Research article

Real-time two-dimensional asynchronous control of a computer cursor with a single subdural electrode

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Objective: To test the feasibility of controlling a computer cursor asynchronously in two dimensions using one subdural electrode.
Design: Proof of concept study.
Setting: Acute care hospital in Toronto, Canada.
Participant: A 68-year-old woman with a subdural electrode implanted for the treatment of essential tremor (ET) using direct brain stimulation of the primary motor cortex (MI).
Interventions: Power changes in the electrocorticography signals were used to implement a "brain switch". To activate the switch the subject had to decrease the power in the 7–13 Hz frequency range using motor imagery of the left hand. The brain switch was connected to a system for asynchronous control of movement in two dimensions. Each time the user reduced the amplitude in the 7–13 Hz frequency band below an experimentally defined threshold the direction of cursor changed randomly. The new direction was always different from those previously rejected ensuring the convergence of the system on the desired direction.
Outcome measures: Training time, time and number of switch activations required to reach specific targets, information transfer rate.
Results: The user was able to control the cursor to specific targets on the screen after only 15 minutes of training. Each target was reached in 51.7 ± 40.2 seconds (mean ± SD) and after 9.4 ± 6.8 switch activations. Information transfer rate of the system was estimated to be 0.11 bit/second.
Conclusion: A novel brain–machine interface for asynchronous two-dimensional control using one subdural electrode was developed.

Keywords: Spinal cord injuries, Assistive devices, Implanted electrodes, Motor cortex, Neural prosthesis, User–computer interface

Introduction

Brain–machine interfaces (BMIs) use signals from the brain to control electronic devices. This technology represents a new opportunity to communicate and interact with the environment for people with limited or no ability to move voluntarily. Some of the individuals who may benefit directly from this technology include people with advanced stages of amyotrophic lateral sclerosis, brain stem stroke, cerebral palsy, and spinal cord injury.[1]

The types of signals used to implement BMI systems are as diverse as the techniques that exist to monitor brain activity. However, most BMIs use electrical recordings from the brain, which can be obtained non-invasively using electroencephalographic (EEG) techniques.[2] Alternatively, electrocorticography (ECoG) is an example of a minimally invasive measurement technique, which uses electrodes placed underneath the

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dura mater allowing recordings directly from the surface of the brain.[3–18]

The operation of a BMI often requires users to adopt specific mental states, which can be identified by temporal or spectral changes in their brain activities. With EEG-based BMIs, these changes have included slow cortical potentials,[19–21] P300 potential,[22,23] and changes in power of oscillatory rhythms.[24] Upon detection of a predetermined change in brain activity, a specific action is triggered creating the interface between the brain and an external device. EEG-based BMIs have been used successfully to facilitate communication for individuals who have lost all ability to perform voluntary movement (e.g. as a result of locked-in syndrome[19]).

The implementation of BMIs frequently involves synchronous control strategies. Under this mode of operation, the user can issue commands (e.g. adopt a brain state) only during specific time periods determined by the BMI itself. Consequently, the BMI system and not the user determines the rate at which commands can be generated. Synchronous BMI implementations have been tested in many contexts. However, this mode of interaction is considered to be unnatural for most applications which can cause significant user frustration.[25]

An important step to expand the applications of BMI technology, and create devices that can be used outside a laboratory environment, is the implementation of asynchronous control strategies that would allow the user to generate a command at any desired instant without the mediation from the BMI. Such a device would likely result in a more natural and intuitive mode of interaction between the user and the BMI.

Asynchronous BMI systems require constant monitoring of brain activity to identify changes, indicating the desire to issue a command. Until recently, only a handful of research groups worldwide had addressed the development of asynchronous BMI systems.[26–29] Despite an increase in the study of asynchronous BMIs, their implementation remains as one of the most important challenges in the development of BMI technology.

