Veni, vidi, vici: experiences and lessons from the Cybathlon BCI race

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October 2016 saw the first Cybathlon championship for athletes with disabilities held in a sold-out arena in Zurich, Switzerland. The Cybathlon featured as the first ever bionic special Olympics event and involved six different disciplines, where everyday-life tasks had to be accomplished by athletes through skillfully piloting robotic and other assistive devices [1]. The visionaries and organizers of this competition have been inspired by a multitude of objectives. First and foremost, the Cybathlon aspired to accelerate the development of assistive technology beyond the still unsatisfactory state-of-the-art. An equally important goal has been to promote end-user and public awareness of such technology, as well as to attract funding agencies willing to support its providers. Additionally, the Cybathlon has attempted to increase end-user acceptance by placing disabled individuals in the center of the development loop, in pair with engineers, clinicians and entrepreneurs.

Fig. 1. The Cybathlon arena.

Arguably the most futuristic and far-reaching among the disciplines of the Cybathlon, the Brain-Computer Interface (BCI) race required the pilots to make their brain-controlled avatar reach the finishing line by delivering mental commands. In a BCI system, neural signals recorded from the brain are fed into a decoding algorithm that translates these signals into motor outputs to control a variety of practical devices for people with severe motor impairments [2]. Feedback from the assistive device establishes a closed control loop. Non-invasive BCI prototypes, complying with Cybathlon's inclusion criteria of being devoid of medical risks related to surgical insertion of neural implants, have been proved to be mature enough to be evaluated by actual end-users with remarkable success [3]. Although the BCI race is an entertainment-oriented application meant to appeal to the Cybathlon live audience, it has been explicitly designed to assess those BCI skills essential for mastering the control of virtually any BCI solution: from assistive mobility and motor substitution to communication and accessibility software [4-7].

Fig. 2. The BCI race, called Brain Runners: Details of the final with our two pilots leading the race, Numa Poujouly (on the right panel) and Eric Anselmo (on the insert of the public streamed video).

More specifically, the BCI pilots should timely send up to three different mental commands in order to accelerate or to avoid different obstacles. Each of these commands should be only employed on specific color-coded segments of the race track ("pads") associated to the particular command ("Rotate" to speed-up in the cyan pads, "Jump" over obstacles in the magenta ones, and "Slide" under electrical fences in the yellow pads). Misplaced commands had the adverse effect of slowing down the pilot's avatar. The BCI race thus tests the BCI ability to support discrete brain-control with an adequate number of commands, while the need for precise command delivery timing assesses the extent of compliance with self-paced, ecological control. Along the same lines, a fourth type of pad (gray) would penalize any command, demonstrating the ability of the pilot-BCI symbiotic system to remain intentionally idle for a considerable amount of time and avoid "false positive" commands.

The race track consisted of a total of sixteen such pads (four of each type) randomly arranged, a challenging venture for the pilots, which was further hampered by the racing conditions: a crowded, noisy and imposing arena, low temperatures and, most importantly, the psychological implications for the pilot, most of whom were performing in front of a crowd for the first time in their lives. It can be thus argued that the Cybathlon provided a venue for testing state-of-the-art non-invasive BCI in a real-world setting —actually, even more challenging than most daily situations!

Notwithstanding the high demands of the competition, our “Brain Tweakers” team vastly dominated the BCI race discipline, winning both the rehearsal event in July 2015 and the gold medal in the official competition, while also placing both our pilots in the final and holding the three best performances throughout the competition! On these grounds, this note is intended to provide an account of our experiences and lessons learned from the Cybathlon event and our preparations towards it, as well as how the Cybathlon objectives applied in our case.

The Brain Tweakers team was composed of five researchers of the Chair in Brain-Machine Interface (CNBI) laboratory at the Swiss Federal Institute of Technology (EPFL) in Geneva, Switzerland and two end-users involved as pilots in the Cybathlon event. CNBI research is focused on the real-time use of human brain signals to control devices and interact with the environment. In the last months, such wide expertise was devoted to the creation of a BCI system able to face the particular challenges of the Cybathlon BCI race.

