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Toward Noninvasive Brain-Computer Interfaces

At the time of this writing, CeBIT'2006 (the world's largest annual trade show for information and telecommunications technology, which brings together around half a million visitors each year) held in Hannover, Germany, has just closed. At CeBIT, the Fraunhofer Institute FIRST together with Charité Berlin presented the Berlin brain-computer interface (BBCI), which attracted much interest and media coverage. In what follows, we comment on the characteristics, technical challenges, and future developments of this interface.

Brain-computer interfaces (BCIs) translate brain signals into control commands. The measured brain signals reflect, to some extent, the intentions of a subject. The control commands may be used for a computer application or a neuroprosthesis [1], [2]. There is a variety of BCI systems being developed that use signals recorded from the scalp, the surface of the cortex, or from inside the brain. It has been shown that invasive BCI systems enable monkeys to operate a robotic arm. Furthermore it was demonstrated that noninvasive BCI systems enable healthy subjects as well as patients to control an Internet browser or simple word processing software [1], [2], [5].

In the BBCI, the brain activity is measured noninvasively, using a standard electroencephalogram (EEG). The characteristics of the EEG make possible the decoding of a number of rudimentary mental states such as the intention of movement, mental calculation, and navigation. More specifically, in the BBCI, we use the paradigm of movement imagination of the left versus the right hand to transfer one bit of information. Physiologically, these states can be identified by an increased activity on the right or left motor cortex, respectively. However, an enormous number of other brain activities, which are due to our normal perceptions and actions, are superimposed over these states. Therefore, EEG signal processing for BBCI requires the enhancement of signals of interest and the suppression of the rest of the "cerebral cocktail party" signals in real time.

[BRAIN-COMPUTER INTERFACES TRANSLATE BRAIN SIGNALS INTO CONTROL COMMANDS.]

An important characteristic of the BBCI is the short (approximately 20 min) calibration time per individual as opposed to a much longer (about 100 h of subject/patient training) of other approaches that require the subject to be trained to regulate the brain activities. As a result, it became possible for BCI novices to reliably operate a BCI within one morning following a succession of steps: 1) placing on an EEG cap (time required is 40 min for 128 channels), 2) performing a calibration

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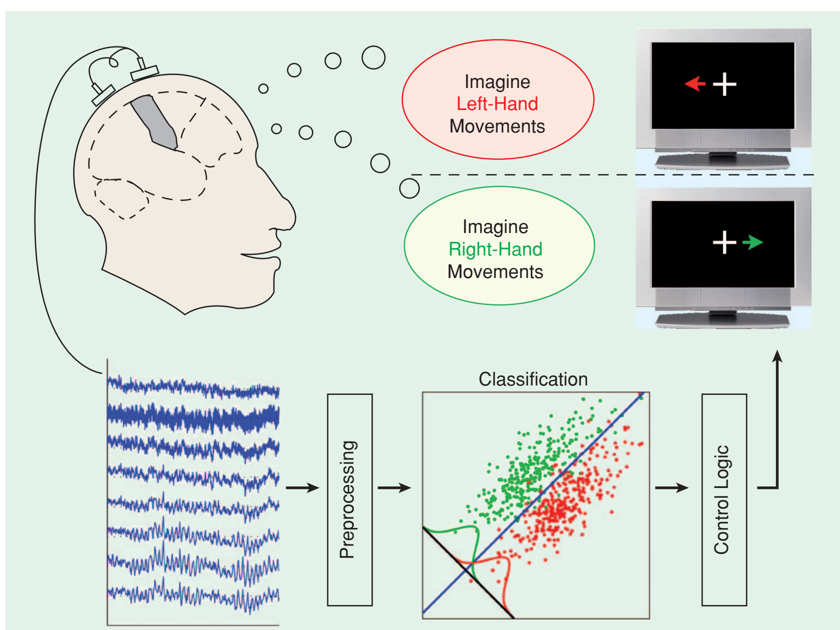

[FIG 1] In a BCI a user can convey his/her intent to a computer by assuming specific mental states, like imaging movements of the left or right hand. The resulting brain signals are preprocessed and classified by the learning system that was adapted to the user's brain signature in the calibration phase. Using control theory, the classifier output is used to drive a technical device or a computer application.

