Artificial Intelligence in Medicine 59 (2013) 61–69

Contents lists available at ScienceDirect

Artificial Intelligence in Medicine

journal homepage: www.elsevier.com/locate/aiim

Asynchronous gaze-independent event-related potential-based brain–computer interface

Fabio Aloise [a,b,*], Pietro Aricò [a,b], Francesca Schettini [a,b], Serenella Salinari [b], Donatella Mattia [a], Febo Cincotti [a,b]

[a] Neuroelectrical Imaging and BCI Lab, Fondazione Santa Lucia IRCCS, Via Ardeatina 306, 00142 Rome, Italy
[b] Department of Computer, Control, and Management Engineering Antonio Ruberti, Sapienza University, Via Ariosto 25, 00185 Rome, Italy

ARTICLE INFO

Article history:
Received 11 November 2012
Received in revised form 30 July 2013
Accepted 31 July 2013

Keywords:
Asynchronous classifier
Event-related potentials
Brain–computer interface
Gaze-independent brain–computer interface
Covert attention

ABSTRACT

Objective: In this study a gaze independent event related potential (ERP)-based brain computer interface (BCI) for communication purpose was combined with an asynchronous classifier endowed with dynamical stopping feature. The aim was to evaluate if and how the performance of such asynchronous system could be negatively affected in terms of communication efficiency and robustness to false positives during the intentional no-control state.
Material and methods: The proposed system was validated with the participation of 9 healthy subjects. A comparison was performed between asynchronous and synchronous classification technique outputs while users were controlling the same gaze independent BCI interface. The performance of both classification techniques were assessed both off-line and on-line by means of the efficiency metric introduced by Bianchi et al. (2007). This latter metric allows to set a different misclassification cost for wrong classifications and abstentions. Robustness was evaluated as the rate of *false positives* occurring during voluntary no-control states.
Results: The asynchronous classifier did not exhibited significantly higher accuracy or lower error rate with respect to the synchronous classifier (accuracy: 74.66% versus 87.96%, error rate: 7.11% versus 12.04% respectively). However, the on-line and off-line analysis revealed that the communication efficiency was significantly improved ($p < .05$) with the asynchronous classification modality as compared with the synchronous. Furthermore, the asynchronous classifier proved to be robust to false positives during intentional no-control state which occur during the ongoing visual stimulation (less than 1 false positive every 6 min).
Conclusion: As such, the proposed ERP-BCI system which combines an asynchronous classifier with a gaze independent interface is a promising solution to be further explored in order to increase the general usability of ERP-based BCI systems designed for severely disabled people with an impairment of the voluntary control of eye movements. In fact, the asynchronous classifier can improve communication efficiency automatically adapting the number of stimulus repetitions to the current user's state and suspending the control if he/she does not intend to select an item.

1. Introduction

Brain–computer interfaces (BCIs) have great potential in providing people who have severe neuromuscular disabilities with an alternative and augmentative communication channel to operate assistive technology devices. To this end, the design of BCI systems should consider aspects of usability with regard to the user interface and the paradigms that are adapted to comply with real-life situations [1]. Recently, increased attention has been paid to newly designed and more effective visual stimulation paradigms for gaze-independent electroencephalogram (EEG)-based BCIs [2].

Visual stimulation paradigms that exploit covert attention [3] phenomena have been applied to BCIs that are based on steady-state visual-evoked potentials (SSVEPs [4,5]) and event-related potentials (ERPs), such as the P300 potential [6–9]. In a recent study, *easiness to use* – measured in terms of effectiveness (i.e., accuracy of the system [10,11]), efficiency (the mental workload that is perceived by the user of the system and assessed by NASA-tlx, for example [12]), and satisfaction (a measure of the immediate and long-term comfort and acceptability of the overall system [13]) – of an eye gaze-independent interface that has been integrated into an ERP-based BCI system was compared with the classical Farwell and Donchin speller [14]. The efficiency and user satisfaction did

* Corresponding author at: Neuroelectrical Imaging and BCI Lab, Fondazione Santa Lucia IRCCS, Via Ardeatina 306, 00142 Rome, Italy. Tel.: +39 06 5150 1456.
E-mail address: f.aloise@hsantalucia.it (F. Aloise).

0933-3657/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.artmed.2013.07.006

