The Cortical Mouse

By Jose C. Principe

Early research on brain–computer interfaces (BCIs) was fueled by the study of event-related potentials (ERPs) by Farwell and Donchin [1], who are rightly credited for laying important groundwork for the BCI field. However, many other researchers have made substantial contributions that have escaped the radar screen of the current BCI community. For example, in the late 1980s, I worked with a brilliant multidisciplinary research group in electrical engineering at the University of Florida, Gainesville, headed by Dr. Donald Childers. Childers should be well known to long-time members of the IEEE Engineering in Medicine and Biology Society since he was the editor-in-chief of *IEEE Transactions on Biomedical Engineering* in the 1970s and the recipient of one of the most prestigious society awards, the William J. Morlock Award, in 1973.

A Piece of Forgotten History in Noninvasive Brain–Computer Interfaces

Childers collaborated with a team of psychologists, Dr. Nathan Perry and Dr. Ira Fischler, from the Psychology Department of the University of Florida to analyze multichannel ERPs. At that time, the objective was to use advanced signal processing (beyond simple averaging) to improve the signal-to-noise ratio of ERPs, which are signatures of cognition. The goal was to detect the occurrence of these events online, i.e., without averaging, as is still the usual practice today. Of course, if this could have been done reliably, a door would have been opened to using a subject's cognitive state to improve communication with microcomputers, which were starting to become widely available at the time. This work was funded initially by the U.S. Air Force through the Rome Air Development Center (RADC) and later by a grant to my lab from the Florida High Technology Council in 1990 under the title "A Novel Way to Communicate with the Computer: The Cortical Mouse."

My role in this group was to introduce artificial neural network (ANN) classifiers to improve the performance of the Fisher's linear discriminant, a technique still widely used in BCIs. At that time, I was excited to work on the NeXT computer, which was an amazing research computer at the time, as only Steve Jobs could envision. It had a very sophisticated operating system (OS) (NeXTStep) based on Unix (which later gave rise to the Mac OS) and a dual architecture with the main central processing unit and a 16-b digital signal processor (DSP) chip (both from Motorola) communicating transparently by very fast direct memory access. This combination opened the door for real-time signal-processing applications on a single platform (and, in fact, for many years, the NeXT computer was the best platform for synthetic music composition). One of the projects in my lab at the University of Florida was to take advantage of this hardware potential for simple speech recognition (e.g., word spotting), intelligent control (tool breakage in milling), and other real-time applications. My collaboration with Childers's group opened yet another opportunity—that of using the NeXT computer for a new interface with the computer using brain waves. The OS controlled the user interface, and the DSP processed the brain waves, both in real time and implemented in the same platform.

We started this work around 1988 and presented the first report to RADC in 1989 [2] and the first paper at the International Joint Conference on Neural Networks (IJCNN) in San Diego in 1990 [3]; the full description can be found in Sina Eatemadi's master's thesis [4] (Figure 1).

The novelty of our approach with respect to Farwell and Donchin's well-publicized work is that our system used a different component of the ERP, the N400, which is related to the cognitive response to congruent or incongruent words in a sentence (enhanced with incongruent words). Fischler showed that this negativity is still present even when the subjects were not asked about the outcome. Moreover, the goal was to create an online system, in which the decisions were made based on a single ERP (without averaging) to achieve real-time interactivity with the user. A brief description of the paradigm is given in the following paragraphs (Figure 2).

The goal of the experiment was to use one's thoughts to move a ball over a wall shown on a computer screen, basically to play ping-pong (or table tennis). An electroencephalogram

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(EEG) channel (Cz or Pz) and an electrooculogram (EOG) channel were collected from the subject (linked ear montage). The subject sat in front of a computer screen that was flashing the words *right* and *left*. If the ball was on the left side of the wall, the goal was to move it to the right side of the wall and vice versa. The subject was instructed to think *yes* if the sequence of two words for moving the ball in the intended direction was flashed and *no* if the wrong word sequence was flashed. The automated classification of the N400 from the EEG would be used to implement the movement of the ball on the screen.

It is now obvious why we called this application a "cortical mouse": the user was controlling the movement of the cursor through brain waves. By using averaging in the lab, we found that this paradigm would indeed enhance the N400 component if the computer flashed the direction that the user was expecting to pass the ball over the wall (Figure 3). Note that this paradigm is not specific to ping-pong because the words right and left can be substituted by any binary question, so the system is quite general.

