

# Brain-computer interface (BCI) operation: signal and noise during early training sessions

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## Abstract

**Objective:** People can learn to control mu (8–12 Hz) or beta (18–25 Hz) rhythm amplitude in the electroencephalogram (EEG) recorded over sensorimotor cortex and use it to move a cursor to a target on a video screen. The recorded signal may also contain electromyogram (EMG) and other non-EEG artifacts. This study examines the presence and characteristics of EMG contamination during new users' initial brain-computer interface (BCI) training sessions, as they first attempt to acquire control over mu or beta rhythm amplitude and to use that control to move a cursor to a target.

**Methods:** In the standard one-dimensional format, a target appears along the right edge of the screen and 1 s later the cursor appears in the middle of the left edge and moves across the screen at a fixed rate with its vertical movement controlled by a linear function of mu or beta rhythm amplitude. In the basic two-choice version, the target occupies the upper or lower half of the right edge. The user's task is to move the cursor vertically so that it hits the target when it reaches the right edge. The present data comprise the first 10 sessions of BCI training from each of 7 users. Their data were selected to illustrate the variations seen in EMG contamination across users.

**Results:** Five of the 7 users learned to change rhythm amplitude appropriately, so that the cursor hit the target. Three of these 5 showed no evidence of EMG contamination. In the other two of these 5, EMG was prominent in early sessions, and tended to be associated with errors rather than with hits. As EEG control improved over the 10 sessions, this EMG contamination disappeared. In the remaining two users, who never acquired actual EEG control, EMG was prominent in initial sessions and tended to move the cursor to the target. This EMG contamination was still detectable by Session 10.

**Conclusions:** EMG contamination arising from cranial muscles is often present early in BCI training and gradually wanes. In those users who eventually acquire EEG control, early target-related EMG contamination may be most prominent for unsuccessful trials, and may reflect user frustration. In those users who never acquire EEG control, EMG may initially serve to move the cursor toward the target. Careful and comprehensive topographical and spectral analyses throughout user training are essential for detecting EMG contamination and differentiating between cursor control provided by EEG control and cursor control provided by EMG contamination.

**Significance:** Artifacts such as EMG are common in EEG recordings. Comprehensive spectral and topographical analyses are necessary to detect them and ensure that they do not masquerade as, or interfere with acquisition of, actual EEG-based cursor control.

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*Keywords:* Sensorimotor cortex; Mu rhythm; Electroencephalography; Learning; EEG; Brain-computer interface

## 1. Introduction

Many people with severe motor disabilities require alternative methods for communication and control.

Over the past decade, a number of studies have evaluated the possibility that scalp-recorded electroencephalogram (EEG) activity might be the basis for a brain-computer interface (BCI), a new augmentative communication interface that does not depend on muscle control (Birbaumer et al., 1999; Farwell and Donchin, 1988; Kostov and Pollack, 2000; Kubler et al., 1999; Pfurtscheller et al., 1993;

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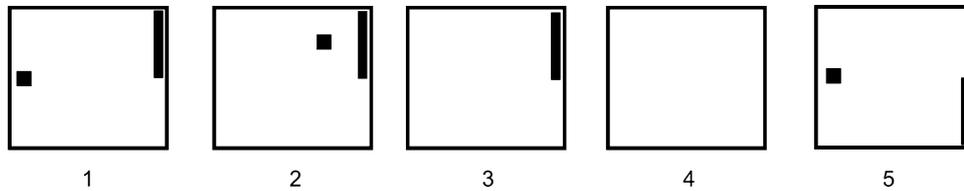


Fig. 1. Cursor control protocol. (1) The target and cursor are present on the screen for 1 s. (2) The cursor begins to move across the screen for 2 s, with its vertical movement controlled by the user. (3) The target flashes for 1.5 s, when it is hit by the cursor. (4) The screen is blank for a 1 s interval. (5) The next trial begins.

