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Technical note

Writing through a robot: A proof of concept for a brain–machine interface

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ABSTRACT

This paper describes a non-invasive human brain-actuated robotic arm experiment, which allows remote writing. In the local environment, the participant decides on an arbitrary word to transmit. A mental speller interface is then used to select the letters. A robot arm placed in the remote environment writes the word on a whiteboard in real time. A multidisciplinary framework such as the one presented here exemplifies a class of interactive applications with possible relevance in a variety of fields, such as entertainment and clinical environments.

1. Introduction

1.1. State of the art

The presence of robots in human society has been increasing exponentially for the last 25 years. The main target fields of human–robot interaction include robot-assisted search and rescue, assistive robots, space exploration, as well as military, industrial and educational applications (see review in [1]). From the clinical point of view, robots provide an opportunity for interaction to those persons with communication problems. For instance, their use has been shown to be useful with autistic children, who usually respond weakly to social cues but respond well to mechanical devices [2]. For some people with physical challenges, an intelligent wheelchair [3] or even the embodiment of a robot [4] provides support and unique opportunities not available in other forms of technology.

Specifically, robot arms represent a useful tool in numerous environments and situations. In this sense, numerous applications have been developed to control real or virtual robotic arms for object telemanipulation (see an exemplary review in [5]).

A particular way to move robots is by means of brain waves through a brain–machine interface (BMI). In general terms, a BMI system consists in recording and interpreting the electrical activity generated by the brain in order to control an external device or media without requiring the use of peripheral nerves or muscles for communication. Traditionally, BMI systems have been used for clinical and rehabilitation purposes for disabled patients, including cursor control [6,7] or prosthetic hand operation [8]. A replication of the latest has been developed in virtual reality for controlling a computer-generated 3D virtual arm [9]. The interest in BMI technology has grown exponentially during the last years not only for clinical applications but also for applications in different fields, including education, communication, military, computer gaming and even biometric authentication (see review in [10]).

Within the frame of human–robot interaction, BMI technology offers an additional mean for communication, for example to control a wheelchair by motor imagination and words association [11] or left-right thinking [12]. A BMI application for navigation in a virtual environment by a tetraplegic patient in a wheelchair has also been demonstrated [13,14]. In [15], remote human brain–robot communication was established to move a robot between two cities separated by 260 km. Within this scope, important advances have been achieved in animal research. A monkey in U.S. was able, through a BMI, to control the gait motion of a human-sized robot located in Japan, at 11 400 km far away. The electrical impulses in the monkey's brain while walking on a treadmill were transmitted to the robot via Internet, making the robot walk, i.e., mimicking the monkey's motion [16].

The first BMI application for written/verbal communication, called the "thought-translation device", was developed in the late 1990s by Birbaumer and colleagues [6,7,17] and based on slow-cortical potentials. This device allowed the user to choose one character from the alphabet in an iterative process. The whole process might last more than 1 min for single character selection.

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Besides active BMI strategies, based on voluntary mental actions, reactive strategies based on brain responses to external stimuli offer a technically different solution. Among these reactive interfaces, that based on the P300 evoked potential is the most widespread. The P300 is the most prominent cognitive event-related potential. It appears in presence of a rare stimulus among several standard stimuli around 300 ms after stimulus presentation. The P300 is not restricted to any particular sensory modality, i.e., it appears both with visual or auditory stimuli [18].

A visual P300-based BMI system allows a more time efficient approach for written communication since the user can select a character every 10 s approx from a mask containing all alphanumeric characters [19,20]. It allows very high accuracy and represents a practical approach since very little training time (less than 5 min) is needed. Compared with other strategies, P300-based BMI systems do not require subjects to learn to modulate their EEG, reducing massively the training time. A performance study has reported that 72% of the subjects achieved a 100% accuracy level, with a mean accuracy 91% with the P300 speller [21]. In a previous related study, only 6.2% of subjects performed at an accuracy level between 90 and 100% with a motor imagery BMI system [22]. The authors compared both approaches in terms of the time performance and found that the P300-based BMI is about two times faster than the equivalent BMI system using motor imagery [22]. In another study, Donchin et al. estimated speed vs. accuracy and stated that speed could be enhanced until 7.8 items/min for 80% accuracy level or 4.3 items/min for 95% accuracy level for able-bodied subjects [19].

