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In October 2016, inside a sold-out arena in Zurich, Switzerland, a paralyzed man named Numa Poujouly steered his wheelchair up a podium. As the Swiss national anthem played, organizers of the world's first cyborg Olympics hung a gold medal around Poujouly's neck. He had triumphed in the tournament's most futuristic event: a video game-like race in which the competitors controlled their speeding avatars with their minds.

The Cybathlon was created as a bionic version of the Paralympic Games. In six different disciplines, people with disabilities skillfully piloted robotic and other assistive devices to make their way around race tracks or through obstacle courses. The stadium crowd cheered for paralyzed people walking in exoskeleton suits and for amputees using powered prosthetic limbs.

The visionaries behind the Cybathlon had several objectives. First, taking a page from the Xprize Foundation, they wanted to use competition to accelerate the development of assistive technologies. The organizers also asked teams to recruit their disabled athletes early in the process so these end-users could help develop the technologies along with engineers, clinicians, and entrepreneurs. Finally, they wanted to raise awareness of cutting-edge technologies that may soon give people with disabilities remarkable abilities.

The Brain-Computer Interface (BCI) Race required pilots to propel their brain-controlled avatars through a race course to the finish line by delivering mental commands. In any BCI system, neural signals recorded from the brain are fed into a decoding algorithm that translates these signals into outputs, which can be used to control a variety of practical devices for people with severe motor impairments. Many experimental BCI systems have been developed to control wheelchairs, robots, and computer cursors.

The Cybathlon's criteria allowed for only non-invasive BCI systems that use scalp electrodes to pick up the neural signals, in contrast to experimental systems that use electrodes implanted in the brain tissue. Non-invasive systems pick up noisier neural signals, but paired with the right signal processing software they can provide signals that are good enough to work with—and they don't bring along the medical risks of brain surgery.

Poujouly, the BCI gold medal winner, was one of two pilots for our Brain Tweakers team. We are researchers at the brain-machine interface lab at the Swiss Federal Institute of Technology (EPFL) in Geneva, Switzerland. Our lab focuses on the real-time use of human brain signals to allow people to control devices and interact with the environment. In 2016, we turned our attention to the creation of a BCI system that could master the particular challenges of the Cybathlon BCI race.

We developed the technology with help and feedback from our two pilots, Poujouly and Eric Anselmo, who helped us determine the best mental commands that gave them intuitive control of their avatars. Teamwork was key to our success: In addition to the collaboration between researchers and pilots, our system also created a symbiotic relationship between man and machine, in which the pilots and the BCI software adapt to each other during the training process. We're proud to say that both of our pilots made it to the final race, and Poujouly's gold medal offers definitive proof that we had a winning strategy. Here we'll tell the story of how the Brain Tweakers team accomplished this feat, and we'll discuss what our accomplishment means for the progress toward practical BCIs that can be used in everyday life.

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The Cybathlon's organizers designed the BCI race to be an entertaining spectacle that would get the audience cheering for the competitors. Yet it was also carefully planned to assess those BCI features essential for controlling virtually any BCI solution, including steering wheelchairs or telepresence robots, managing prosthetic limbs, and using communication software that enables people to type out words by moving a computer cursor to pick out letters.

What all these things have in common is [[TKTKTKTK—what features must a BCI have to enable efficient control of an external device? List a few: Ability to record a certain number of neural signals? Good signal processing that can filter out noise? Etc?]].

Our pilots were both eager to help accelerate the development of this technology. The 48-year-old Anselmo has been paralyzed for more than two decades; at the age of 21 he was in a car crash and suffered a spinal cord injury around the C5/C6 cervical vertebrae in his neck. Poujouly, now 30 years old, was a teenager doing a jump on his bike when he fell and injured his spinal cord, also around the C5/C6 vertebrae. Both are tetraplegic, with no sensation or muscle control below the waist and [[TKTK—do they have limited control of trunk and arms??]]. To navigate their daily lives, they use wheelchairs controlled by [[TKTKTK]] and other assistive devices like [[TKTKTK]]. They've both expressed frustration with the current state-of-the-art technologies, and are eager for devices that might enable them to [[TKTKTK—what would they really like to be able to do on their own?]].

The Cybathlon's "BrainRunners" race required pilots to send three distinct mental commands to either speed up the running avatar or help it avoid obstacles. The competitors had to employ each command only on a certain color-coded segment of the race track: They used a "speed up" command on cyan sections, a "jump" command on magenta sections that were filled with protruding blocks, and a "slide" command on yellow sections that contained electric fences. Sending the wrong command as the avatar raced across these distinct sections caused it to slow down.