A strategy to implement asynchronous BMIs has been the use of steady-state visual-evoked potentials (SSVEP)[30] generated with a set of light sources flashing at known (and distinct) frequencies. To issue a command, the BMI user looks at a specific flashing source. The BMI detects the presence of the stimulation frequency (and harmonics) in the EEG activity recorded over the visual cortex. A fundamental drawback of this approach is that it relies on the user's ability to perform reliable ocular movements, which may not be assumed for every potential user of this technology. However, there is evidence suggesting that SSVEP can be used for BMI control even without reliable gaze function.[31] Using this approach it has been possible to control a prosthetic hand,[32] a simulated telephone,[33] computer cursor control,[34] and virtual car navigation.[35]

A second approach for the implementation of BCI systems is the use of the oddball paradigm in which a person is asked to determine the category of each item presented within a sequence.[36] If one of the categories occurs only with very low frequency, an event-related response (ERP) with a latency of 300 milliseconds occurs whenever the individual categorizes the corresponding item. This ERP is commonly referred to as P300 and has been used to create BMIs. In one example of these systems, characters are arranged in a matrix and each row and column is illuminated at random and quick succession. To use the system the user is asked to count the number of times that a desired character flashes. With each occurrence a P300 is elicited making it possible to determine, usually after averaging, the desired character. Examples of P300-based BCIs can elicit responses using visual,[22,36–38] auditory,[39,40] and tactile[41] stimulation.

Another approach used to create asynchronous BMIs consists of the identification of specific features in EEG or ECoG signals, including changes in power of specific frequency bands,[7] motor potentials (ERPs),[3–5] or a combination of both power changes and ERPs[10] generated internally (i.e. not elicited using an external stimulus). These features have been detected using a variety of signal-processing techniques including correlation values,[3–5] wavelet coefficients,[42–46] and adaptive autoregressive parameters combined linearly and compared to a predetermined threshold.[7] When one of these features is identified in the brain activities the BMI responds accordingly. Devices implemented in this way have been used to control a video game,[45] functional electrical stimulation systems,[47] simulated wheelchair navigation,[28,48] upper limb prosthesis control,[32] and virtual keyboard operation.[27]

Finally, an additional approach to asynchronous BMI implementation, and also based on modulation of sensorimotor rhythms through motor imagery, requires the user to exert continuous control over certain aspects of the activity of the brain. An example of this approach uses the self-regulation of μ oscillatory rhythm amplitude translated directly into the position of a computer cursor on a screen.[1,49–51] While this approach has proven to be effective, the ability to control the oscillatory rhythm with the necessary accuracy often requires several weeks or months of training[1] and demands constant attention from the user.

We believe that a viable BMI system suitable for work outside of a research environment would use a small number of electrodes, an asynchronous mode of operation, and would not require the user to be constantly engaged in the operation of the device. We are introducing a novel approach for the development of an asynchronous BMI system to control the two-dimensional movements of a computer cursor using a single subdural electrode by implementing a brain switch (i.e. an ECoG activity level detector) in combination with a novel algorithm for two-dimensional control. The result of this proof of principle study is a system that uses simple signal processing, requires little training, and is minimally intrusive allowing the user to concentrate on the task at hand rather than on the operation of the BMI itself.

Methods

The single subject of this study was a 68-year-old woman with a subdural electrode implanted for the treatment of ET using direct brain stimulation of the MI. She was recruited at the Movement Disorders Clinic of the Toronto Western Hospital and gave her written informed consent to participate. These experiments were approved by the University Health Network Research Ethics Board, Toronto, Canada.

The subdural electrode (model Resume II, Medtronic, Minneapolis, MN, USA) was placed on the right precentral gyrus over the long axis of the motor cortex and had four recording contacts (platinum–iridium, 4 mm diameter, 10 mm center to center distance) (Fig. 1). The electrode connector remained externalized for 2 days after implantation to optimize stimulation parameters making it possible to record using the same subdural electrode. The work presented here was conducted one day after the initial electrode implantation.