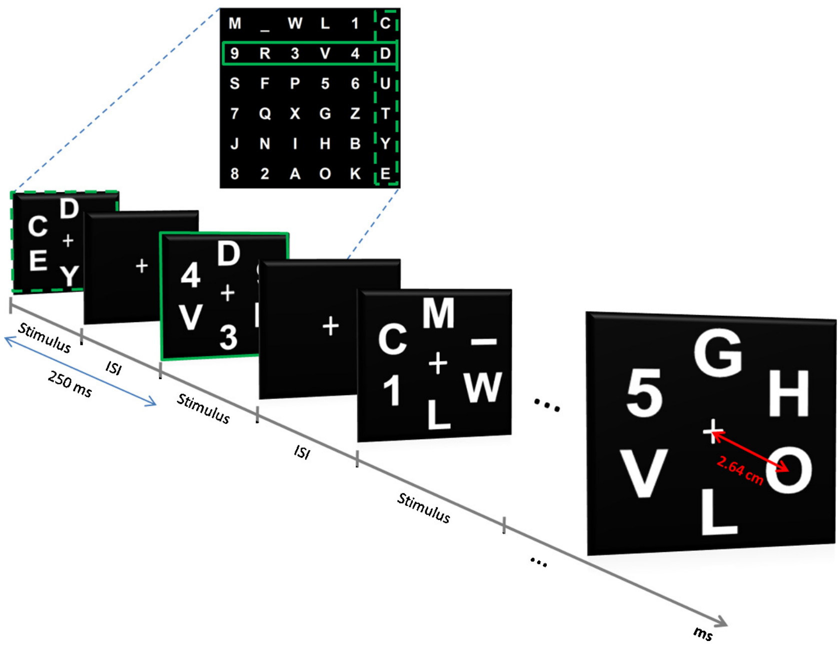

Fig. 1. The GeoSpell interface. The rows and columns of the classic Farwell and Donchin's P300 Speller are reorganized in 12 groups. Each group contains 6 characters placed at the vertices of an hexagon, 2.64 cm distant from a fixation cross in the center. Each character belongs to two groups where it has the same spatial position.

not differ significantly between the 2 interfaces, and the efficacy of the former exceeded the accuracy threshold for effective spelling (>70% [15]).

To increase the overall usability of a BCI system in a real-life context, the system should not deliver commands when system control is intended to keep the output neutral or unchanged (voluntary no-control). This mode of operation, defined as asynchronous [16], has been implemented in several BCIs that have examined various features of EEGs, such as sensory motor rhythms [17–20], high frequency SSVEPs [21], and ERPs [22–24]. Other asynchronous paradigms that combine control features have been proposed, such as the P300 potential with SSVEPs [25] and N200 potential with motion visual-evoked potentials (mVEPs, [26]).

Current ERP-based asynchronous BCI systems provide solutions only for a dynamic adaptation of the number of repetitions of the stimulus to the user's actual psychophysiological state, whereas they are unable to abstain from issuing a command if the user diverts his attention from the stimulation or if the EEG signal is not sufficiently reliable. This limit was first addressed by Zhang et al. [27], who implemented a statistical model. Later Aloise et al. [28] proposed a classification algorithm with the introduction of certain thresholds to distinguish between a subject's voluntary control and a no-control state and dynamically adapt the number of stimuli per selection. This approach was validated in healthy subjects [28] and potential end-users [29]. This system was also evaluated with regard to communication efficiency (as defined by Bianchi et al. [30]), and the asynchronous system had greater efficiency in terms of communication speed and time to recover from errors compared with the synchronous version [31].

Based on our earlier studies [14,28,29], we have combined an ERP-based BCI system, operated by gaze-independent stimulation interface, with a classifier that delivers its decision (or abstains from making a decision) after a variable number of stimulation sequences, depending on the quality of the input signal and the user's intention.

Our rationale is based on the following considerations. In visual gaze-independent ERP-based interfaces, the spatial distribution of target and no-target stimuli in the visual field is the same, increasing the difficulty in discriminating stimuli for the user. Earlier studies [8,14] on gaze-independent BCIs have demonstrated that under such conditions, the short-latency visual-evoked potentials (VEPs) that are induced by target or no-target stimuli do not differ and that the elicited P300 potential generally has a lower amplitude and lower temporal stability (increase in latency jitter [32]) with respect to classical matrix-based interfaces.

Thus, factors might prevent the correct selection of threshold values for the asynchronous classifier that is to be operated due to the lack of varying short-latency VEP responses in the classification process [33], possibly leading to decreased accuracy. Another limit might be encountered in the correct discrimination of control and no-control states when the subject fails to divert his gaze from the stimulation interface, rendering the induced ERPs to be similar between the 2 states.

We examined the effectiveness (expressed as the accuracy of the system and its reliability against false positives) and communication efficiency, which takes into account errors and unwanted abstentions ([30], see below for details), of the gaze-independent ERP-based BCI speller, hypothesizing that the performance of the applied asynchronous classifier is not negatively affected by the covert operation mode.

2. Materials and methods

2.1. Participants and study design

Nine healthy subjects (mean age = 26.4 ± 4.4 years) gave their written informed consent for participation in the study, which was approved by the local ethical committee of Fondazione Santa Lucia, IRCCS Rome, Italy. All subjects had previous experience with ERP-based BCI systems and had normal or corrected-to-normal vision.

In the GeoSpell stimulation interface (Fig. 1), the 36 alphanumeric characters of the Farwell and Donchin speller are arranged on the vertices of 12 hexagons; we refer to each hexagon herein as a group or stimulation class. Each character belongs to 2 groups, in which it is displayed on the same vertex. A fixation cross was displayed at the center of the stimulation interface at all times. The distance between the fixation cross and each character was fixed