The implementation of the brain control was all done online in the NeXT computer and at a speed that would create an interactive environment. The video control for word presentation and ball movement was implemented in the NeXT OS, and the EEG was digitized by a stereo microphone that included

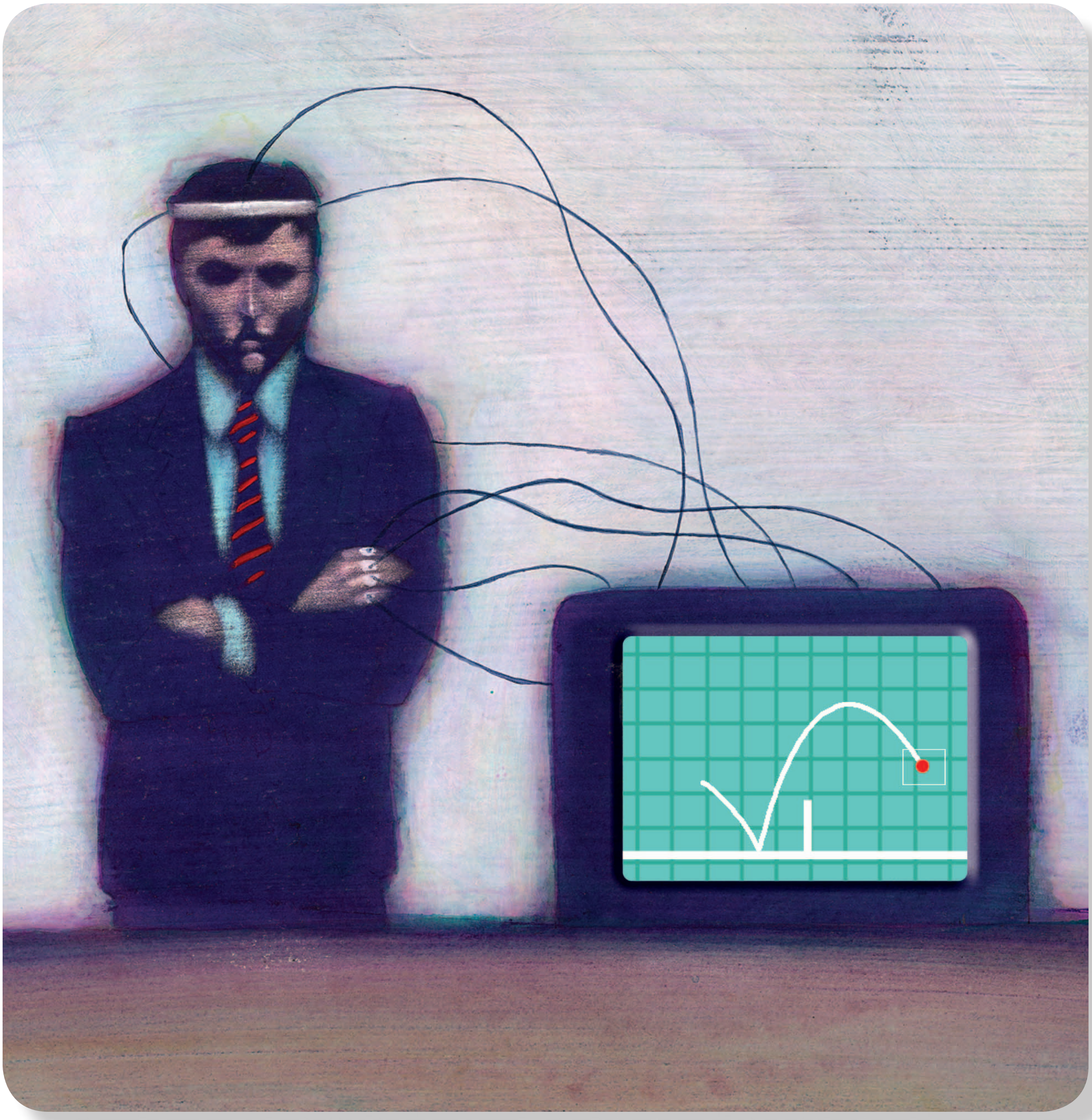

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FIGURE 1 Shown here is Sina Eatemadi explaining the cortical mouse setup on video. On the right, the Grass machine collects the EEG; the NeXT computer is in the background in front of a user ready to use the cortical mouse. (Image courtesy of Jose C. Principe.)

