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Editorial

Toward gaze-independent brain-computer interfaces

See Articles, pages 893–900 and 901–908

The ability to communicate by speech, text or gestures is essential to human interaction. This ability is impaired in many people who are affected by debilitating neuromuscular disorders such as amyotrophic lateral sclerosis (ALS), brainstem stroke, or spinal cord injury. Conventional assistive devices (e.g., letter boards, cheek or tongue switches, or eye trackers) that aim to restore communication functions all require muscular control, which is often lost in the progress of neuromuscular disorders.

A brain-computer interface (BCI) uses brain signals, rather than muscular control, to establish communication with the outside world. Thus, BCI systems may be useful for restoring communication functions to people with or without disabilities. Many BCI systems described in the literature are based on event-related potentials (ERPs). In an ERP-based BCI system, the user communicates his intention by selectively attending to a desired external stimulus. ERPs are different for desired and undesired stimuli. The BCI system uses this difference to determine the desired stimulus from the brain signals. One well-known implementation of an ERP-based BCI is the so-called "P300 matrix speller" that was first described by (Farwell and Donchin, 1988). In this system, the user pays attention to a character in a matrix while each row and column is intensified rapidly and randomly. The brain produces ERPs to the row or column containing the intended character; ERPs are smaller for the other rows or columns. The BCI typically averages several ERPs, detects the row and column with the strongest ERP, and thereby identifies the character the user wants to select.

The ERPs in question are composed of an endogenous component (modulated by covert attention), as well as an exogenous visual-evoked potential (VEP) component. The communication performance of the matrix-speller depends on the extent to which these two ERP components are modulated by attention to the target stimulus. As a result, most of the work on ERP-based BCI systems has focused on optimizing the stimulation parameters to maximize the ERP response to the target stimulus. These parameters included matrix size (Allison and Pineda, 2003), stimulation frequency (Sellers et al., 2006), and stimulation intensity (Takano et al., 2009).

By combining optimized stimulation parameters and improved classification algorithms (Krusienski et al., 2006), a recent study (Guger et al., 2009) showed that 80% of the healthy population can make effective use of the matrix speller BCI. The wide applicability of this approach in people without disabilities has been further demonstrated in several application contexts, such as web browser navigation (Mugler et al., 2008), environmental control (Edlinger et al., 2009), wheelchair navigation (Rebsamen et al., 2007), and mouse movement (Citi et al., 2008). In addition to work in healthy individuals, several studies have also evaluated the utility of the matrix speller for restoring communication function in severely disabled individuals (Hoffmann et al., 2008; Kübler and Birbaumer, 2008; Nijboer et al., 2008; Piccione et al., 2006; Sellers et al., 2006; Sellers et al., 2010; Silvoni et al., 2009; Vaughan et al., 2006; see Donchin and Arbel, 2009 or Mak and Wolpaw, 2009 for comprehensive reviews). These studies clearly established that the matrix speller can in fact be operated by people with disabilities. At the same time, the communication performance reported in these studies with disabled individuals typically remains below what is reported in similar studies with healthy individuals.

The apparent decrease in spelling performance in patients compared to healthy individuals may be related in part to cognitive impairment (Phukan et al., 2007) or to the inability to maintain gaze. Eye gaze is often impaired or lost in subjects affected by ALS: although some people with ALS maintain residual eye movement for years (Cohen and Caroscio, 1983; Palmowski et al., 1995; Birbaumer and Cohen, 2007), others progress to near-complete or complete paralysis. This is problematic, because recent studies (Brunner et al., 2010; Treder and Blankertz, 2010) showed that the traditional design of the matrix speller not only relies on the P300 evoked potential, which does not depend on eye gaze, but also on other ERP components such as visual evoked potentials, which strongly depend on foveation and thus the ability to control eye gaze direction. This dependence of the matrix speller BCI limits the practical value of this BCI approach for individuals that will lose the ability to maintain gaze in the progress of their disease.

