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Better Minds: Cognitive Enhancement in the 21st Century

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We would all like to have a better, more capable mind. Since the mind’s biological substrate, the brain, is involved with everything we do, there are many, many reasons why we might want to improve on what we were born with. Most of us would like to be able to remember things better, from the trivial, “Where did I put my keys?” to the important, “What is the date of our wedding anniversary?” We would like to be more quick and clever in a wide variety of contexts. We humans probably evolved our unusually high cognitive abilities to help us solve problems, to deal with adversity successfully in our prehistoric environment. It would be great if our cognitive skills and abilities kept in step with changes in how people live, but they haven’t. We are living in a modern world, born with the same brains that our savage ancestors had 30,000 years ago.

The kinds of problems we need to solve today are distinctly different than those the Cro-Magnons had. Few of us need to know how to find water, to hunt for food, to escape from predators, and to build a fire. Instead, we need to know which career path to choose, how to get along with people next door that don’t look the same, where to live and what type of car to buy. We worry not about whether some plant we might eat is poisonous, but whether it has enough iron and vitamins. Without animals to run after or from, and with an excess of fattening food around, we obsess over how to keep fit in a world that does not require us to exert ourselves.

Some of the world’s “biggest problems” are not actually the ones we usually think of. Are drought and starvation problems? There is plenty of food and water for everyone; it is just not distributed fairly or effectively. Is energy supply a problem? There is far more energy than we need beamed straight from the sun every day. It just needs to be collected and used more effectively. Global warming is not a problem, the problem is flooding and weather-related catastrophes we are not presently equipped to deal with. In fact, one could argue that all the land that can’t be farmed or even inhabited because it is too cold is a problem that global warming will help solve!

Diseases are a real problem, but not quite the same problem that prehistoric humans faced. Losing teeth 10,000 years ago could quickly lead to starvation. Even an infected scratch from a saber-toothed tiger you escaped from could be lethal without antibiotics. Our modern diet and sedentary lifestyle has introduced a number of health problems that our evolutionary heritage never had to deal with, such as obesity, alcoholism, and heart attacks. Unnatural chemicals in our

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ЭВОЛЮЦИЯ ОТ КУТЮР - ЧАСТЬ 2

EVOLUTION HAUTE COUTURE - PART 2

THEORY

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PART 2

ЭВОЛЮЦИЯ ОТ КУТЮР:
ИСКУССТВО И НАУКА В ЭПОХУ ПОСТБИОЛОГИИ

Часть 2: Теория. Составление и общая редакция Дмитрия Булатова // Калининград: БФ ГЦСИ, 2013

Что такое радикализация и избыточность технологического и научного прогресса? Каков эволюционный потенциал, заложенный в основных технологических трендах XXI века – робототехнике, IT, биомедицине, нанотехнологии? Каждое из этих направлений максимально проблематизирует традиционно сложившиеся границы жизни и смерти, демаркации нормы и патологии, различения между смоделированным объектом и биологическим существом. Рассмотрение этих вопросов вряд ли возможно без учета опыта современного технобиологического искусства, которое обладает парадоксальным свойством не только подтверждать своими стратегиями существующие технологические версии современности, но и оговаривать их границы. Искусство, рождающееся в новых условиях постбиологии – в условиях искусственно оформленной жизни, – не может не делать эту искусственность своей неизбежной темой. Вопрошая о причинах и следствиях технического прогресса и его определяющей роли в современном обществе, известные представители современного искусства, науки и философии пытаются выяснить, что лежит в основе возникновения "искусственной", "технологической" реальности и как эта реальность воздействует на нас? Возможно ли переизобрести язык, конструирующий и описывающий мир технологий? Задача этой книги – показать, как художники создают новые формы и новые идентичности – но не в качестве протагонистов определенного историей технологического нарратива, а в качестве его творцов.

EVOLUTION HAUTE COUTURE:
ART AND SCIENCE IN THE POST-BIOLOGICAL AGE

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How can the radicalization and redundancy of science and technology progress be defined? What is the evolutionary potential of 21st Century technology trends such as robotics, IT, biomedicine, and nanotechnology? Each of these trends actualizes traditionally formed boundaries of the beginning and end of human existence, the demarcation of norm and pathology, and the distinction of the non (or semi) organic model or entity. These, and other issues, cannot be taken into consideration without the experience of contemporary techno-biological arts – the representatives of which do not so much confirm the technological versions of contemporaneity, as determine these versions' boundaries. Art created under new conditions of postbiology – that is, under conditions of an artificially fashioned lifespan – cannot help but take this artificiality as its explicit theme. In questioning the causes and consequences of technological progress and its central role in today's society, renowned representatives of contemporary art, science and philosophy are attempting to elucidate the foundation that gives rise to "artificial," "technological" reality, as well as to explain how this reality impacts us. Is it possible to reinvent a language that can simultaneously construct and describe the world of technology? The aim of this book is to show how artists are creating new forms and new identities – not as the protagonists of a historically-determined technological narrative, but as its creators.

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PART 2

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искусство и наука в эпоху постбиологии
art and science in the post-biological age

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food and environment cause all sorts of diseases, from cancer to brain damage. And modern competitiveness causes chronic worrying and stress-related illness due to the unnaturally continuous activation of our sympathetic (fight-or-flight) nervous system. The good news is that we are much better at dealing with diseases than we were even two centuries ago. The bad news is that they still cause much suffering and death.

War is another real problem still causing suffering and death. Thanks to our tribal brains, countless lives and valuable resources continue to be wasted on fighting so-called enemies. Aggressive and defensive instincts that may have helped our ancestors in small tribes with scarce resources are maladaptive today. Feuds linger long past the relevance of their initial causes, whether between two neighbors, two gangs, two nationalities, or two races.