Therefore, although BMI applications for written communication do exist, they mostly involved human–computer rather than human–robot interaction. In particular, combined solutions for writing through a robot arm operator with thoughts have not been explored yet.

1.2. Objectives

Here we describe a BMI experiment for remote (or local) writing via human brain-actuated robot arm. The novelty that this experiment brings to the state of the art is the combination of BMI and robotics to develop a new experience in the field of remote written communication. The synergy of resources from BMI plus robot operators illustrates a class of applications with great potential in different domains. The assessment of the usability of such a system needs of user studies that are beyond the scope of the present technical note. Specific queries to be addressed in future works are pointed out.

2. Materials and methods

The present experiment was developed in the frame of the INTERACCION 2009 conference held simultaneously in Barcelona (Spain) and Armenia (Colombia).

2.1. Local environment

One female volunteer sat comfortably at a desktop, with her arms and feet resting relaxed on the lap and the floor, respectively. She was instructed to sit and concentrate on each letter of the word in turn during the flashing stage (see Section 2.5). A webcam allowed the audience in Colombia to see her and the local environment in real time.

2.2. Remote environment

A Mitsubishi RV-2AJ operator robot with 5 degrees of freedom and anthropomorphic articulation was used for writing execution. The robot combines a maximum speed of 2100 mm/s with an accuracy of ±0.02 mm. Therefore, it is appropriate for small environments and for academic and research purposes in particular. Because of the physical limitations, the maximum number of characters per word was limited to six.

The robot has a Mitsubishi CR1-571 controller responsible for the control and communication protocol. The communication between the robot controller and the robot server was through the RS-232 serial port. For this communication, the SerialCommRV2AJ API was developed [23]. This API was created using the Java Communications API in order to access the serial port and send/receive commands from the controller.

2.3. Communication between environments

The HTTP protocol was used for the communication between the two environments. HTTP requests to the robot server were resolved through an application based on Java Servlets [24]. Writing requests sent by the BMI system in Barcelona were received and stored by the *ServletWritter*. Then, characters were sent to the API responsible for processing the alphanumeric characters (*RV2AJWritter*), which generated the corresponding files with instructions and trajectory coordinates. These files were then sent to the robot controller through the serial port (*SerialCommRV2AJ*). The writing process was finally carried out based on the positioning system of the robot. Fig. 1 shows an overview of the system architecture.

For visual feedback of the robot's actions, and since the robot was located at a remote laboratory about 8500 km from the local BMI set-up, MJPG video streaming was generated with a network camera (Axis Network Camera 214 PTZ) pointing to the robot.

2.4. EEG recording system

Eight Ag/AgCl electrodes (Fz, Cz, Pz, P3, P4, PO7, PO8 and Oz, International 10/20 System) were arranged on the head of the subject. A ground electrode was placed on the forehead and reference on the right earlobe. The voltage signal was fed on the *g.USBamp* amplifier (gtec, Guger Technologies OEG) and acquired at 256 Hz. Impedances were kept below 5 kΩ. A Notch-filter (network 50 Hz rejecting) and a band-pass filter (Butterworth 5th order) between 0.1 and 30 Hz were applied. The High-Speed Online Processing toolbox (Guger Technologies OEG) running under Simulink/MATLAB (Mathworks, Inc.) was used for real-time parameter extraction.

2.5. The P300-speller

We use a BMI system based on the P300-speller approach proposed in [19,20]. The system presents the user with a 6×6 matrix, each cell containing one alphanumeric character. The user focuses attention on the cell containing the character (letter or number) to be communicated while the rows and the columns of the matrix are intensified repetitively in a random sequence. To maintain the concentration on the task, the user has to count mentally how many times the selected target cell flashes. When the row or column containing the attended cell is intensified (i.e., the target stimulus is presented), the P300 response is elicited.