Sutter, 1992; Wolpaw et al., 1991; reviewed in Kubler et al. (2001) and Wolpaw et al. (2002)). EEG-based communication systems measure specific features of EEG activity and use the results as control signals. In some systems, these features are potentials evoked by stereotyped stimuli (Farwell and Donchin, 1988; Sutter, 1992). Other systems, such as our own, use EEG features that are spontaneous in the sense that they are not dependent on specific sensory events (Birbaumer et al., 1999; McFarland et al., 1993; Pfurtscheller et al., 1993).

With our current EEG-based communication system, users learn over a series of training sessions to use EEG to move a cursor on a video screen (see McFarland et al. (1997a) for full system description). During each trial, the user is presented with a target along the right edge of the screen and a cursor on the left edge (Fig. 1). The cursor moves across the screen at a steady rate, with its vertical movement controlled by EEG amplitude in a specific frequency band at one or several scalp locations. The user's task is to move the cursor to the height of the target so that it hits the target when it reaches the right edge of the screen. At present, cursor movement is typically controlled either by the amplitude of mu-rhythm activity, which is 8–12 Hz activity focused over sensorimotor cortex, or by the amplitude of higher frequency (e.g. 18–25 Hz) beta rhythm activity, also focused over sensorimotor cortex.

Effective BCI operation has several requirements. First, the user must learn to control the EEG feature, such as mu-rhythm amplitude, that determines cursor movement. Second, signal processing must extract the EEG feature from background noise. For example, we use spatial filtering operations that improve the signal-to-noise ratio (McFarland et al., 1997b). Third, the system must translate

this feature into cursor movement so that the user is able to reach each of the possible targets. In our system, cursor movement is a linear function of mu-rhythm amplitude. This linear function has two parameters, an intercept and a slope. We use an adaptive algorithm to select values for these parameters that make all the targets equally accessible to the user (McFarland et al., 1997a; Ramoser et al., 1997).

Electromyographic (EMG) activity from scalp and facial muscles and electrooculographic (EOG) activity from eye movements and eyeblinks may constitute artifacts that obscure the EEG activity used by a BCI system (Goncharova et al., 2003; McFarland et al., 1997a). Increase in EMG from facial muscles is a normal response to difficult tasks (Cohen et al., 1992; Waterink and von Boxtel, 1994). EOG may correlate with cognitive load (Ohira, 1996). EMG and EOG artifacts may masquerade as EEG; and, unless care is taken, some people may actually control cursor movements with these artifacts rather than with EEG. These non-EEG artifacts can be detected and differentiated from actual sensorimotor rhythm control by sufficiently comprehensive spectral and topographical analyses (Wolpaw et al., 2002). This study examines EMG contamination in new BCI users during their first 10 training sessions. The central goal was to explore the relationship between EMG artifacts and the acquisition of EEG control.

## 2. Methods

### 2.1. Users

The BCI users were 7 adults (2 woman and 5 men, ages 26–49) (Table 1). Five of these users were from a

Table 1  
User characteristics, training parameters, and initial and final performance levels

User	Age	Gender	Disability	Frequency (Hz)	Control locations	Accuracy (%) Session 1	Accuracy (%) Session 10 <sup>a</sup>
A	26	M	None	12	C3	93	100.0
B	29	M	None	13	CP3,C4	93	97
C	38	F	None	10	CP4,CP3	81	93
D	40	M	T7 SCI <sup>b</sup>	10	C3	68	96
E	49	F	None	24	C3,CP4	59	80
F	32	M	C6 SCI	12	C3,C4	78	58
G	44	M	None	12	C3,C4	68	48

<sup>a</sup> For Users A–C, who acquired control quickly and moved to the 3-choice format on Session 3 or 4, this value is for the final two-choice session.

<sup>b</sup> Spinal cord injury.

consecutive series. The other two were selected from many users studied over a 7 year period to provide representative examples of the presence and characteristics of EMG contamination in initial BCI training. Five had no disabilities. Two had spinal cord injuries (one at T7 and one at C6) and were confined to wheelchairs. All gave informed consent for the study, which had been reviewed and approved by the New York State Department of Health Institutional Review Board. After an initial evaluation defined the frequencies and scalp locations of each person's spontaneous mu- and beta-rhythm activity, he or she learned EEG-based cursor control (2–3 sessions/week) over several months. The data presented here comprise each user's first 10 training sessions.