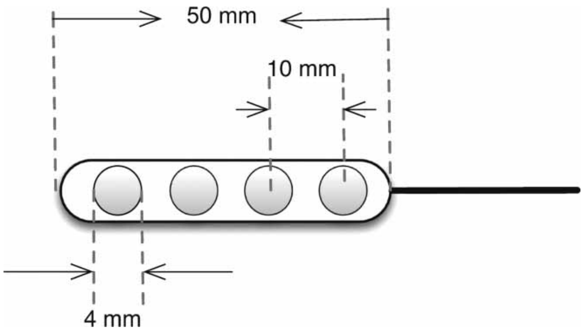


Figure 1 Graphical representation of the subdural electrodes used to conduct this work. The quadripolar electrode was placed over the right primary cortex of the participant.

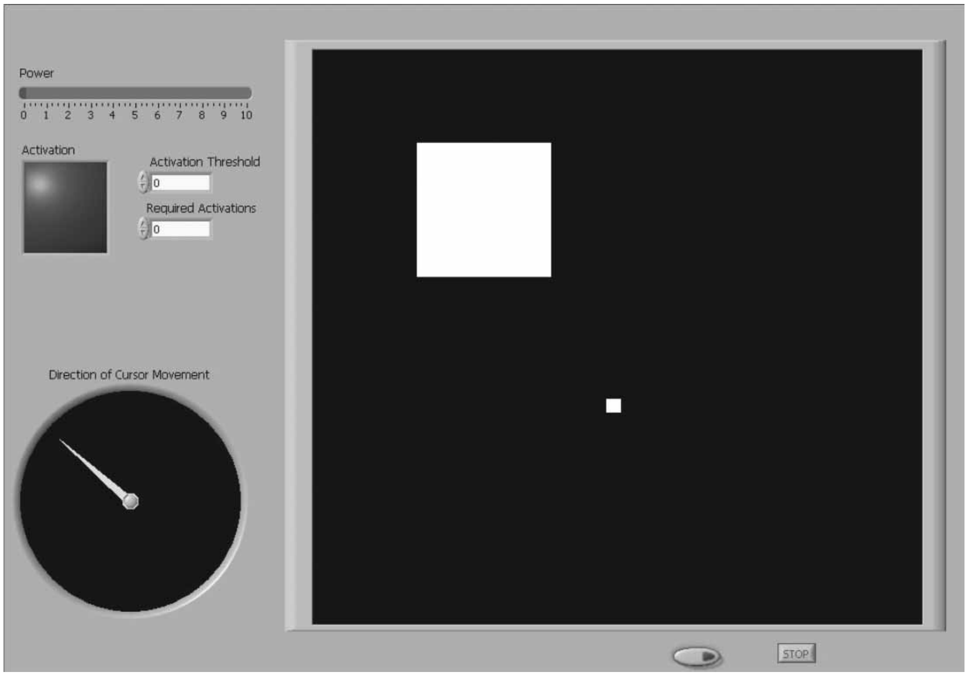
Stimulation of the primary motor cortex

As part of a different study unrelated to the work presented here, electrical stimulation was applied directly through the subdural electrode in a monopolar configuration to determine the exact functional location of each contact by observing contra-lateral contractions using 9 mm Ag-AgCl disposable electromyography (EMG) electrodes. The findings of the stimulation were used to identify movements that could be later used as activation strategies through motor imagery. The stimulation frequency was varied from 3 to 20 Hz using a pulse width of 60 μs. Stimulation amplitude was increased gradually to 10.5 V. The recorded muscles included right and left frontalis, orbicularis oculi, triangularis (also known as depressor anguli oris), first dorsal interosseus, and tibialis anterior. Band-limited EMG signals (2 Hz to 2.5 kHz) signals were amplified (Intronix Technologies Corporation, model 2024, Bolton Province: ON, Canada) and digitized at a rate of 5000 samples per second (Micro 1401, Cambridge Electronic Design, Cambridge, UK). The stimulation revealed the contact closest to the cortical representation of the contra-lateral upper extremity. Only signals from this single electrode were used for the development of the project presented here. No simultaneous activation of disparate anatomical sites was observed (i.e. stimulation did not elicit contractions in the face, upper and lower extremity at the same time).