Data epochs of 800 ms, the window starting 100 ms before the stimulus and ending 700 ms after, are buffered for signal processing. Data from target and non-target trials are down-sampled to 64 Hz and separated into two data sets offline. The elicited EEG response is computed for each data set (target and non-target). The algorithm detects the character by determining which row and which column elicit the best P300 response (see [21] for further details). Then, the weights for the LDA (linear discriminant analysis)

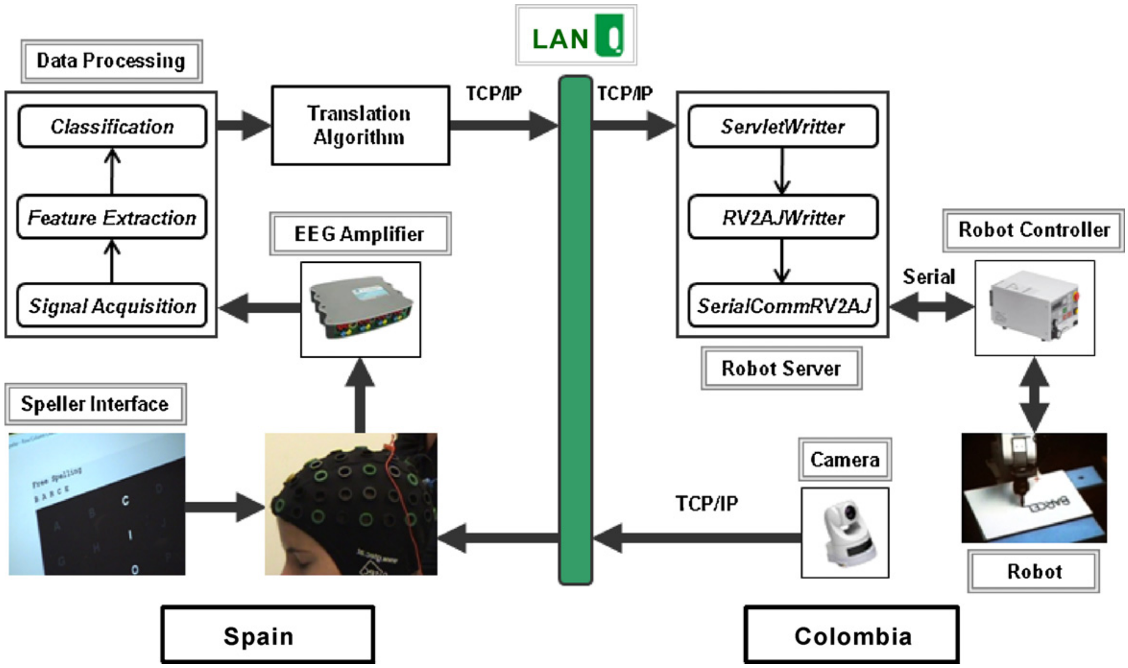

Fig. 1. Overall system architecture at the local (Spain) and remote (Colombia) environments.

classifier are estimated offline using the gBSAnalyze commercial package (gtec, Guger Technologies OEG).

3. Procedures

3.1. Training stage

Prior to the final experiment, the user completed a short training session in order to get acquainted and confident with the task. In this training session, the "copy spelling" mode was used, which allowed entering arbitrary letters that the participant had to select, in our case, the vowels "OIAUIE". The user did not receive any feedback about performance since a classifier was not generated at that time. Then, the LDA weights were computed and save for the later online classification during the test stage. Since the user successfully selected the six vowels in the first run, only one training run was required. The training session was carried out five days before the conference.

3.2. Test stage

For the test stage, a set of specific movements for the robot operator was implemented. The corresponding trajectories for each of the 27 characters of the Spanish alphabet were individually programmed. The "free spelling" mode was used, which allows writing words freely without any previous input. The user decided to write "BARCEL", i.e., the first six letters of the word "BARCELONA" (see Fig. 2).

Immediately after the speller system detected the character that elicited the best P300 response, the character ID was passed to the robot via Internet, as a variable in the URL query string. After the desired word was completed, the symbol "_" had to be chosen as end-of-word character. In order to write a second word, and due to the limited placed on the whiteboard, the robot was programmed to clean the board before writing the following word.