## 2.2. BCI training protocol and data collection

The user sat in a reclining chair facing a 51 cm video screen 3 m away, and was asked to remain motionless during performance. Scalp electrodes recorded 64 channels of EEG (Sharbrough et al., 1991), each referenced to an electrode on the right ear (amplification 20,000; bandpass 1–60 Hz). A subset of channels located over sensorimotor cortex (Table 1) were digitized at 196 Hz and used to control cursor movement online as described below. In addition, all 64 channels were digitized at 128 Hz and stored for later analysis.

The user controlled vertical cursor movement as the cursor moved horizontally across the screen at a fixed rate. Thus, as Fig. 1 shows, the cursor moved vertically under user control and horizontally under computer control. The user's task was to move the cursor vertically so as to intercept the target. The distance from the left edge to the right edge of the screen was 308 steps. The trial ended when the cursor touched the right edge and thereby hit or missed the target. To control vertical cursor movement, one or two EEG channels over sensorimotor cortex of one or both hemispheres were derived from the digitized data according to either a common average reference method or a Laplacian transform (McFarland et al., 1997b). Every 100 ms, the most recent 200 ms segment from each channel was analyzed by an autoregressive algorithm (Marple, 1987), and the amplitude (i.e. square root of power) in a 3 Hz-wide mu- or beta-rhythm frequency band was calculated. The amplitudes of the 1–2 channels were combined to produce an EEG control signal according to our standard algorithm, in which cursor movement is a linear function of the EEG control signal (McFarland et al., 1997a). That is, if  $\Delta V$  was the cursor movement,  $S$  was the control signal,  $b$  was the gain, and  $a$  was the mean control signal for the user's previous performance,

$$\Delta V = b(S - a) \quad (1)$$

was the function that determined each cursor movement. (This form of the linear equation is used so that  $a$  and  $b$  can

be defined independently of each other.) The intercept  $a$  was defined as the average value of the signal,  $S$ , for the last 3 trials with each target (i.e. for the two-choice format, this was the average of  $S$  for the 3 most recent top targets and the 3 most recent bottom targets) (McFarland et al., 1997a). Thus, the intercept minimized directional bias, maximized the influence that the user's EEG control had on the direction (i.e. upward or downward) of cursor movement, and helped make all targets equally accessible. The slope (or gain)  $b$  determined the magnitude of the cursor movement for a given value of  $(S - a)$ .

Each session consisted of 8 3 min runs separated by 1 min breaks, and each run consisted of 20–30 trials. As illustrated in Fig. 1, each trial consisted of a 1 s period between target appearance and cursor movement, a 2 s period during which cursor movement occurred, a 1.5 s post-movement reward period, and a 1 s inter-trial interval. After users learned the two-target version, 3-, 4-, and 5-target versions were gradually introduced. Because the present report focuses on initial training, the analyses are limited to the first 10 training sessions. Offline topographic and spectral analyses were performed over the course of these sessions. If these analyses revealed evidence of EMG contamination, users were urged to relax cranial muscles as much as possible during performance.

## 2.3. Data analyses

Results are reported in terms of topographical and spectral analysis of  $r^2$  values. The value of  $r^2$  was computed as the correlation between the amplitude of the signal used to control cursor movement and target position (i.e. top or bottom), and thus represents the proportion of variance in the signal that is accounted for by target position (Sheikh et al., 2003). In representative users, the significance of the  $r^2$  differences was evaluated at the frequency used for cursor control on-line.

## 3. Results

Table 1 presents each user's characteristics, training parameters, and initial (Session 1) and final (Session 10) performance levels. All users performed well (and significantly ( $P < 0.0001$  by  $\chi^2$  test)) above chance (i.e. 50% correct) for Session 1. Due to their excellent early performance, Users A–C were shifted to the 3-target task after 2 or 3 sessions. Users D and E improved more gradually and were given 10 sessions of two-target training. The performance of Users F and G declined over the 10 sessions.