48-year-old Eric Anselmo and 30-year-old Numa Poujouly were our two pilots. Both suffer from tetraplegia with no motor or sensory function preserved in sacral segment S4-S5 due to accident-inflicted traumatic Spinal Cord Injuries (SCI) at spinal level C5/C6, at the age of 21 and 17, respectively. They both score “A” in the American Spinal Injury Association Classification (ASIA). Eric had previous BCI experience and has been in contact with CNBI through his participation back in 2011 in a large collaborative European project focusing on the clinical evaluation of BCI prototypes. On the contrary, for Numa, the eventual winner of Cybathlon’s BCI race recruited through CNBI’s clinical partners in Geneva, the Cybathlon was his first BCI expedition.

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OK for them if Eliza contact them directly?

Fig. 3. Brain Tweakers pilots: Eric Anselmo (left) and Numa Poujouly (right).

The demonstrated usability and robustness of our brain-controlled devices, including our success in the Cybathlon BCI race, is due to a set of principles we consistently apply [1, 8]. Some of these principles we conventionally adopt, namely, the non-invasiveness and self-paced paradigms, have been dictated by the Cybathlon inclusion criteria (which ruled out invasive or stimulus-driven BCI paradigms) or the competition's demands (e.g. need for portable hardware). We have therefore employed a lightweight active EEG system (gTec gUSBamp+gGAMMAbox, Schiedelberg, Austria) and a motor-imagery (MI)-based BCI paradigm. MI is the mental rehearsal of a movement without overt motor output [9]. The imagination of different types of movements elicits changes in cortical sensorimotor rhythms that the BCI software has to identify and the pilot has to learn to modulate voluntarily. These sensorimotor rhythms are individual and specific to the imagined movement —i.e., they appear in different frequency components, normally in the range 8-30 Hz and specific cortical locations. These distinct spatio-spectral patterns of EEG activity allow the association of MI tasks to commands for an external device; in this case, the Rotate, Jump and Slide commands executed by the pilot's avatar in the BCI race.

We have naturally greatly exploited the ensemble of signal processing and pattern recognition methodology that had already demonstrated its versatility and enjoyed substantial end-user validation in the recent past [3, 5-7]. In addition, several further advances are directly related to our Cybathlon efforts. To name a few, we have first refined our algorithmic decision making to comply with the 3-command control required for the BCI race. A great deal of work has been devoted to improving the ability to stay "idle", an issue often overlooked in the scientific literature, but one that was vital for the BCI race and real-world BCI applications. Furthermore, we have substantially improved our arsenal of ocular and muscular artifact detection methods, as required by the organizers.

Nevertheless, it is our mutual learning approach [8] for pilot training —the methodology that optimally balances and coordinates the machine's and the user's learning capacities— that has been the key to the victory. It is hence indispensable to report hereby our training strategy and highlight the essential feedback of our pilots therein. BCI training sessions started six and three months before the Cybathlon event for Eric and Numa, respectively. In the first months, training sessions were scheduled once per week and they have been intensified as the event was approaching. Pilots were trained at their home with the supervision of one or more of our team members for at least two hours per session.

In a first BCI calibration phase, both pilots were asked to imagine to repetitively move their right hand, left hand or both feet in order to model the emerging brain patterns and associate them to the three control commands of the Brain Runners game. However, after few sessions it became clear that three mental classes (even after trying additional MI tasks) was not sufficiently robust and would require extensive training time. Thus, in an incremental learning approach, the BCI system was initially calibrated to recognize two mental tasks associated to the imagination of movement of both hands or both feet, found to be the optimal pair for both our pilots.

After the initial calibration, pilots performed several closed-loop control sessions receiving continuous, visual BCI feedback. It is precisely this phase that allows a BCI user to learn to optimally modulate his brain rhythms. Therefore, during the online sessions the BCI system was periodically re-calibrated to reflect the pilot's new task-dependent brain activity, while the pilots learned to generate more discriminant and coherent brain patterns. As soon as this type of mutual learning approach led to adequate and stable performances for two mental commands, the BCI was fixed and further training focused on getting our pilots accustomed to the Brain Runners game. At this stage, the two mental commands were associated to the "Rotate" and "Jump" actions of the avatar.

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Comment: which MI for each?