Experimental setup

The activity from the subdural contact was band-limited (1–100 Hz) and amplified (100 000 times) using a high-performance amplifier (Model P511, Grass Technologies, West Warwick, RI, USA). The preprocessed ECoG signal was then digitized using a portable data acquisition system (model NiDAQPad-6016, National Instruments, Austin, TX, USA) at a rate of 200 samples per second.

The subject sat comfortably, approximately 50 cm away from a computer monitor. The monitor displayed a single square target (3.5 cm × 3.5 cm) and a rectangular computer cursor (2 mm × 2 mm), both contained in a rectangular area of 16.5 cm × 14 cm (Fig. 2). The cursor and the target could only move within the boundaries of this area. The monitor also showed a needle dial displaying the cursor's direction of movement and a bar that gave a visual indication of the estimated power in the ECoG activity. Finally, the display also contained a visual indicator activated when the ECoG power was below a threshold for a determined period of time (i.e. when a switch activation occurred). Both the threshold and the time required for the signal to be below the threshold level could be set at run time. The software



Activation Threshold 0

Required Activations 0

Figure 2 **Experimental task display. The participant was asked to direct the cursor (small white square) toward a target (large white square) of 3.5 cm × 3.5 cm in size. The target moved to a different location, selected randomly, every time it was reached by the cursor. The direction of the cursor changed each time the brain switch was activated and it could only move within a rectangular 16.5 cm × 14 cm area.**

was implemented using the LabView programming language (National Instruments).

Signal processing

The BMI was implemented as a "brain switch." To do this, the activity recorded with the subdural electrode was first band-pass filtered between 7 and 13 Hz. Next, a 250 ms window of samples was taken and each sample was squared, and then passed through two integrators, consecutively. Following the processing, the mean value of the window was calculated. Finally, a moving average was calculated using the mean values of the five most recent windows. A switch activation was generated whenever the value of this moving average was maintained below an experimentally determined threshold for 1.25 seconds. This value was set according to the user's subjective appreciation of ideal for minimizing false activations while still been able to activate the brain-switch with reasonable effort. The participant achieved modulation of the ECoG signals using motor imagery of the hand contralateral to the site of implantation (identified previously as a suitable approach through cortical stimulation).

Experimental task

The subject was asked to control a computer cursor in two dimensions towards a target. The target disappeared and reappeared in a random location when it was reached by the cursor. The participant completed three runs. The subject navigated the cursor to four (run 1) or five (runs 2 and 3) different positions.

Our experimental measurements included: (1) the number of activations required to complete each run, (2) the number of activations required to reach a specific target, (3) the time required to complete a run, and (4) the time as well as the number of activations required to reach each one of the targets were measured.

Asynchronous control strategy

A new asynchronous control strategy was implemented to control the two-dimensional movement of the cursor on the screen using the brain switch. This strategy was presented in ref.[52] With this strategy, the activation of the switch is used to indicate that the current behavior of the device under control is not the desired one. This differs from a traditional function given to single switches were they are used to initiate a desired behavior from the device.

To control the cursor on the screen, the participant had to activate the switch repeatedly. The participant would activate the switch only if she was not satisfied with the direction of the cursor at any moment. If the switch was not activated, the cursor would continue to move in the undesired direction until reaching the end of the experimental area. Each time the switch was activated the cursor changed its direction. The new direction of cursor movement was determined in the following way: first, the screen was divided into a matrix of eight rows and eight columns. Whenever the switch was activated, the control algorithm would select a target described by an x, y pair corresponding to the column and the row towards which the cursor should move. Each x and y value was selected independently on the nth switch activation according to

$$c_{[n]} = \operatorname{argmin}(\gamma_{[n]}(c)) \tag{1}$$

where

$$c = cx = cy = \{0,\ 1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7\} \tag{2}$$

was the set of all possible values that x and y could adopt representing the rows and columns into which the screen was divided, and

$$\gamma_{[n]}(c) = H_{[n]}(\Delta t)\gamma_{n-1}(c) + \chi_{[n]}(c) \times \left\{1 - H_{[n]}(\Delta t)\gamma_{[n-1]}(c)\right\} \tag{3}$$