Fig. 2 shows for Sessions 1 and 10 of each user the  $r^2$  topographies at the frequency used to control cursor movement (Table 1). These  $r^2$  values represent the proportion of the total variance in the signal that is correlated with target position. Users A–C, who had

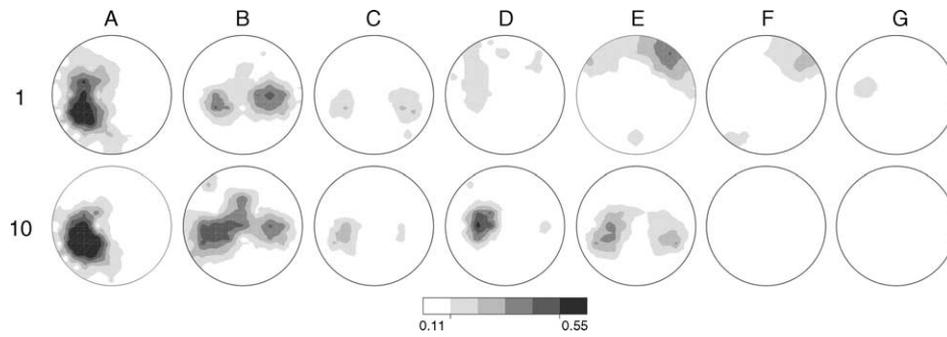


Fig. 2. Topographies of  $r^2$  in the frequency band used for cursor control for individual users for Sessions 1 and 10. User A–C show actual EEG control focused over sensorimotor areas for both sessions. Users D and E show diffuse mainly frontal non-EEG control in Session 1 and EEG control focused over sensorimotor cortex in Session 10. Users F and G show diffuse non-EEG control in Session 1 and no control in Session 10.

the best early performance, show control that is focused over sensorimotor areas in both Sessions 1 and 10. This focus is characteristic of actual sensorimotor rhythm control (Wolpaw et al., 2003). These 3 users show no evidence of EMG or other non-EEG activity correlated with target position. Users D and E show in Session 1 more diffuse control most prominent near the forehead. This distribution is consistent with EMG from facial or temporal muscles. Nevertheless, by Session 10 this frontal activity is gone and Users D and E display well-focused sensorimotor rhythm control similar to Users A–C. In contrast, Users F and G display minimal and poorly focused control in Session 1 and essentially no control in Session 10.

Fig. 3 further characterizes these 3 groups by showing  $r^2$  spectral analyses (i.e. correlation with target position) for

activity recorded over sensorimotor cortex (location C3) and over the forehead (location AF7) for Sessions 1 and 10 for Users A, D, and G. User A shows control sharply focused in the mu and beta (and gamma) rhythm bands over sensorimotor cortex that is prominent in Session 1 and even more prominent in Session 10. He shows little or no control at the frontal location. Values of  $r^2$  for the control channel at 12 Hz were significantly greater than those on the forehead at both times ( $P < 0.01$  in both cases). In sum, he shows from the start actual EEG control that grows stronger with training. User D shows modest broad-banded control at both locations in Session 1. For Session 10, he shows control sharply focused in mu and beta rhythm bands over sensorimotor cortex. At the frontal location, he shows weak broad-banded control (plus some evidence of the mu

