer Interface (BCI).

INTRODUCTION

Imagine a minimally invasive laparoscopic procedure: the surgeon performs a gall bladder removal, and looks at the internal abdomen, displayed on a screen. In an instance, the surgeon moves the scalpel erroneously in a seemingly correct direction, which is actually erroneous due to the inversion inherent in the setup. The erroneous move carries a potential high damage to the patient. However, even before executed, a neural EEG signal comes up, predicting the not-yet-executed erroneous act, and an automatic system interferes to freeze the motion of the scalpel, avoiding potential damage to the tissue. This is the essence of a Brain–Computer Interface (BCI). A crucial condition for such a system to function is that the signal of failure is clearly discriminated from success. This study asks what are the neural signals of action outcome failure and success, what are the similarities and differences in terms of waveform, scalp distribution, latency, amplitudes, and spectral response. We focus on user-initiated errors, rather than the frequently used, environment-induced errors.

Electroencephalography (EEG)-based BCI was shown to benefit from feedback signals based on Event-Related Potentials (ERPs), that were associated with errors elicited by the system, such as miss-interpretation of a user intention by the interface (Ferrez and Del R. Millán, 2008a,b). ERPs are embedded in the continuous EEG and are time locked to the experienced events (Pfurtscheller and Lopes Da Silva, 1999; Sörnmo and Laguna, 2005). This type of ERPs was termed Error-Related Potentials (ErrPs) and is based on external errors in BCI systems (Ferrez and Del R. Millán, 2008a,b). Moreover, ErrPs can be used for supervised learning of the BCI classifier (Iturrate et al., 2010). However, for a BCI system to respond efficiently, it is crucial to identify the source of the error – user initiated, or system initiated. In this context, user errors can be viewed as internal errors generated by the user (Hill and Raab, 2005), while, interface system errors are external errors induced by the interface misinterpretation of the user intent (Hill and Raab, 2005). Externally induced errors can be caused by user-independent factors. Here we wish to identify the distinct characteristics of ERPs related to user internal

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Abbreviations: AAR, Automatic Artifact Removal; ACC, Anterior Cingulate Cortex; BCI, Brain–Computer Interface; ECoG, electrocorticography; ERN, Error-Related Negativity; ERPs, Event-Related Potentials; ErrPs, Error-Related Potentials; ERSPs, Event-Related Spectral Perturbations; FEF, Frontal Eye Field; FIR, finite-impulse response; FRN, Feedback-Related Negativity; ITC, Inter Trial Coherence; Pe, Error Positivity; PPC, Posterior Parietal Cortex.

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errors and successes during the execution of motion task. This is important for the design of a BCI system and for understanding the role of erring in learning.

ErrPs are evoked in response to diverse cognitive erroneous conditions and are characterized by an early Error-Related Negativity (ERN), a fronto-central component peaking 50–100 ms post-error, and sometimes followed by an Error Positivity (Pe) component with a centro-parietal or fronto-central distribution (Gehring et al., 1993; Falkenstein et al., 2000) and peaking in the range of 300–500 ms (O'Connell et al., 2007). Correct trials may also evoke smaller ERN and Pe as part of the comparison process (Falkenstein et al., 2000). Feedback on an error evokes a fronto-central component termed Feedback-Related Negativity (FRN) peaking at 150–300 ms post-feedback (Hajcak et al., 2006; Bediou et al., 2012). The Anterior Cingulate Cortex (ACC) is the hypothesized origin of ERN and FRN (Falkenstein et al., 2000; Hajcak et al., 2006; Bediou et al., 2012). The ACC participates in action monitoring and detects unexpected performance errors (Contreras-Vidal and Kerick, 2004).