Equation (3) describes a temporo-spatial exclusion mask used to ensure that the control system eliminated the rejected direction temporarily each time the cursor changed its behavior, so that it would not be selected in subsequent activations. This was accomplished with the temporal weighting factor $H_{[n]}(\Delta t)$ in equation (3) defined as

$$H_{[n]}(\Delta t) = \exp(-\Delta t/\tau) \tag{4}$$

where Δt is the time between the last two switch activations (n and $n-1$). The time constant τ was set to 250 seconds.

The function $\chi_{[n]}(c)$ was a spatial weighting factor reducing the probability that any directions similar to a rejected one were selected. It was defined as

$$\chi_{[n]}(c) = \begin{cases} 1- \quad (r/\alpha s) & \text{if } r \le \alpha_{\mathrm{s}} \\ \quad 0 & \text{if } r > \alpha_{\mathrm{s}} \end{cases} \tag{5}$$

where r is the distance between a rejected direction and neighboring directions. The parameter α_{s} is an arbitrary constant defining the spatial extent of the effect of equation (5). α_{s} was set to 8 extending the effect of equation (5) to the entire screen. Fig. 3 depicts the access strategy used. Additional details can be found in ref.[52] and the open source software libraries for the control strategy are available at http://jsilva.komodoopenlab.com/index.php/Projects/Access. Once the new values of x and y were selected, the direction of movement was determined by first estimating λ according to

$$\lambda = [\operatorname{sig}(x) + 1] + [10(\operatorname{sig}(y) + 1)] \tag{6}$$

The value of λ was then translated to an angle according to Table 1. The angle determined the direction (out

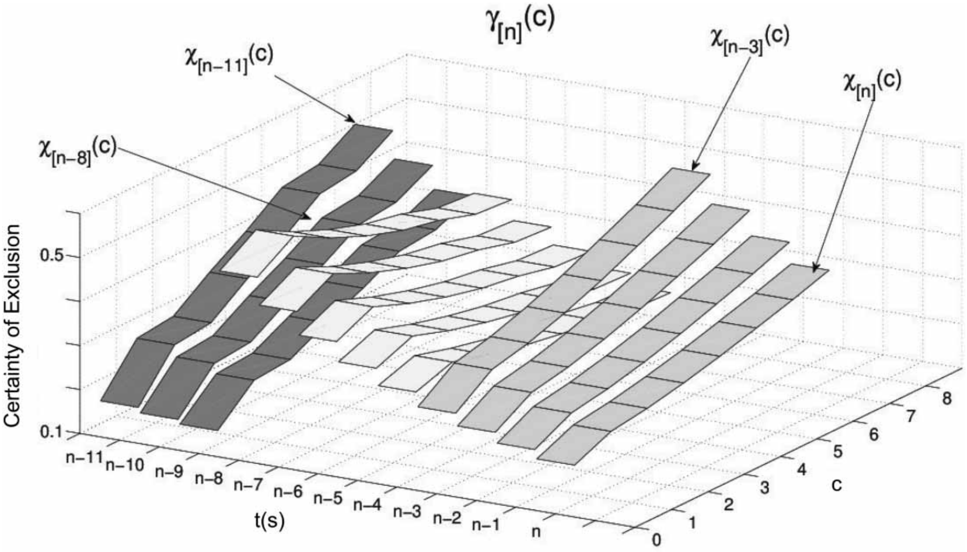


Figure 3 Temporo-spatial exclusion mask described by equation (3). This function ensured that rejected directions of movement, as well as neighboring directions, were eliminated temporarily to avoid their selection. The figure shows three switch activations at instants $n-3$, $n-8$, and $n-11$. Each of these switch activations and their effect on the exclusion mask until the next activation occurs are shown in different shades of gray. The set of possible values for any dimension (x or y), representing the rows and columns into which the screen was divided, is depicted by C.