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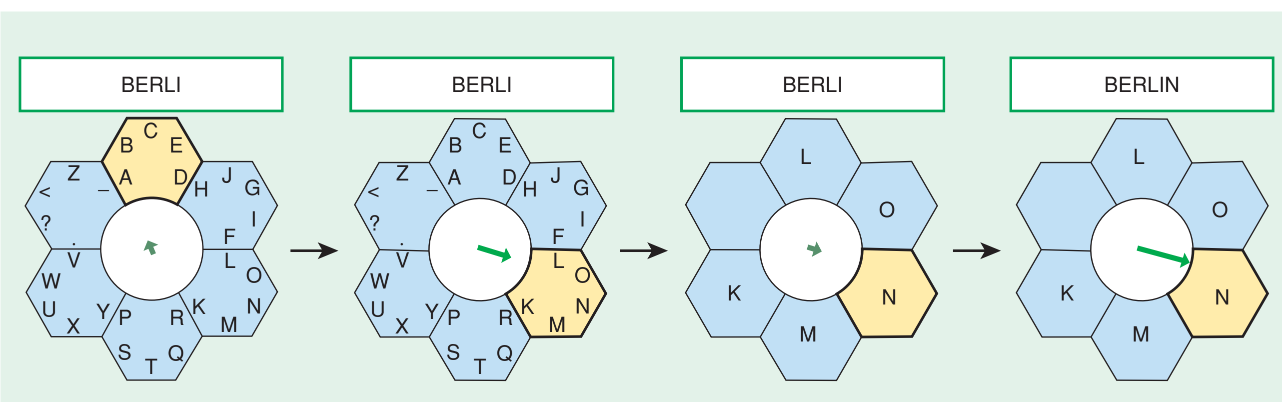
session (time required is 20 min) during which the subject imagines various movements, 3) using the data from this calibration session to extract features that reflect the dynamical attributes of brain signals [3], 4) removing outliers and artifacts, 5) using advanced machine learning techniques such as support vector machines to build a classifier [3], [4], and 6) starting a BCI experiment such as the mental typewriter (described later) with real-time feedback. Steps 3–5 are semiautomatic and require about 5 min of computing time on a standard PC. The result is crosschecked manually by a brief visual inspection. Step 6 is fully automatic and runs in real time. A block diagram of the system is illustrated in Figure 1.

The challenge in designing a mental typewriter such as the novel Hex-o-Spell used in step 6 is to map a small number of BCI control states (typically two) to a high number of symbols (26 letters plus several symbols) while accounting for the low signal-to-noise ratio in the control signal. The Hex-o-Spell can be controlled by two mental states: 1) imagined right-hand movement and 2) imagined right-foot movement. The initial configuration is shown in Figure 2(a). In this figure, there are six hexagons around one circle. In each hexagon, there are five letters or other symbols (including < for backspace). The arrow in the center of the circle is used for the selection of a symbol. By imagining a right-hand movement, the arrow turns clockwise like the arrow of a clock. When the arrow points in the direction of the desired hexagon, an imagined foot movement stops the rotation and the arrow starts extending. When this imagined scenario lasts long enough, the arrow touches the hexagon and thereby selects it. Then all other hexagons are cleared, and the five symbols of the selected hexagon are moved to individual hexagons as shown in Figure 2(c). The arrow is reset to its minimal length. Next the same procedure (rotation if desired and extension of the arrow) is repeated to select one symbol. A language model is used to determine the order of the symbols within one hexagon depending on the context (the details of which are beyond the scope of this article).