a 12-b analog digital converter (ADC) that was directly fed into the DSP port (125-Hz sampling frequency). Since we only had two channels, we used one of the EEG channels and the EOG channel in the experiment. The signal-processing program (low-pass filtering and detection of eye movements) and the classifier were coded in assembly language and achieved real-time operation. The EEG was collected synchronously with the presentation of the word on the screen (4,096 ms), which gave approximately 500 samples (Figure 4). These 500 samples were used to determine whether or not eye movements were present during the experiment (in case of eye movement, no decision was made).

In trials without eye movements, the information pertaining to the subject's decision was captured on a window of 100 samples beginning at 1,600 ms after the presentation of the first word to focus on the N400 signature. These samples were fed to a tap delay line that was connected to a single hidden layer multilayer perceptron (four hidden processing elements) with two outputs that would classify the trial as a *yes* trial (and the ball would be moved in the direction that the computer flashed) or a *no* trial (and the ball would remain in the same position). Note that if an error was made, the ball would move in the wrong direction; therefore, it would take much longer to make the ball go over the wall.

The ANN classifier was trained offline to find the best weights, but once trained, the decision was computed very quickly, as the number of operations was small even though all the arithmetic was fixed point. One of the difficulties was the amount of training data required. First, the ANN was large $(100 \times 4 \times 2 = 800 \text{ parameters})$ and then we found out that the N400 was subject specific; both of these conditions created a data bottleneck to properly train the ANN. We modified the input delay line of the ANN to 16 taps to improve generalization (one sixth of the weights), but this created another problem because of the time jitter of the N400 response. In any case, in the RADC report [2] and the IJCNN paper [3], we presented that two of the four subjects achieved around 80% accuracy in the test set, while the others subjects were barely at chance level. Eatemadi's master's thesis [4] has more details. Figure 5 shows a low-resolution screen capture of the NeXT computer display. In the computational neuroengineering laboratory (CNEL), we still have a movie showing the real-time brain control of the cursor.

In conclusion, these experiments done in 1989 and 1990 showed that it is possible to use brain waves for communication and control using single-trial ERPs. The method was not effective as a novel way to communicate with the computer because the bit rates were very low (15-word presentations per minute) and, at that time, we did not pursue this research further. But, of course, for a quadriplegic, a rate of 15 b/min is infinitely better than 0 b/min; therefore, we missed the impact that this technology could have on the motor-impaired population, as subsequent research has taught us. Since the IJCNN paper did not use

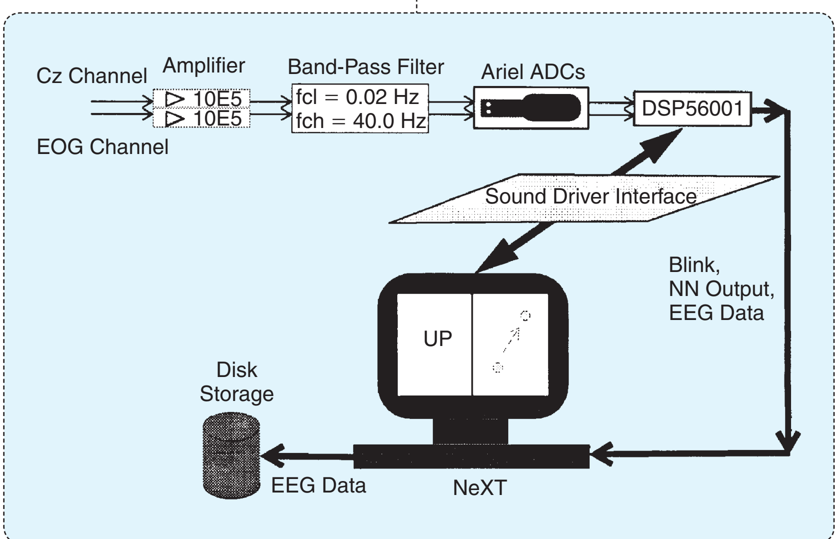

FIGURE 2 An overall block diagram of the cortical mouse in the NeXT computer. (Figure courtesy of Jose C. Principe.)