Table 1 Estimation of direction of movement

λ	Estimated direction	λ	Estimated direction
0	$\mathrm{atan}(x/y) + \pi$	12	0
1	$3/2\pi$	20	$\mathrm{atan}(x/y) + \pi$
2	$\mathrm{atan}(x/y) + 2\pi$	21	$\pi/2$
10	π	22	$\mathrm{atan}(x/y)$

The value of λ, estimated according to equation (6), was used to determine the direction of movement of the cursor according to the values presented in this table.

of the 44 possible options) of the moving cursor. Using this approach, it was ensured that the motion of the cursor always converged to the direction intended by the participant.

Results

The participant was able to operate the brain-switch after only 15 minutes of usage. Consequently, it was possible for the participant to control the movement of the cursor and reach all of the targets successfully. Fig. 4 shows several activations of the switch along with the processed ECoG activity.

The participant was able to reach all targets and the average time needed to reach each target was 51.7 ± 40.2 seconds. She needed 53 ± 5.6 activations to reach an individual target and each activation required 5.5 ± 3.41 seconds. Each run was completed in 250.4 ± 9.6 seconds. Results for individual runs are presented in Table 2.

While the activation of the brain switch carries a single bit of information, the control strategy made it possible to select one of the 44 possible directions in which the cursor could move. The information transfer required to represent these directions, assuming an error-free system, would be $\log_2(44) = 5.46$ bits. This figure represents the upper limit for the presented system and indicates the information required to specify the desired direction. In our experiments, it took the participant on average 0.86 minutes (51.7 seconds) to reach the target. Assuming this is the time that the system required to transmit the necessary information, an estimate of the information transfer rate would be 5.46 bits/0.86 minutes = 6.3 bits/minute (0.11 bits/second).

Discussion

We presented a novel approach to provide two-dimensional asynchronous cursor control using a quadripolar electrocorticographic electrode. A single subdural contact was used to implement a brain-switch using comparison of the power levels of 7–13 Hz with an experimentally determined threshold. Subdural electrodes are considered safe, even for prolonged use, and are they implanted routinely with minimal complications.[53] The single participant of this research study was able to control the direction of the cursor to reach targets on a computer screen.