At the CeBIT'2006 computer fair in Hannover, Germany, we gave two demonstrations of the BBCI system operating with two users. These demonstrations were excellent tests for the BBCI robustness. In the fair pavilion, several noise sources (electric and acoustic) were present, and the air was very dry such that the EEG electrode gel was drying out; last but not least, the subjects were under psychological pressure to perform well (for instance in front of several TV cameras). The preparation of the experiments started at 9:15 a.m. (steps 1–5), and the live performance started at 11:00 a.m. The two subjects were either playing brain-pong (our BBCI version of the classic teletennis game by Atari 1972) against each other or writing sentences with the Hex-o-Spell mental typewriter described earlier. Except for short breaks and one longer lunch break, the subjects continued performing the experiment until 5:00 p.m. The BBCI system demonstrated high performance stability in this endurance test. The typing speed was between 2.3 and 5 chars/min for one subject and between 4.6 and 8.3 chars/min for the other subject. This speed was measured for error free, completed phrases (i.e., all typing errors were corrected using the backspace of the mental typewriter). For a BCI-driven typewriter, this is a world-class spelling speed, especially taking into account the environment and the fact that the subjects were not trained on the usage of the BBCI typewriter interface, as both subjects used the typewriter application only two times before.

With the availability of interfaces such as BBCI that require no subject training, in addition to rehabilitation (mostly targeted by BCIs) other applications come within reach: human-machine interaction, computer gaming, monitoring of user safety (alertness, drowsiness, concentration, cognitive workload, and emotion). In addition, monitoring of the human brain in real time will hopefully contribute to gathering new insights into the brain activity. Many challenges remain, among which three are particularly important. First, (as mentioned earlier) the BBCI can process a limited number of brain activities. This limitation comes primarily from the EEG's characteristics: a



[FIG 2] The mental typewriter Hex-o-spell. The two states classified by the BCI system control the turning and growing of the green arrow, respectively (see also text). Letters can be chosen in a two-step procedure. First a subgroup is selected, and then the hexagon that contains the desired letter.

high temporal sampling (1,000 Hz) and a limited spatial resolution (1 cm). As a result, using the EEG (and hence, the BBCI), only macroscopic cortical sources of a certain intensity and orientation can be observed. For instance, when imaging movement activities, the motor cortex signals between 1–10 μV can be measured with EEG. More complex brain activities and thoughts, such as thinking about the line of a poem or even a simple word, remain systematically unobservable. How to extend the number of brain activities that can be processed by BBCI is a topic of future work. Second, the preparation of the EEG sensors is very time consuming and not suitable for daily life. Although there are several approaches underway to construct dry or capacitive electrodes, so far sensors remain a major bottleneck for a wider application of BCI technology. Ideally, an EEG cap should be slipped on like a baseball cap and should start measuring instantly and reliably; the design of the cap should be pleasing and inexpensive. Third, the inability to use a BCI by roughly one third of the subject population has been observed by several research groups. The physiological and psychological reasons of this phenomenon are unclear for now. Research on these topics and other related to building better BCI systems remains a challenging and cross-disciplinary endeavor.

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REFERENCES

[1] A. Kübler, B. Kotchoubey, J. Kaiser, J.R. Wolpaw, and N. Birbaumer, "Brain-computer communication: Unlocking the locked in," *Psychol. Bull.*, vol. 127, no. 3, pp. 358–375, 2001.

[2] J.R. Wolpaw, N. Birbaumer, D.J. McFarland, G. Pfurtscheller, and T.M. Vaughan, "Brain computer interfaces for communication and control," *Clin. Neurophysiol.*, vol. 113, no. 6, pp. 767–791, 2002.

[3] B. Blankertz, G. Curio, and K.-R. Müller, "Classifying single trial EEG: Towards brain computer interfacing," in *Advances in Neural Information Processing Systems 14*, T.G. Dietterich, S. Becker, and Z. Ghahramani, Eds. Cambridge, MA: MIT Press, 2002, pp. 157–164.

[4] G. Dornhege, B. Blankertz, G. Curio, and K.-R. Müller, "Boosting bit rates in noninvasive EEG single-trial classifications by feature combination and multi-class paradigms," *IEEE Trans. Biomed. Eng.*, vol. 51, no. 6, pp. 993–1002, 2004.

[5] *Towards Brain-Computer Interfacing*, J. Millán, T. Hinterberger, D.J. McFarland, and K.-R. Müller, Eds. Cambridge, MA: MIT Press, to be published in Spring 2007.

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