Internal erroneous responses to cognitive tasks, including choice and time estimation, evoke ErrPs which have been extensively studied (Miltner et al., 1997; Falkenstein et al., 2000; Holroyd and Coles, 2002). Outcome errors occur when the movement goal is not achieved (Krigolson et al., 2008; Milekovic et al., 2012, 2013) and have been studied in various experimental conditions and tasks such as: collision avoidance in a one-dimensional (1D) motion task with electrocorticography recordings (ECoG) (Milekovic et al., 2012, 2013); a two-dimensional (2D) motion task with EEG recordings (Spuler and Niethammer, 2015); a 2D aiming task (Krigolson et al., 2008; Bediou et al., 2012); and a 2D throwing tasks (Maurer et al., 2015). During a collision avoidance task the participant controls a virtual agent and has to escape from falling blocks (Milekovic et al., 2012, 2013; Spuler and Niethammer, 2015). In the 1D task the participant is able to move the agent to the left or to the right (Milekovic et al., 2012, 2013), while in 2D task any direction on the plane is available to the user (Spuler and Niethammer, 2015). Collisions are caused by user miss-performance (internal outcome errors) and evoke ERNRs and ErrPs for ECoG- (Milekovic et al., 2012, 2013) and EEG- (Spuler and Niethammer, 2015) based studies, respectively. Peaks of ERNRs have shown a latency in the range of 100–800 ms post error and a spectral response in the delta band (0–4 Hz) and gamma band (above 40 Hz) (Milekovic et al., 2012). ERNRs are localized in the motor, somatosensory, parietal, temporal and pre-frontal cortex (Milekovic et al., 2012). ErrPs have central distribution, that peaked at the FCz and Cz electrodes and are composed of ERN at 2 ms, Pe at 268 ms, N400 at 486 ms and minor positive component at 742 ms (Spuler and Niethammer, 2015). Related spectral response is in the delta band (1–4 Hz) mainly at Cz electrode vicinity, and theta band (5–7 Hz) shared by Fz and FCz electrodes vicinities (Spuler and Niethammer, 2015). Internal outcome errors during 2D aiming tasks evoke FRN with peak latencies of 227 or 268 ms (Krigolson et al., 2008; Bediou et al., 2012). ERN resembling ERP is evoked by internal outcome error in 2D throwing task and peaked at about 250 ms after the ball release and at about 550 ms respectively before the target is missed (Maurer et al., 2015). An additional later negative component with a peak at about 300 ms after release and at about 500 ms before error is evoked and represents monitoring process (Maurer et al., 2015).

The experiments on internal user errors described above used tasks limited to 1D or 2D continuous motion without haptic feedback (Krigolson et al., 2008; Bediou et al., 2012; Milekovic et al., 2012, 2013; Maurer et al., 2015; Spuler and Niethammer, 2015).

ERPs evoked by successful outcome of correct aiming, evoked positive ERP with peak latency of 300 ms at FCz and Pz electrodes (Krigolson et al., 2008). A fronto-central pre-ERN peaking at about 90 ms prior to correct aiming seems to have reflected a prediction of high probability successful outcome (Bediou et al., 2012). Negative ERP was evoked in a continuous throwing task in response to hitting a target (Maurer et al., 2015). This ERP peaked at about 250 ms after the ball release and 550 ms before the target was hit and possibly represents prediction of successful outcome (Maurer et al., 2015).

The goal of this study was to characterize and compare ERPs evoked by user internal outcome errors and successes during continuous three-dimensional (3D) motion task. User errors were represented by user initiated internal outcome error of failing to hit – missing – a tennis ball. User successes were defined as repelling a ball during a continuous 3D virtual tennis game. In an attempt to increase the validity of the results to the real-world conditions, we stayed away from artificial experiments and designed the experiments in this study to resemble reality. We added depth to the experimental world. It has been established that processing of 2D visual scenes lead to reduced accuracy, and poor performance compared to virtual worlds with depth (Lev et al., 2010; Lev and Reiner, 2012; Pang et al., 2015). The same applies to haptic-proprioceptive processing – accuracy of motor task performance is reduced (Lev et al., 2010; Lev and Reiner, 2012; Pang et al., 2015). We designed a task that engaged the participants in motor/kinematic prediction, active action and planning, to allow natural errors to emerge.

The characteristics of the 3D task, the virtual immersive experimental world, and the haptic controller conveying a sensation of the world physics, simulates the physical world and hence suggests ecological validity with a relatively high chance of application to real-life.

EXPERIMENTAL PROCEDURES

Experimental system

The experiment was carried out in a 3D virtual tennis game. Participants played a virtual 'tennis' game against a computer player in a highly immersive 3D game world.

A projector (resolution of 1280 × 720 and refresh rate of 120 Hz), projected the scene on a half-transparent

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