Investigating schemes for implementing the third Brain Runners command necessary for the "Slide" action was the issue that has benefited the most from our pilots' feedback. Over subsequent developmental iterations, a few principles of Human-Computer Interaction were explored and rejected or refined by our pilots to eventually converge onto a code-based approach [6]; the "Slide" action of the avatar is executed once a sequence of MI-enabled "Rotate" and "Jump" commands takes place within a configurable timeout. It is thus worth noting that an important feature of our system came as a result of the constructive dialogue between the Brain Tweakers pilots and researchers.

For these training races, our pilots would compete against a single bot-opponent. Eric completed more than 100 such races, marking an average performance of 124.8±18.0 seconds and an all-time record of 78.2 seconds. Numa's corresponding numbers have been 127.0±23.5 seconds in 35 training races with a record of 90.8 seconds. At this stage, exploiting the high degree of our BCI's reconfigurability and personalization, the optimal parameterization was easily found for each pilot, another crucial aspect of our mutual learning approach. Finally, two joint training sessions were scheduled one month and one week before the Cybathlon, respectively. In these two "face-off" events, our pilots were asked to race against each other in a crowded environment with people supporting and inciting them, so as to habituate them to the best possible extent with 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 such performances in the challenging official Cybathlon races. Both Eric and Numa won their qualification tracks to advance into the final with the two best performances of the overall BCI race competition, 90 and 123 seconds, respectively. Eric's mind-blowing 90-second performance has been a whole 42 seconds faster than the best time achieved by another team throughout the competition. Although Eric experienced a lapse of performance during the final that cost him a medal, Numa raced at his regular pace to capture the gold one for himself and the title for Brain Tweakers with 125 seconds!

Fig. 4. Joint training sessions of our pilots, two views.

Fig. 5. Numa Poujouly in the podium with the gold medal. Luca Tonin is behind.

Our pilots' own accounts are invaluable for a deeper assessment of BCI's current user acceptance and limitations, as well as of the competition's accomplishments. "BCI is one of the technologies of the future" Eric quotes, and specifies that they can be already useful in many applications. Numa is even more enthusiastic: "In the near future, BCI technology might have unlimited possibilities in several fields: from driving assistive systems to interacting with one's own smart home". However, they both identify limitations to be overcome before reaching this point, such as the obtrusiveness and time-consuming setup of the hardware and the small number of commands supported by the system. Lack of robustness is another major criticism in Eric's experience, while he also finds open-loop BCI calibration sessions "really boring", as opposed to the "cool" online-feedback BCI and, especially, racing training. Although Numa agrees on the unexciting nature of the open-loop BCI sessions, he reports having put his utmost effort into this phase in order to create the best possible BCI for himself. Both our pilots felt "immediately in control" in the beginning of our training sessions and agree that "the first time the avatar responded to my thoughts made me really happy". Eric further recalls having trouble understanding the engineers' instructions during his first contact with BCI, while he had to dedicate considerable time and effort for training. Nonetheless, the team spirit developing, the sense of improvement and the full commitment to the project made the training process a totally positive experience, as maintained by both Eric and Numa.

It is exactly to our team work that they attribute the success of the Brain Tweakers, as well as the simplicity and configurability of our control paradigm. Importantly, our mutual learning approach led both of them to eventually “not think of moving our limbs any more when playing the game, but simply about what the avatar should do”, in a natural and ecological manner. This level of internalization of BCI control notwithstanding, “full concentration is still required”, according to Eric. Numa shares the same opinion and additionally reveals that he performed autogenic training and deep meditation before each race, in order “to isolate himself and be completely focused on the game”. Regarding their motivations for participating in the Cybathon, Eric explains that he wanted to honour his previous involvement and contribute further to BCI research, while Numa was curious about BCI technology and the outcome of long-term BCI training. They also report that they were not intimidated but, rather, excited and motivated by the sold-out attendance of the event.

Fig. 6. Brain Tweakers pilots celebrating Numa’s gold medal.

Concluding, we strongly believe that our team’s experiences shared here confirm, on the one hand, a totally successful event that has satisfactorily accomplished all its goals and has set a new standard for the way further developments in assistive technology should be pursued. On the other hand, we hope that this note has provided further evidence of the prospects of BCI technology and its maturity for making the critical transition from laboratory settings to translational applications.

Fig. 7. Brain Tweakers team at the end of the Cybathlon event.

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