Recent studies have pursued two avenues to remove or mitigate this limitation. The first avenue has been to replace visual stimulation with stimulation of other sensory modalities such as the auditory (Klobassa et al., 2009; Kübler et al., 2009; Schreuder et al., 2010; Hill and Schölkopf, 2012; Hill et al., 2012) or tactile senses (Brouwer and van Erp, 2010; van der Waal et al., 2012). While auditory and tactile BCIs do not depend on eye gaze, they have three major shortcomings: (i) useful communication performance (i.e., >70% accuracy as suggested by Kübler et al., 2001) is limited to a small set of symbols (e.g., Guo et al., 2010, 4.2 selections per minute, 86% accuracy, 8 symbols); (ii) selections are performed indirectly by mapping non-visual stimuli such as tones to symbols (e.g., alphabetic characters, see Riccio et al., 2012 for review); and (iii) attention to non-visual sensory stimulation (e.g., in an auditory ERP speller) requires higher workload than attention to visual stimulation (Käthner et al., 2013). Because of these three shortcomings, auditory and tactile BCIs are rarely adopted by patients

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that have not yet fully progressed to a stage where they lost their ability to control eye gaze.

The second avenue for mitigating the limitations of the traditional matrix speller has been to optimize the visual interface of the matrix speller by presenting the visual stimuli near the center of foveation. This not only overcomes the dependence on eye gaze, but also supports direct selection from a full set of alphabetic symbols. Using this approach, recent papers report up to 2.4 selections per minute with close to 95% accuracy for a set of 30 symbols (Acqualagna et al., 2010; Acqualagna and Blankertz, 2011; Liu et al., 2011; Treder and Blankertz, 2010; Treder et al., 2011). While these results are encouraging, the communication performance of this new generation of speller designs, which do not depend on eye gaze, still remains below that of the traditional matrix-speller BCIs (e.g., 4–6 characters per minute, Nijboer et al., 2008; Sellers et al., 2010; Townsend et al., 2010; Lu et al., 2013). It is possible that this drop in performance may be addressed by broadening the focus of these designs beyond just the P300 component.

Different studies have tested this hypothesis by investigating stimulus presentation paradigms that also modulate ERPs other than the P300. These paradigms included moving stimuli that elicit motion visual evoked potentials (M-VEPs, Guo et al., 2008; Hong et al., 2009) and face stimuli that elicit ERPs involved in face recognition (i.e., the N170 and N400f ERPs, Kaufmann et al., 2011,Kaufmann et al., 2013; Zhang et al., 2012), and resulted in improved spelling performance.

The paper by Acqualagna and Blankertz aimed to determine whether the N200 and P300 components could both be modulated by covert attention, i.e., without shifting gaze, in a BCI context. Specifically, they implemented a rapid serial visual presentation (RSVP) paradigm in which letters were presented one-by-one in random order at the center of the screen. To improve the modulation of the N200 and P300 components, the authors enhanced the differences between the shapes of the different letters using different fonts and colors.

This study in twelve healthy subjects reported an average accuracy of 95% (3.3% chance) at a rate of about 1.4 characters per minute, which presents an improvement over previous RSVP BCI designs with the same stimulus timing. This improved performance is presumably achieved in part because this design modulates both the N200 and the P300 components, and thus provides additional information that is useful for the identification of the attended stimulus.

In summary, the experimental paradigm described in Acqualagna and Blankertz, (2013) modulates the N200 and P300 components without requiring the subject to shift gaze. Similar approaches may eventually lead to ERP-based spellers that modulate a range of ERPs (e.g., N170, N200, N400f and P300) by covert attention, without the need to shift gaze. In conclusion, with additional validation in people affected by debilitating neuromuscular disorders and limited gaze, this approach may provide the basis for an effective and practical brain-based spelling solution for this population. Thus, the results presented in this study further encourage the exploration of the value of this and similar BCI approaches for restoration of communication function in people with severe neuromuscular disorders.

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Peter Brunner [a,b,c,*]

Gerwin Schalk [a,b,d,e,f]

[a] *Brain-Computer Interface R&D Program, Wadsworth Center, New York State Department of Health, Albany, NY, USA*

[b] *Department of Neurology, Albany Medical College, Albany, NY, USA*

[c] *Institute for Computer Graphics and Vision, Graz University of Technology, Graz, Austria*

[d] *Department of Neurological Surgery, Washington University School of Medicine, St. Louis, MO, USA*

[e] *Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA*

[f] *Department of Biomedical Sciences, School of Public Health, State University of New York at Albany, Albany, NY, USA*

* *Address: Brain-Computer Interface R&D Program, New York State Department of Health, C654 Empire State Plaza, Albany, NY 12201, USA. Tel.: +1 518 402 5747; fax: +1 518 486 4910.*

E-mail addresses: pbrunner@wadsworth.org (P. Brunner), schalk@wadsworth.org (G. Schalk)

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