Brain-machine interfaces through control of electroencephalographic signals and vibrotactile feedback

Fabio Aloise[1], Nicholas Caporusso[1,2], Donatella Mattia[1], Fabio Babiloni[1,3], Laura Kauhanen[4], José del R. Millán[5,6]. Marnix Nuttin[7], Maria Grazia Marciani[1,8], and Febo Cincotti[1]

[1]NEILab, Fondazione Santa Lucia IRCCS, Rome, Italy. [2]DI, Università di Bari, Italy. [3]DFUF, Università degli Studi di Roma "La Sapienza", Italy .[4]LCE, Helsinki University of Technology, Finland. [5]IDIAP Research Institute, Martigny, Switzerland. [6]Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland [7]DME, Katholieke Universiteit Leuven, Belgium. [8]DN, Università degli Studi di Roma "Tor Vergata", Italy.
f.cincotti@hsantalucia.it

Abstract. A Brain-Computer Interface (BCI) allow direct expression of its user's will by interpreting signals which directly reflect the brain's activity, thus bypassing the natural efferent channels (nerves and muscles). To be correctly mastered, it is needed that this artificial efferent channel is complemented by an artificial feedback, which continuously informs the user about the current state (in the same way as proprioceptors give a feedback about joint angle and muscular tension). This feedback is usually delivered through the visual channel. We explored the benefits of vibrotactile feedback during users' training and control of EEG-based BCI applications. A protocol for delivering vibrotactile feedback, including specific hardware and software arrangements, was specified and implemented. Thirteen subjects participated in an experiment where the feedback of the BCI system was delivered either through a visual display, or through a vibrotactile display, while they performed a virtual navigation task. Attention to the task was probed by presenting visual cues that the subjects had to describe afterwards. When compared with visual feedback, the use of tactile feedback did not decrease BCI control performance; on the other side, it improved the capacity of subjects to concentrate on the requested (visual) task. During experiments, vibrotactile feedback felt (after some training) more natural. This study indicated that the vibrotactile channel can function as a valuable feedback modality in the context of BCI applications. Advantages of using a vibrotactile feedback emerged when the visual channel was highly loaded by a complex task.

1 Introduction

Visual presentation of stimuli is the most common feedback modality in neurofeedback paradigms for self-regulation of the brain's electrical activity. Thus, it is comprehensible that current brain-computer

communication systems mainly operate with visual stimuli [1]. However, components of the visual system such as vision, visual attention, focusing gaze are physiologically engaged during the dynamic contact between the body and environment. Furthermore, the visual sense may be compromised on some patients who are in need of BCI support. Thus, towards more efficient brain-computer communication, it seems important to also obtain evidence of how the extra-vision somatosensory modality performances during self-regulation of the brain's electrical activity.
Only few studies have tested other feedback modalities for brain-computer interfaces (BCIs). For instance, Hinterberger et al [2] tested auditory feedback, but, to our knowledge, no one has trained subjects with tactile feedback.
This study aims to explore the benefits of vibrotactile feedback for user training and accurate control of an EEG-based Brain Computer Interface.

2 Material and Methods

Thirteen subjects, two of which suffered from paraplegia due to lesions to their spinal cord, were involved in the experimentation. The experimental task consisted of moving a placeholder visible on a "Task" monitor, with the goal of stepping through a sequence of 10 "rooms" (**Fig. 1**.C), following a path constrained by narrow "gates" between adjacent rooms.
Subject's intention to move the placeholder was mediated by a BCI-like controller. In a first setting, the visual feedback of this controller was visible in a "Control Monitor" (**Fig. 1**.A). The horizontal position of a cursor was partially regulated by the subject, moving a computer mouse. In fact, the cursor movement was affected by noise and delay, so that (inaccurate) motion was as similar as possible to a typical BCI-controlled cursor trajectory. To achieve this goal, the processing chain of the BCI2000 software [4] was setup like in a mu-rhythm-based cursor control task, except for the fact that the amplitude of the spectral "EEG" component of interest was modulated by the mouse position; also, the time-series of cursor drift from an actual EEG-modulation recording was added sample by sample to the cursor control signal.

In a second setting, the feedback of this BCI-like controller was given through a stripe of eight tactors (**Fig. 1**.B), positioned on the shoulders of the subject, along a stripe that runs from the left to the right shoulder, behind the neck. A. Only one tactor at a time was active, encoding information about the horizontal position of a tactile cursor.
Subjects practiced for ~ 30 min with the Control Monitor alone (both visual and tactile) to stabilize performance before challenging the task.