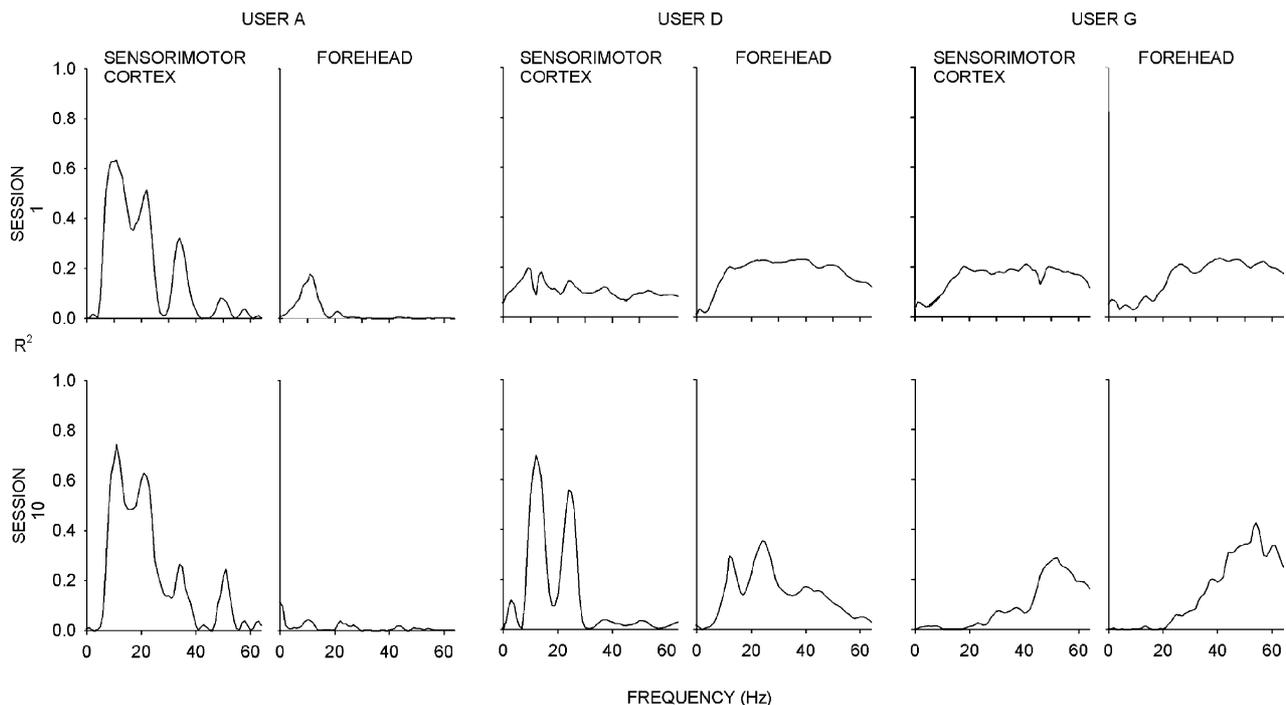


Fig. 3. Spectra of  $r^2$  (i.e. correlation with target position) over sensorimotor cortex and over the forehead for Sessions 1 and 10 for Users A, D, and G. In both sessions, User A shows actual EEG control focused over sensorimotor cortex. In Session 1, User D shows broad-banded non-EEG control at both locations; while in Session 10, he shows actual EEG control focused over sensorimotor cortex and minimal broad-banded non-EEG control over the forehead. In both Sessions 1 and 10, User G shows only broad-banded non-EEG control at both locations.

and beta rhythm control concentrated over sensorimotor cortex). Values of  $r^2$  for the control channel at 10 Hz were significantly greater than that on the forehead for session 10 but not for session 1 ( $P < 0.01$ ). In sum, he shows initial EMG activity that wanes with training and is replaced by clear EEG control. User G shows broad-banded control at both locations. This non-EEG control is evident in both Sessions 1 and 10. Values of  $r^2$  for the control channel at 12 Hz were not significantly different from those on the forehead at either time. He shows no evidence of EEG control.

Thus, the 7 users appeared to fall into 3 groups: Users A–C who displayed clear EEG control almost from the beginning and no non-EEG artifact; Users D and E who displayed non-EEG artifact initially and achieved clear EEG control with reduced artifact by Session 10; and Users F and G who displayed non-EEG artifact throughout the 10 sessions, and never achieved actual EEG control.

