Efficient Brain-Computer Interface based on Event-Related Potential

その他のタイトル	事象関連電位に基づく効率的Brain-Computer Interfaceに関する研究
学位授与年月日	2014-03-24
URL	http://doi.org/10.15083/00006825

論文の内容の要旨

論文題目：Efficient Brain-Computer Interface based on Event-Related Potential

（事象関連電位に基づく効率的 Brain-Computer Interface に関する研究）

氏　　名：徐　雅明

Millions of people around world suffer from degenerative diseases that impair the normal neural pathways that control muscle movements. At late-stages of these diseases, people lose all voluntary muscle control and become completely "locked in" to their bodies, unable to communicate through normal or traditional means. Brain-computer interfaces (BCIs) can allow these patients to communicate again by creating a new communication channel directly from the brain to an external output device. Recent studies on amyotrophic lateral sclerosis (ALS) patients showed that event-related potential (ERP) based BCI technology could create new pathways of communication for paralyzed people. Although these technical demonstrations are encouraging, practical applications of ERP-based BCI technology that meet the needs of people with severe disabilities are significantly impeded primarily by two issues. Firstly, ERPs as the control signals in the ERP-based BCIs have an unfavorable ratio between signal (pure ERP components) and noise (neural background activity and various artifacts), which leads to unreliable ERP classification. Second, current epoch-based ERP classifications are still inefficient because they do not exploit full potentials of ERP signals. Mainly due to these two issues, current ERP-based BCI systems have produced impressive laboratory demonstrations but no device of appreciable clinical value. This dissertation set out to address these problems to work towards an efficient ERP-based BCI system that can advance the practicality.

Chapter 1 firstly outlines why BCIs are critically important, and then gives a general introduction of brain-computer interfaces including neurophysiological foundation of BCIs, invasive and non-invasive neuroimaging techniques, commonly used control signals for BCIs, existing signal processing and classification methods, and its applications. Next, we emphasize why we focus on optimizing EPR-based BCIs in this study, and then point out two issues which impede clinical practicality of the current ERP-based BCIs. (1) ERPs as the control signals in the ERP-based BCIs are with unfavorable ratio between signal and noise. This leads to unreliable ERP classification due to low discriminability of ERPs; (2) Current epoch-based ERP classifications are still inefficient since they have not exploited full potentials of ERP signals. Finally, two themes of the dissertation are raised to overcome the two issues. THEME I is

to elicit more discriminable ERPs by optimizing stimulus paradigm, while THEME II tries to address the challenge of unreliable single-trial ERP classification.

Chapter 2 reviews the ERP-based BCIs. A so-called Farwell-Donchin stimulus paradigm used to encode user's intention is introduced. Then, the intention decoding algorithms are also introduced in detail. More importantly, we indicate the dominance of supervised learning methods for ERP-based BCIs. Finally, we introduced performance measures for evaluating ERP-based BCIs. Although the ERP-based BCIs have shown their wide success during the past more than 20 years, there are still several technical challenges (two issues introduced in Chapter 1) existed, which hinder the practical using of the ERP-based BCIs.

Chapter 3 concentrates on **THEME I** of this dissertation, which is about how to elicit more discriminable ERP signals by optimizing stimulus paradigm. We are motivated to optimize stimulus paradigm to elicit more discriminable target and non-target ERPs. Thus, we review the previous studies on optimizing stimulus paradigm. Surprisingly, the classical Farwell-Donchin paradigm has not been comprehensively optimized in terms of spatial manipulation, such as stimulus size and inter-stimulus distance. Consequently, we investigate the stimulus-size effect and inter-stimulus distance effects on ERPs, respectively. Based on the spatial manipulation of the stimulus paradigm, we devise a 3×3 matrix paradigm with larger stimulus size and larger inter-symbol distance, compared with conventional 8×8 matrix paradigm. In order to keeping the degree of communication freedom (DOCF) same with the 8x8 matrix paradigm, a two-level strategy is applied for the 3×3 matrix paradigm. Moreover, a statistical language model is integrated into the two-level 3×3 matrix paradigm to further improve the efficiency of the BCI operation. Finally, the optimized ERP-based BCI paradigm based on spatial manipulation and information theory is named as 3×3 two-level predictive (TLP) paradigm. The 3×3 TLP paradigm is expected to elicit more discriminable ERP signals (i.e., larger P300 potentials), which may increase BCI operation accuracy. Moreover, the TLP paradigm may further improve BCI operation efficiency due to predictive technology applied.