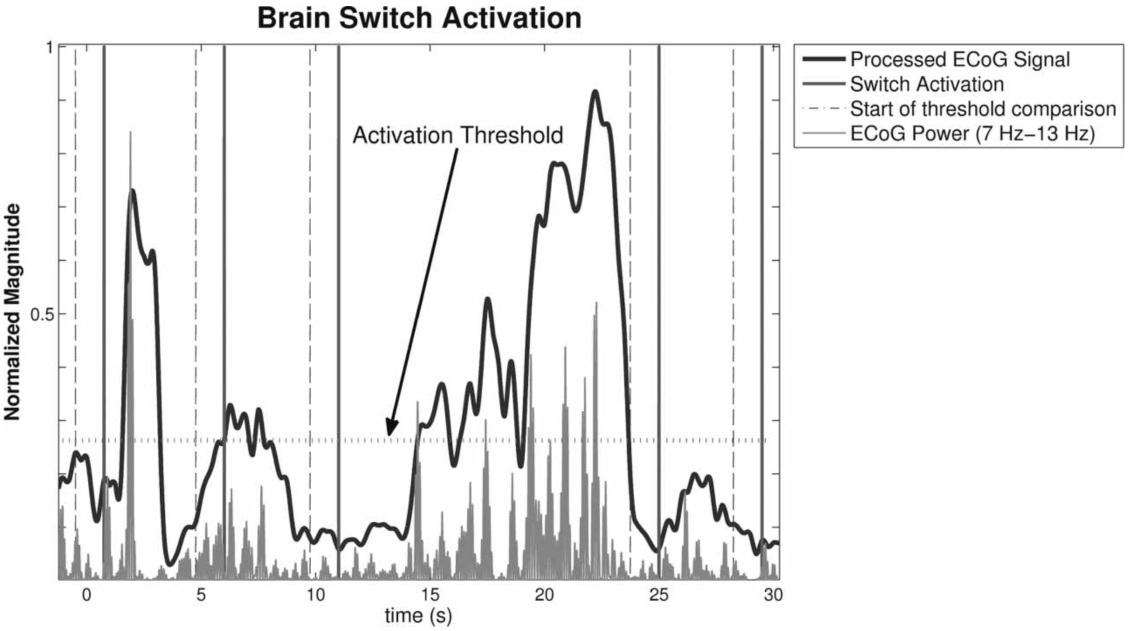


Figure 4 Brain switch activation. The figure shows five activations of the switch along with the ECoG power in the 7–13 Hz bandwidth and the processed signal used for switch activation. The vertical hatched lines show the time required for the processed signal to be below the threshold before an activation could be generated. After an activation, the system could not be activated again for 3 seconds.

Table 2 Results for individual runs. Figures describing performance of the BMI during three

	Trial No.		
	1	2	3
Number of targets acquired	4	5	5
Time required to complete run (seconds)	257.3	254.6	239.3
Activations required to complete run	59	52	48
Average time between activations (seconds)	5.1 ± 3.1	5.8 ± 3.5	5.6 ± 3.7
Average number of activations per target (seconds)	12.5 ± 9.7	8.2 ± 6.1	8.2 ± 6.1

The control strategy used changed the direction of the cursor in movement with each brain-switch activation. The movement of the cursor converged to the direction desired by the user after an average of 8–12 activations. This represented less than 30% of the 44 possible directions in which the cursor could move.

One of the limiting factors of the information transfer rate of BMI systems is still the small number of commands that these devices can generate. With a single identifiable brain-state it is possible to generate one command. Increasing the number of brain states that can be identified has been a strategy to increase the information throughput of BMI systems[54] accomplished by implementing sophisticated computational methods[48] and/or by increasing the features in brain signals that a person can control voluntarily.[1]

A second strategy to increase the information transfer rate of BMIs has been to use neural signals with richer information content leading to the development of BMI systems that use small populations of neurons acquired invasively. While it has been possible to control robotic arms and computers using this approach, many of these systems rely heavily on various constraint equations to restrict the movement of the device beyond the desirable envelope. Another concern, that is still an issue, which most likely will be resolved with new technology and surgical techniques, is that it is still necessary to assess the long-term viability of these highly invasive systems.

The methods used to improve the communication transfer rate of BMI systems often result in devices that are difficult to use, or require extensive training. The system that we presented here uses self-regulation of oscillatory rhythms at 7–13 Hz detected via comparison of a threshold. The use of this approach has been reported extensively for BMI applications.

The information transfer rate of the presented system, 6.3 bits/minute, is low compared to other BMI systems. Information rates as high as 70 bits/minute have been reported using evoked potentials.[55] In the context of two-dimensional cursor control, a recent study showcased the use of EEG signals modulated using motor imagery.[18] After at least five 1-hour sessions of experience using motor imagery and selection of relevant frequencies, two participants of that study were able to navigate a cursor to one of eight targets in less than 10 seconds using four different imagined movements, one for each direction (up, down, left, and right). In comparison, it took the participant of this study an average of 51.7 seconds (±40.2 seconds) to reach each target in the system presented here.