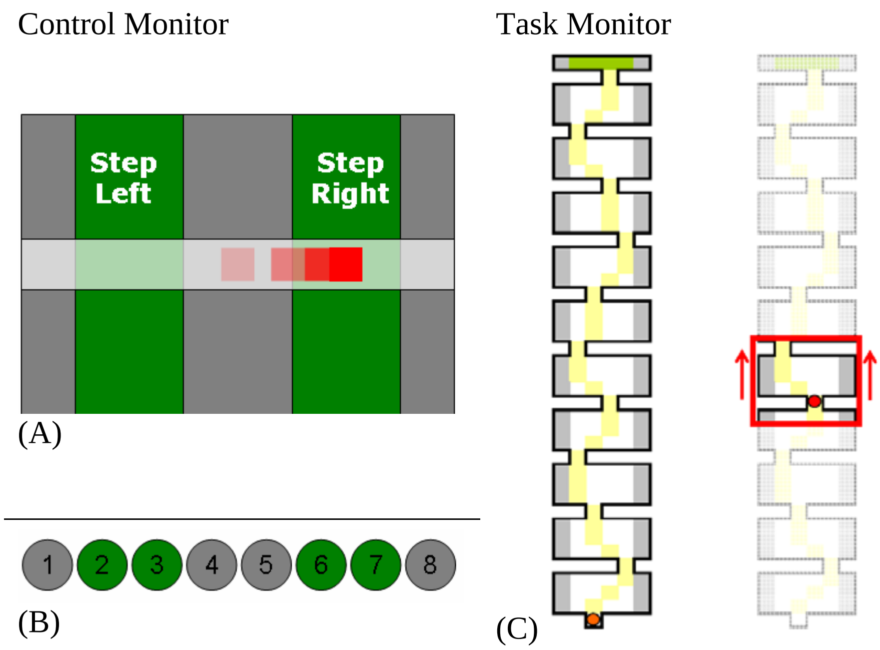

Fig. 1. *Panel A:* visual feedback of the pseudo-BCI controller; the subject had partial control on the red cursor, whose position was converted at discrete times (2 s) into navigation commands (step left, right or no stepping). *Panel B*: vibrotactile feedback of the pseudo-BCI controller; each tactor of the stripe encoded the tactile version of the visual cursor. *Panel C*: scheme of the task; the drawing to the left represents the whole maze, with the ideal path marked in yellow. In the drawing to the right, the scrolling red frame shows the portion of the maze visible at once of the task display.

Each room of the navigation space measured 4 x 4 steps and access to the following room was allowed only through a narrow “gate”. In the task monitor, movement was strongly discretized (one step every 2 seconds), so that the subject could not infer the status of the controller by looking at the placeholder’s motion.
To force subjects to keep their visual attention on the Task Monitor, a colored (green or yellow) key appeared at random times once or twice

for each “room”. Before proceeding to the next “room”, the subject had to report the color of the last key. If wrong, the subject had to navigate again the same room, thus making the path to the final goal longer (and more time consuming).

Subjects had to perform six runs of the task. The visual or the vibrotactile feedback was provided in alternate runs. Type of feedback of the first run was randomized across subjects.

Control commands and navigation trajectories were recorded, and several indices of performance were computed offline: rate of steps in the ideal path (SIP), rate of steps in an acceptable path (SAP), time to complete the 10 room path, rate of correct answers to the attentional task (key color).

T-test was performed on these indices to compare the effects of visual vs. tactile feedback.

3 Results

The rate of steps within the ideal path was comparable in the two conditions (80.9% vs. 83.7%, $p>0.05$), in line with studies I and II. Considering slightly swinging trajectories around to the ideal path as acceptable, visual feedback allowed higher performance (92.1% vs. 89.2%, $p=0.004$). Nevertheless, the number of keys incorrectly reported is clearly higher during the runs with visual feedback (86.0% vs. 97.5%, p=10-4). Given the payload set for wrong answer, this yielded a significantly longer time to destination in the same condition (182 s vs. 131 s, p=2×10-4)

Remarkably, two of the subjects reported appearance of blue and red keys (which were never delivered), only during runs with visual feedback.

The subjects reported a good level of comfort in the experimental session lasting about 1 hour. Prolonged test are needed to assess long-term compliance.

4 Discussion and conclusions

The tactile feedback modality was used and compared to the visual while subjects were required to perform a visually guided navigation task. We reduced the experimental variables, by setting up a pseudo-BCI control, which retains the typical inaccuracy, delay, and attention requirements of an EEG-based BCI.

If we only consider the ability of subjects to guide the placeholder towards the gates, the accuracy obtained with visual and tactile feedbacks was comparable. A deeper analysis, showed that with tactile feedback subjects tend to stay closer to the ideal path, thus pacing on a more straight line. The most notable difference was in the attentive resources that subjects were able to devote to the task. A significantly higher rate of mistakes was made when visual attention was divided between the Control and Task Monitors.

In summary, we found that tactile feedback (i) permits an appropriate training of users to BCI operation; (ii) does not interfere with simultaneous visual stimuli; (iii) may improve performance when the subject's attention is highly loaded by a simultaneous visual task.

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