The race cleverly tested BCI systems' ability to support brain-control with an adequate number of different commands and with precise timing of command delivery. What's more, the track had a fourth kind of section, colored gray, which required the pilots to issue no command at all. These sections required the pilot to keep the BCI intentionally idle for a stretch of time, while the BCI software had to avoid interpreting any stray neural signals as "false positive" commands.

The race track consisted of 16 sections (four of each type), randomly arranged. The challenge was made greater by the racing conditions: Pilots had to maintain concentration and mentally control their avatars in a noisy and distracting arena with the psychological pressure of performing in front of a crowd. The Cybathlon's conditions were arguably more challenging than those that a

BCI user would face in trying to use the system in a real-world setting to complete the tasks of daily life.

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To capture our pilots' brain signals, we used a lightweight EEG (electroencephalography) system consisting of a flexible cap studded with electrodes and a specialized biosignal amplifier. These components are commercially available and often used in neuroscience research. EEG measures the electrical activity of millions of brain cells, and because it uses scalp electrodes to record through skin, bone, and tissue the signal is fairly messy. Our approach to this challenge was to work with our pilots to find strong signals that they could generate reliably, and to use fine-tuned signal processing software that we developed for prior BCI experiments and customized for the Cybathlon race.

For a robust neural signal, we used a motor-imagery (MI)-based BCI paradigm, asking our pilots to imagine performing specific movements (which they couldn't perform with their paralyzed limbs). As they visualized these different motions the EEG electrodes picked up changes in the rhythmic patterns of electrical activity in the motor cortex, the region of the brain that controls voluntary movement [[TKTK—is this correct, that you were recording only from motor cortex?]]. The BCI software had to learn to identify these patterns, and the pilot had to learn to modulate them voluntarily. Each individual has brain patterns that are as unique as fingerprints, so our BCI needed to recognize each pilot's distinct patterns of neural activity, which ranged across locations in the motor cortex and varied in signal frequency (typically between 8-32 Hz). These distinct spatio-spectral patterns of EEG activity allowed us to associate each pilot's MI tasks with commands for an external device; in this case, the three commands executed by the pilot's avatar in the BCI race.

To tweak our signal processing software for the Cybathlon, we first had to improve our ability to filter out electric signals from the eyes and head muscles, which the EEG electrodes also pick up. This filtering both refined the neural signal and complied with the Cybathlon's rules; the organizers stressed that controlling the BCI with eye or muscle signals would be considered cheating. We also had to refine our algorithm to manage three commands (our prior experiments used only two), and to recognize an "idle" state, which is often overlooked in research labs but is vital for real-world BCI applications.

The most important component of our victory, however, was our "mutual learning" approach for pilot training—a methodology in which the user and the BCI adapt to each other to achieve optimal performance. It's therefore important to explain our training strategy and highlight the essential feedback of our pilots.

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Our research team had previously worked with Anselmo on a BCI experiment, and he began training with the racing BCI six months before the Cybathlon. Poujouly, whom we recruited through his clinic [[TKTK—what does this mean—his doctor recommended him for the project?]], had never used a BCI before he began training three months before the event. We conducted the training sessions in the pilots' homes, starting with two-hour sessions once per week and increasing the frequency as the event approached.

Our first task was to calibrate the BCI system to recognize the individual patterns of Anselmo and Poujouly. We asked both pilots to imagine repeatedly moving their right hand, left hand, or both feet in order to model the associated brain patterns and link them to the three commands necessary for the BrainRunners game. However, after few sessions it became clear that three mental MI tasks didn't provide sufficiently clear and robust signals, and this technique would require extensive training time [[TKTKT—do you mean training time for the pilots or for the software, or for both?]].

So we found a work-around. We calibrated the BCI system to recognize just two mental tasks: the imagined movement of either both hands or both feet. To create a third identifiable neural signal, we had the pilots imagine a quick sequence of movements, first moving both hands and then both feet. We came to this solution after trying many other ideas [[TKTK—can you give examples of other ideas you tried?]] and getting our pilots' perspective; through this constructive dialog, we settled on the code-based approach.

After the initial calibration, pilots performed control sessions while receiving continuous visual feedback from the BCI. It was during this closed-loop training that the pilots learned to modulate their brain signals to produce the most distinctive patterns. Because the Cybathlon's BrainRunners game was so complex, we used a more basic task in this training phase. The users simply looked at a computer screen and tried to move a bar either up or down using their two commands. As the pilots got better at generating clear neural signals, we periodically recalibrated the BCI system to reflect the pilot's altered brain activity.