While slower, it is important to point out that the system presented here does not require constant modulation of brain signals; the user need only to be engaged in the control of the system occasionally. In our system, each one of the switch activations required the user to sustain the power level of the 7–13 Hz band below a threshold. Each target was reached after 9.6 switch activations. With this in mind, the average overall time in which the user was actively engaged in the control of the system was 11.7 seconds for each one of the presented targets. In comparison, participants of the study presented by Felton *et al.*[18] had to constantly modulate their EEG activities for 7.99 seconds.

What is unique about our work is that it showcases the integration of a very simple ECoG processing method combined with a technique for real-time two-dimensional asynchronous control. Our goal was to test this combination. While the data does not allow us to make conclusions with this respect, we believe that the system presented allows the user to concentrate on the task at hand. The attention of the user is not divided between the goal (the intended action) and the cues provided by the interface for its operation. In addition, the timing of the interaction is not determined by an automatic agent. Instead, the user decides when to use the system.

While the processing of the ECoG signals that we implemented had a dwell time of 1.25 seconds and a refractory period of 3 seconds, both representing a limiting factor in the communication rate of this system, it is important to mention that the control strategy has no restrictions over the time at which a switch activation may occur or the number of directions that can be made available to the user. In this work, the speed at which the cursor can change direction is not dependent on the control mechanism but rather on the methods used to detect the power changes in the ECoG signals. It is very likely that the combination of the control strategy presented here with different strategies for implementing a brain switch results in an increase in the speed at which control commands can be generated increasing the usability of this system.

Previously the control strategy presented here was tested using EEG recordings.[56] The time required to learn how to decrease the power in the 7–13 Hz band required 5 days using EEG compared to 15 minutes using ECoG. The reduction in time necessary for acquiring control over brain oscillations appears to be consistent with results from other research groups developing ECoG-based BMI technology.[15] In this implementation, it appears that the use of a subdural electrode provides an advantage over surface recordings. We believe that the work presented here represents a simple alternative for BMI implementation to control two-dimensional movements.

There are important limitations to this study. First, this study was conducted with a single participant. The electrodes used for the implementation of the system described here were implanted over MI as part of an experimental treatment for the treatment of ET and Parkinson's disease. The participant was the last of fewer than 10 candidate individuals who received this treatment. No further surgeries are planned and consequently, there will be no more individuals to conduct similar experiments until the effects of applying electrical stimulation to MI are better understood. As a result, these experiments are very unique, and it may take several years before similar experiments can be performed again as at the present time it is not clinically justified to place ECoG electrodes over the MI area. Details of the treatment, including surgical implantation, stimulation protocols, and outcomes can be found in Moro *et al.*[53]

Further, the extremely small number of individuals undergoing this treatment resulted in very limited available time window in which it was possible to conduct studies. As a consequence, other limitations of this work include a small number of tests conducted with different activation thresholds and activation time constants. This entire study was conducted in approximately 3 hours which did not give an opportunity to optimize (e.g. select relevant frequencies) the system or to allow for extensive training of the participant.

It is worth mentioning that the participant reported enjoying the experience thoroughly. We cannot say the same thing for our previous BMI systems, where it was our impression that the users were either indifferent or were looking forward to the end of the experiments. In this particular case, the patient had a break in the middle of the session and returned enthusiastically on her own to continue to participate in the experiment. Although this is a single case study, we believe that this observation is important and may suggest that patients are able to do this kind of task with ease.

Conclusions

We presented a novel BMI system for the control of two-dimensional trajectories using a single subdural contact. The participant of this study was able to navigate a computer cursor successfully using motor imagery after only 15 minutes. The system used and asynchronous control strategy that allowed the participant to concentrate on the operation of the system only when she wanted and did not demand her constant attention. She expressed enjoying the use of the system thoroughly.

Performance results indicate that the system requires further development and optimization to be competitive with other BMIs reported in the literature. However, these early results suggest that the implementation of the asynchronous control strategy used to create BMI systems may represent a viable approach for the development of this technology.

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