Chapter 4 devotes to **THEME II** of this dissertation, which is about the proposed trial-based ERP classification algorithm. Main contributions of the chapter are: 1. we propose a more reasonable ERP model; 2. Ensemble of epochs within-trial strategy is proposed and implemented in maximum a posterior (MAP) approach. First, we state straightforward trial-based approach for ERP-decoding. However, this method has never been successfully applied in any practical system. This should be attributed to “curse of dimension” issue of multi-class classification. Then, we elaborate current state-of-the-art epoch-based approach including their theoretical ERP models. However, this approach suffers from low signal-to-noise ratio (SNR) of EEG signals and a so-called “overlap” effect. Learnt their strengths and avoided their weaknesses, we propose a trial-based ERP classification method. The method is built on a more reasonable multi-class ERP model in order to overcome the “overlap” effect. It integrates all ERP-epochs within-trial and fuses natural language information to compensate the low

SNR of ERP-epochs. Therefore, the proposed method is expected to achieve a better ERP decoding performance.

Chapter 5 describes the experiment protocols designed to verify our approaches proposed in each of the two themes: (1) Whether the proposed 3×3 TLP paradigm could elicit larger ERPs, compared with the classical Farwell-Donchin paradigm; (2) whether the proposed ERP classifier could outperform straightforward trial-based classifiers and state-of-the-art epoch-based classifiers. Moreover, subjective behavior data are also collected during experiments, such as visual fatigue, etc.

Firstly, as we expected, the 3×3 matrix paradigm (Cz: 5.73 μV) elicited significantly larger P300 potentials, compared with the 8×8 one (Cz: 4.05 μV). Larger P300 might be particularly important for clinical application, because ALS patients usually suffer from P300 attenuations. Moreover, the 3×3 paradigm achieved less visual fatigue and easier gaze deployment. Larger P300 potentials naturally lead to better discriminant performance (single-trial binary ERP classification accuracy: 79.05% ± 2.22% (3×3) vs. 73.20% ± 2.03% (8×8)). This should be attributed to larger target ERP amplitudes and relatively smooth background activities generated under the 3×3 paradigm.

Secondly, online accuracy and ITR were significantly higher by 20.83% and 33.60% for the 3×3 TLP compared to the conventional 8×8 row/column (RC) paradigm, respectively. Time to complete a spelling task (correctly spell an English sentence with 57 symbols) was also significantly decreased by 36.45% for the 3×3 TLP. It is worth noting that two subjects could even improve their online accuracies from below 50% to more than 80% with the transition from the 8×8 RC to the 3×3 TLP. The results were due to the fact that high single-step accuracy was achieved by the 3×3 SC and redundant steps were partly reduced by applying predictive technology.

Thirdly, totally 18 heterogeneous ERP-decoding methods are compared. They include 12 straightforward trial-based 9-class SVMs, 4 conventional epoch-based methods (NCC, swLDA, lSVM, gSVM), and the proposed method with/without statistical language model. The proposed method with subject-optimal k-order and n-gram significantly outperformed all other methods in terms of single-trial ERP classification accuracies. Note that single-trial ERP classification accuracies (76.26% ± 2.06%) for the proposed method were increased by 18.01% when compared with state-of-the-art swLDA (64.62% ± 2.89%). Why the proposed method seems to be successfully on single-trial ERP classification? First, it reduced the overlap effect since k-order multi-class ERP model applied. Second, the classifier output based on trial-feature and statistical language information was significantly more robust. Third, the proposed method could be well trained even by limited training samples. It is worth noting that subjects with low accuracy achieved by conventional methods profit more than subjects with high accuracy. This might be promising for clinical application, since motor-impaired patients usually suffer from low accuracy. Moreover, current gaze-independent BCIs are still incomparable with the BCIs rely on overt attention in terms of accuracy, or they need more stimulus repetition. The proposed approach may improve their performances.

Chapter 6 makes conclusions. The principal results demonstrate that the significantly larger EPRs are elicited by spatial optimization of the classical Farwell-Donchin paradigm, dramatically improved online performances in terms of accuracy, information transfer rate, and speed are achieved by further incorporating a statistical language model into the optimized stimulus paradigm, and significantly higher single-trial ERP classification accuracy is achieved by integrating within-trial epochs (multiclass ERP model) and fusing prior language knowledge (statistical language model) in MAP (Maximum A Posteriori) approach.

In summary, the results presented in this dissertation encompass two advances that are critical to the successful translation of brain-computer interface from their current state of primarily laboratory demonstrations into practical communication devices for the paralyzed.