Once this mutual learning technique had produced pilots and software working in harmony, we focused on getting our pilots accustomed to the BrainRunners game. We linked the both-hands movement to the "speed up" command, the both-feet movement to "jump," and the hands-then-feet movement to the "slide" command.

In the initial training races, our pilots competed against a single opponent controlled by a computer. Anselmo completed more than 180 such races, with an average completion time of 127 seconds and an all-time record of 83 seconds. Poujouly did 57 training races with an average time of 130 seconds and a record of 86 seconds. At this stage, exploiting our BCI's reconfigurability and personalization, we could easily find the optimal parameters for each pilot [[TKTK—I left this sentence in but don't understand it, what does it mean to find the optimal parameters?]], another crucial aspect of our mutual learning approach.

Finally, two joint training sessions were scheduled in our lab in the month leading up to the Cybathlon. In these two face-off events, our pilots raced against each other in a crowded lab while our staff loudly cheering them on. We hoped that racing in this environment would prepare them for the real competition scenario.

There can be no better proof of our training protocol's effectiveness than the fact that our pilots were able to replicate their excellent performances in the official Cybathlon races as a stadium full of people watched. Both Anselmo and Poujouly won their qualification races to advance to the final with the two best performances of the overall BCI race competition: 90 and 123 seconds, respectively. Although Anselmo had a performance lapse during the final race that cost him a medal, Poujouly raced at his regular pace to capture the gold for himself and the glory for the Brain Tweakers team. He won with a time of 125 seconds, coming in 31 seconds before the next competitor!

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While our Brain Tweakers team feels wonderful about winning the Cybathlon race, we researchers know we had an even greater challenge still ahead of us: transforming this experimental technology into devices that can be of real practical use to people with disabilities.

Our pilots' accounts give us a better understanding of the limitations of today's cutting-edge BCI technologies. They note that the EEG cap takes a long time to set up and isn't exactly inconspicuous, limiting the appeal of EEG-based systems for daily use. Today's typical EEG systems require gel to be placed under each electrode to facilitate conductivity through the scalp, so the user needs help to get everything in place. But already researchers are making advances with dry electrodes that don't require gel, which should lead to more user-friendly systems. Other researchers have suggested that people with disabilities might be willing to have permanent electrodes inserted just under the skin of the scalp—but any system that requires surgery will face additional regulatory hurdles.

The calibration process, in which our team of experts recorded the pilots' brain patterns to train the BCI, also seems ill-suited for an everyday technology. Anselmo and Poujouly also describe these sessions as long and boring. However, our research team is now working on calibration software that could be easily run by a rehab therapist who isn't expert in BCI technology, or even by the users themselves. We're working with our clinical partners on a program that could guide anyone through the calibration process in a series of simple steps. [[TKTK—can you do anything about making it less boring? Or should we just stress Poujouly's point, that calibration may be boring but it's important to get the best and most personalized BCI for each patient?]]

Our BCI for the BrainRunners game also demonstrated how satisfying and intuitive the technology can be. Both our pilots say they felt an immediate sense of control, even in the earliest training sessions. Our mutual learning approach, in which man and machine adapted to each other, established a symbiotic system, and when the pilots reached the stage of training for the Cybathlon race they say the experience became even more fulfilling. "The first time the avatar responded to my thoughts made me really happy," says [[TKTK—which pilot said this?]] And as they became accustomed to the simple control system, the avatar's movements became instinctual. "I was not think of moving my limbs, but simply about what the avatar should do," says [[TKTK—which pilot said this?]]

As we consider how to move this technology from the lab to the real world, we'll have to consider several more factors. Good performance with our BCI still required intense concentration; Poujouly even meditated before his races to put his mind into the proper focused state. Will such focused concentration be possible for a user who's trying to employ a BCI in the routine tasks of daily life? What's more, our BCI's ability to manage three commands (plus the idle state) was a great technical achievement, but real-world users of a BCI might want many more. [[TKTK—are there other factors you want to mention here about the difficulties of making a real-world technology?]]

Both our pilots are enthusiastic about the future of BCIs and imagine a wide range of uses for such technologies, including systems to control cars and to interact with a smart home. We researchers also imagine [[TKTK—what do you think are the most practical near-term applications of BCIs? What's the next step for BCI tech? What are you working on now?]]

[[I'll work on the ending later!]]

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