During the test experiment, all letters were chosen, sent and written correctly. Flash and dark times for each column or row were adjusted to 100 ms and 75 ms, respectively. Flash repetitions were set to seven for each row/column, as a compromise between

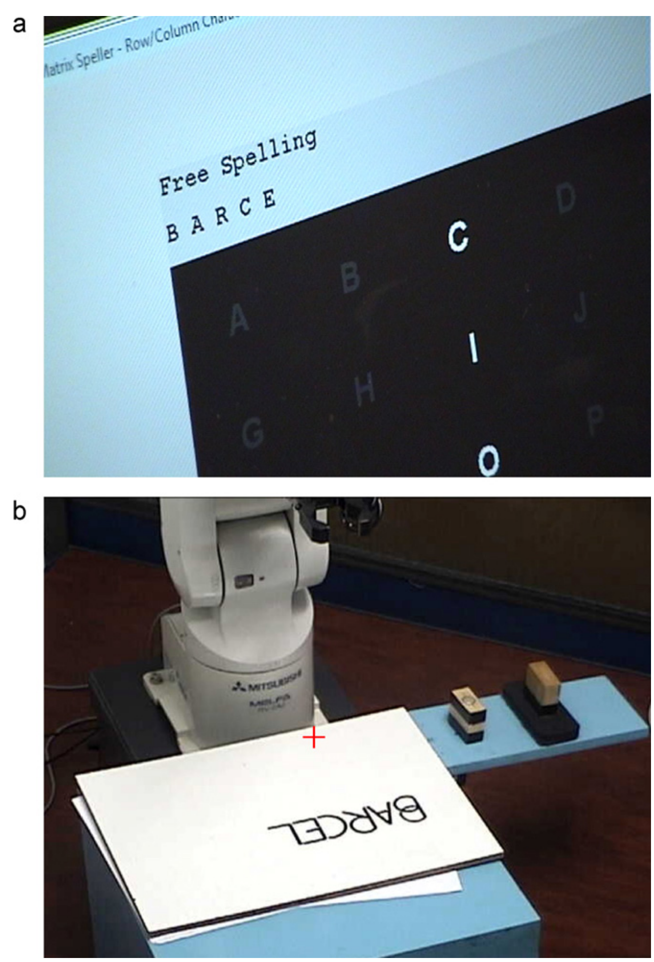

Fig. 2. (a) Snapshot of the P300-speller interface during the experiment. (b) Snapshot of the remote environment during the demonstration. The robot arm placed in Colombia writes on a whiteboard the letters ("BARCEL") mentally selected by the participant in Barcelona.

accuracy and writing velocity. Therefore, one character selection lasted 14.7 s (6 × 6 matrix, 175 ms for row/column, 7 flash repetitions). This led to a transfer rate of 4.1 letters/min. In the remote environment, the robot needed 5 s in average for writing a letter. Regarding the time delay for the communication between the two environments, averaged round-trip time was 217 ms (ping, DOS-command).

4. Discussion

The P300-based BMI system was successfully used for remote writing via a human brain-actuated robot arm. The participant was able to mentally select all the letters correctly during both the training and the final session even with a reduced number of flash repetitions ($n = 7$). This led to a transfer rate of 4.1 letters/min. This performance is in line with previous results that have reported high accuracy (>90%) even with only 6 flashes per trial [25]. Speed could be increased by using word-completion or a language model's predictions. When the language model's predictions are accurate, many successive characters can be selected by a single gesture. These techniques are usually applied in writing systems based on gaze direction [26], which have existed in the assistive technology for some years. Although EEG-based systems cannot compete in speed against gaze-controlled systems, they represent an alternative for those cases where gaze-based technology is not suitable. Indeed, the integration of BMI with other interfaces is encouraging since it enriches existing collaborative environments as well as raises further opportunities in specific situations due to several considerations like physical or cognitive constraints.

Our current research direction includes a large user study to evaluate the feasibility of the system in terms of long periods of use, fatigue and efficiency. More importantly, it will allow us to estimate the degree of usability within the context of possible human brain–robot interfaces given the current technology available.

5. Conclusions

Summarizing, a proof of concept for a human brain–robot interface for remote writing was presented. The system allows a user to select by thought arbitrary words and to send them to a robotic arm, which receives the command via Internet and writes the word on a whiteboard in real time. Users can easily operate the system after 5 min of training with very high accuracy level. Future research should explore the viability of the system in terms of usability. BMI applications to control robots or even virtual surrogates may also have broad repercussion in entertainment and clinical environments.

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Conflict of interest statement

There are no conflicts of interest between the authors and other people or organizations.

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