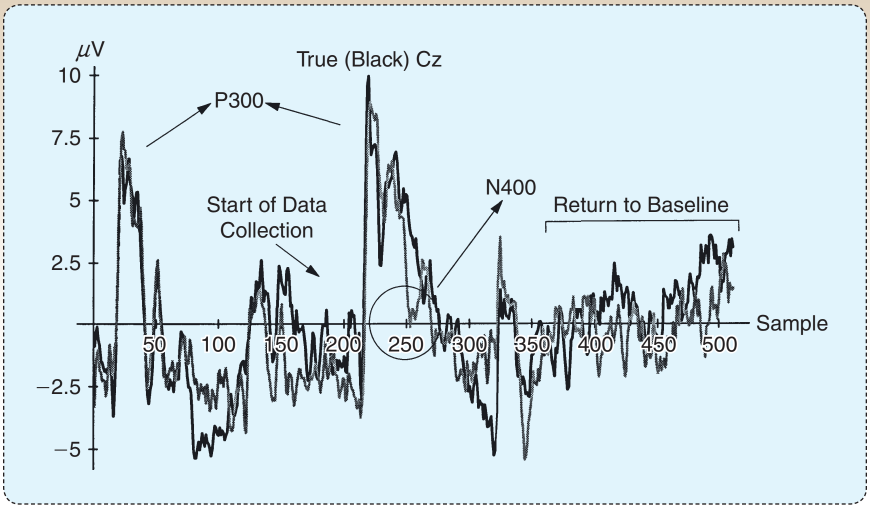

FIGURE 3 The difference between true and false N400 responses for one subject (from [4]). (Figure courtesy of Jose C. Principe.)

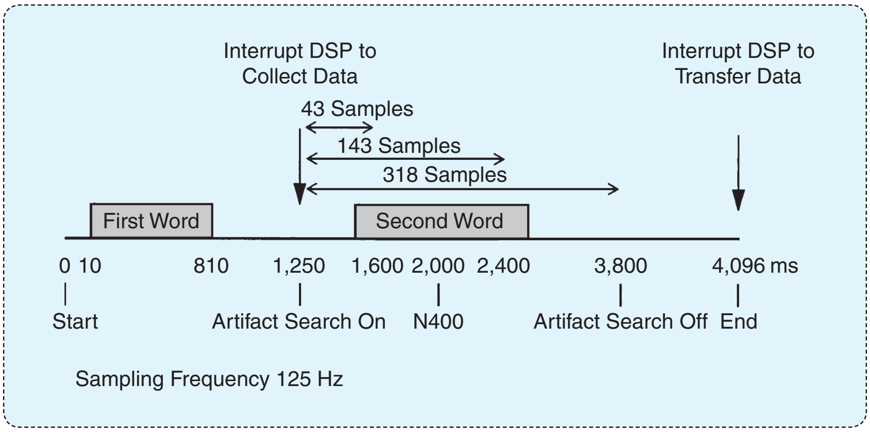

FIGURE 4 Timing information for the synchronous data collection (from [4]). (Figure courtesy of Jose C. Principe.)

"brain–computer interface" anywhere in the text, the paper has never been referenced in the BCI literature. Even so, this study, as well as others going on at that time, added to the historical record in this important field.

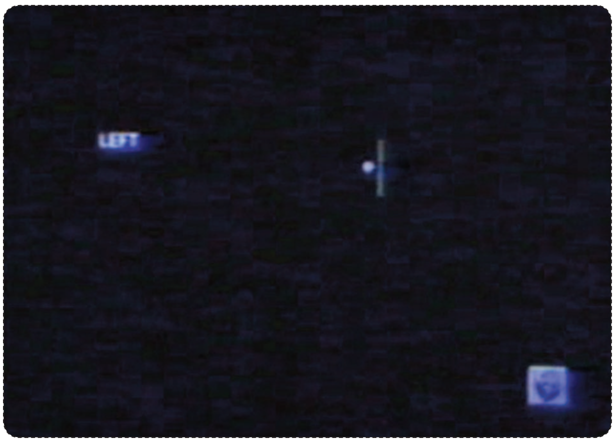

FIGURE 5 A screen capture of the NeXT computer display showing the word that was flashed and the position of the ball and the wall. The computer would move the position of the ball using the user's EEG after each presentation of the second word. (Image courtesy of Jose C. Principe.)

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References

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