Further analysis characterized the EMG contamination seen in Users D–G. A clear difference became apparent between Users D and E in whom EMG contamination waned and EEG control developed, and Users F and G in whom EMG contamination remained and EEG control did not develop. Fig. 4 shows for Users D and G  $r^2$  spectra (i.e. correlation with target position) over sensorimotor cortex and over forehead for correct trials (hits) and for incorrect trials (misses) for Session 3. For User D (and also for User

E), broad-banded EMG control is much more prominent with misses than with hits. For User D,  $r^2$  at 10 Hz was significantly greater for the control channel (C3) than for the forehead channel (AF7) for correct trials ( $P < 0.01$ ) but not for errors. In contrast, for User G (and also for User F) EMG activity is more prominent or equally prominent with hits than with misses. For user G,  $r^2$  at 12 Hz was not significantly different for the control channel (C3) than for the forehead channel (AF7) for either correct trials or errors. In sum, for the users who eventually developed actual EEG control, target-related EMG activity was most prominent in unsuccessful trials, while this difference was not seen for the users who never developed EEG control.

#### 4. Discussion

EMG contamination was present in the first BCI training sessions in some users. The 3 who achieved actual EEG control of cursor movement most quickly did not display EMG contamination. In the other 4, EMG contamination, mainly from forehead muscles, was most prominent initially and waned over the first 10 sessions. In two of these 4, actual EEG control gradually developed. In the other two, actual EEG control did not develop. In the two in whom EEG control gradually developed, target-related EMG activity tended to be associated with misses rather than with hits.

