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ORIGINAL ARTICLE/ARTICLE ORIGINAL

Online denoising of eye-blinks in electroencephalography

Débruitage en ligne de clignements des yeux en électro-encéphalographie

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Summary
Objective. — Due to its high temporal resolution, electroencephalography (EEG) has become a broadly-used technology for real-time brain monitoring applications such as neurofeedback (NFB) and brain—computer interfaces (BCI). However, since EEG signals are prone to artifacts, denoising is a crucial step that enables adequate subsequent data processing and interpretation. The aim of this study is to compare manual denoising to unsupervised online denoising, which is essential to real-time applications.
Methods. — Denoising EEG for real-time applications requires the implementation of unsupervised and online methods. In order to permit genericity, these methods should not rely on electrooculography (EOG) traces nor on temporal/spatial templates of the artifacts. Two blind source separation (BSS) methods are analyzed in this paper with the aim of automatically correcting online eye-blink artifacts: the algorithm for multiple unknown signals extraction (AMUSE) and the approximate joint diagonalization of Fourier cospectra (AJDC). The chosen gold standard is a manual review of the EEG database carried out retrospectively by a human operator. Comparison is carried out using the spectral properties of the continuous EEG and event-related potentials (ERP).
Results and conclusion. — The AJDC algorithm addresses limitations observed in AMUSE and outperforms it. No statistical difference is found between the manual and automatic approaches on a database composed of 15 healthy individuals, paving the way for an automated, operator-independent, and real-time eye-blink correction technique.

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MOTS CLÉS
Clignement des yeux ;
Débruitage ;
Électro encéphalographie ;
En ligne ;
Non supervisé ;
Séparation aveugle de sources

Résumé

Objectifs. — Grâce à sa haute résolution temporelle, l'électro-encéphalographie (EEG) est devenue une technologie répandue pour des applications de suivi de l'activité cérébrale en temps-réel, comme le *neurofeedback* (NFB) et les interfaces cerveau—machine (ICM). Cependant, les signaux EEG étant sensibles aux artéfacts, le débruitage est une étape essentielle qui permet un traitement et une interprétation convenables de la donnée. Le but de cette étude est de comparer les méthodes de débruitage manuel et de débruitage en ligne non supervisé, essentiel pour les applications temps-réel.

Méthodes. — Débruiter l'EEG pour des applications temps-réel exige l'implémentation de méthodes de débruitage en ligne non-supervisées. De plus, afin d'être génériques, ces méthodes ne devraient pas s'appuyer sur une référence électro-oculographique (EOG), ni sur un modèle temporel ou spatial des artéfacts. Deux méthodes de séparation aveugle de source (SAS) sont analysées dans ce papier avec le but d'automatiquement corriger en ligne les artéfacts de clignements des yeux : l'algorithme d'extraction de multiples signaux inconnus (AEMSI) et la diagonalisation conjointe approchée des cospectres de Fourier (DCAC). Le test de référence choisi est l'examen manuel de la base de données complète, réalisée rétrospectivement par un opérateur humain. La comparaison est réalisée en utilisant les propriétés spectrales de l'EEG continu et les potentiels évoqués.

Résultats et conclusion. — L'algorithme DCAC résout les limitations observes dans AEMSI et s'avère plus performant. Aucune différence statistique n'est trouvée entre les approches manuelle et automatique sur une base de données composée de 15 sujets sains, ouvrant la voie pour une technique de correction de clignement des yeux automatique, sans opérateur et temps-réel.

Introduction

Electroencephalography (EEG) is a non-invasive measure of cerebral electrical potentials recorded at several scalp locations. Due to its high temporal resolution and portability, EEG has become a broadly-used technology for brain monitoring [45]. Unfortunately, EEG time-series are prone to several different types of artifacts, i.e., electric potentials that are not generated by the brain. Artifacts may have biological, instrumental or environmental origin. Occasionally, their energy may be some order of magnitude greater than that of the neurophysiological signal of interest [12,76]. In this context, proper denoising is a crucial step for EEG data analysis [30]. *Denoising* refers to the removal of components/sources that are not considered ''useful'' or ''informative'' with respect to the application. Many methods have been developed for this purpose [20,29,73,81,82]. With respect to their data processing procedure, the denoising methods can be classified into four categories, which we have termed: manual, offline, block—online and online (Fig. 1). These are defined below:

- *manual*: the complete recording is available, from beginning to end. A human operator inspects the recording on an epoch-by-epoch basis and marks artifactual epochs. Epochs containing artifacts are either entirely rejected (approach not considered in this study), or the artifactual sources are rejected, thus providing denoised/corrected epochs [35,80,84];
- *offline*: the complete recording is available, from beginning to end, and is processed automatically by an expert algorithm, such as FASTER [57], MARA [90], ADJUST [51], PureEEG [27], SASICA [8] or Autoreject [32];
- *block online*: The recording is processed automatically on an epoch-by-epoch basis, with epoch length greater than 500 ms, for instance, as in LAMIC [56] or FORCe [16]. Block-online unsupervised approaches typically require blocks (sometimes called trials) of about 1 to 4 s length [16,23,56];
- *online*: the recording is processed online as before, but instantaneously. Although these methods may work on a sample-by-sample basis, the EEG acquisition in practice is carried out by buffered blocks. These methods are different from those belonging to the previous category in that the block size may be very small (typically, 10 to 50 ms). In this way, the processing may be considered as ''real-time''.

The *manual* procedure is often considered the gold standard in terms of quality [35]. However, it is fully supervised and thus time-consuming. It also introduces an operator-dependent bias with consequent problems of consistency and repeatability. Automated offline approaches can exploit the whole EEG database, and thus are generally efficient in addition to being consistent [8,57]. Some of these offline approaches require an initial supervised calibration to learn detection thresholds [51] or classifiers [39,66,90]. Obviously, neither the *manual* nor the *offline* procedure is of any use in