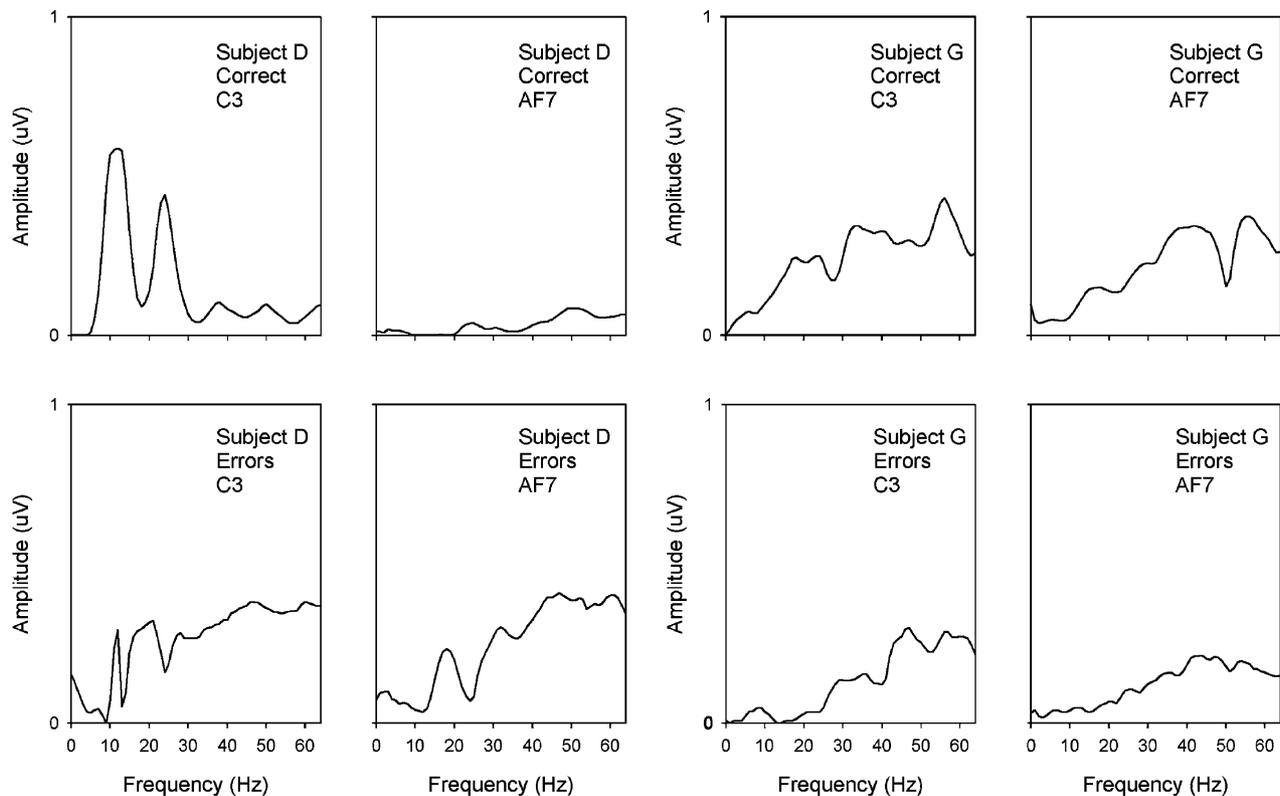


Fig. 4. Spectra of  $r^2$  (i.e. correlation with target position) over sensorimotor cortex and over the forehead for incorrect trials (misses) and correct trials (hits) of Session 3 from Users D and G. In User D, target-related EMG is much greater for misses than for hits. In contrast, for User G, target-related EMG is slightly greater for hits than for misses.

This was not true for the two users in whom EEG control did not develop.

These results suggest that EMG activity may be associated with poor performance. At the same time, it is necessary to consider the possibility that BCI users may use EMG activity rather than EEG activity to perform the cursor movement task. Spectral and topographic data should be recorded and analyzed in sufficient detail to detect the presence of EMG artifacts and to determine their role in performance. It is our experience that, to some extent, each individual user is unique. At present, artifact detection and elimination is not sufficiently developed to allow use in real time on short data segments. It is also not possible to predict which subjects are at risk for problems with EMG contamination. This probably depends upon many factors such as the ease with which training progresses. The important contribution of this study is the demonstration that EMG activity often occurs during early training, and thus that it is necessary to monitor subjects during the course of acquisition in order to evaluate the role of such artifacts in cursor control.

As noted earlier, increased EMG activity from facial muscles is a normal response to difficult tasks (Cohen et al., 1992; Waterink and von Boxtel, 1994). EMG contamination that is prominent when users are having difficulty may represent an emotional reaction to a difficult task or to failure. It may represent one aspect of the frustration that can also include other peripheral responses, such as heart rate changes, and central components such as generalized EEG desynchronization due to increased arousal. The data of Users D and E, in whom target-related EMG was more prominent during unsuccessful trials than during successful trials, is consistent with this interpretation. For this reason, we generally encourage users to relax during BCI training. As EEG control develops, such reactions tend to disappear. This trend is similar to that originally noted by Pavlov (1927), who described an initial generalized conditioned reaction that gradually became more specific with further training.

The primary danger for BCI training is that users will control cursor movement with EMG rather than with EEG. This appeared to be the case in Session 1 for Users F and G. Offline topographical analyses, performed between sessions, can detect EMG during initial BCI training, and users can be urged to relax cranial muscles. As apparently illustrated by Users D and E of the present study, such requests are often effective in reducing EMG contamination.

While EMG can contaminate signals recorded over sensorimotor cortex regions, it is much more prominent at frontal locations. Indeed, an early BCI study that used such locations was misled by EMG contamination (Lauer et al., 1999) and was later retracted on the basis of comprehensive spectral and topographical analyses (Lauer et al., 2000). The danger of EMG contamination was the primary motivation for a recent detailed description of the scalp EMG

associated with frontalis and temporal muscle contractions (Goncharova et al., 2003).

In summary, EMG activity is most prominent early in BCI training and in users who have initial difficulty in developing actual EEG control. It is sometimes most evident in unsuccessful trials, and in such cases may represent an emotional reaction to perceived task difficulty. In such cases, EMG may lessen as training progresses and actual EEG control develops. BCI studies, particularly those using EEG rhythms recorded from frontal head regions, should incorporate the comprehensive spectral and topographical analyses needed to recognize EMG contamination.

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