Stop and consider: What would it take to solve the real problems facing modern humans today? It would take major changes in human nature. It would take a major update to our prehistoric brain's hardware and software. I propose that cognitive enhancement brought about by neuroengineering could make us better adapted to the modern world. It could quell our aggression, allow us to appreciate all people, and help us devise new technology: for global distribution of food, water, and energy; for preventing diseases and accidents; for dealing with natural disasters; for seeing both sides of every disagreement.

Natural Cognitive Enhancement

There are (at least) two natural ways to enhance cognition, at very different time scales. Across generations, preferential survival and reproduction of the more clever members of the tribe have resulted in the differences between us and the other Great Apes, i.e., a tremendous expansion of our neocortex endowing us with the capacity for complex language and symbolic thought. It is possible to speed up evolution. Farmers, pet owners and horticulturalists have been doing this for centuries: selective breeding. It is unlikely that this approach will ever be popular for enhancing human intelligence. In fact, when modern medicine keeps alive a person who is about to die from a foolish accident or bad decision, and they go on to have offspring, the overall intelligence of the human gene pool is diminished. Thanks to medical advances, evolution is actually heading backwards in some ways.

On the shorter time scale of one lifetime, learning from others or from experience can make one wise and capable. Learning produces immediate results, and because everyone already uses this form of cognitive enhancement, it will be comparatively easy to promote the idea of better and faster learning through neurotechnology.

Neurotechnology for Better Learning

What is a thought? What is a memory? We know surprisingly little about such basic and fundamental aspects of our nervous system. Thousands of neuroscientists are working hard across the globe to reveal the secrets of what is often described as the most complex thing we know of, the brain. In the Laboratory for Neuroengineering at Georgia Tech,[1] we are trying to add a few pieces to the puzzle of how learning works, and how to improve it. As a model for human brains, we study simple nervous systems of a few thousand neurons and glial cells in vitro. The Petri dishes we use have arrays of microelectrodes embedded under the cells, through which we can deliver artificial sensory input to the neuronal networks cultured on them (Figure 1). We can also record electrical activity patterns in these cultured neural networks, and try to

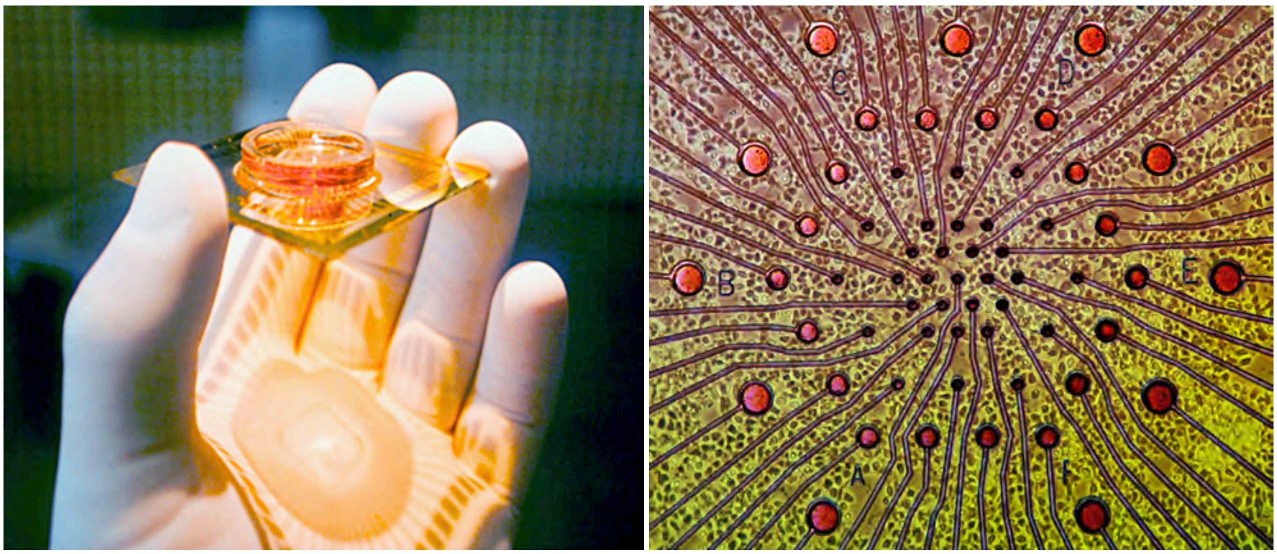

Figure 1. Multi-electrode array Petri dish (left) with cultured network of a few thousand brain cells from a rat embryo, and 60 tiny electrodes (right).

decode the patterns with powerful microscopes and computers.

Hybrid Neural Systems

By interfacing the cultured networks to robots or simulated animals, we can study their behavior, and try to induce changes that represent simple forms of learning. In the year 2000 at Caltech, we developed the first hardware and software to “embody” cultured networks, to allow their activity patterns to move robotic arms or wheels, and to translate data from the robots’ sensors into electrical stimulation patterns for the networks. One such hybrid robot, or “hybrot”, was MEART, the Semi-living Artist. In collaboration with SymbioticA,[2] we connected a robotic drawing arm to cultured networks, sometimes thousands of miles apart, via the internet. We hoped to induce learning in MEART’s living biological brain, by sending the culture dish stimulation based on what its video camera eye saw of the drawing in progress. Judging from the types of drawings MEART produced (Figure 2), it is not clear much learning was happening, but the complexity of behavior produced by a network of even a few thousand brain cells was

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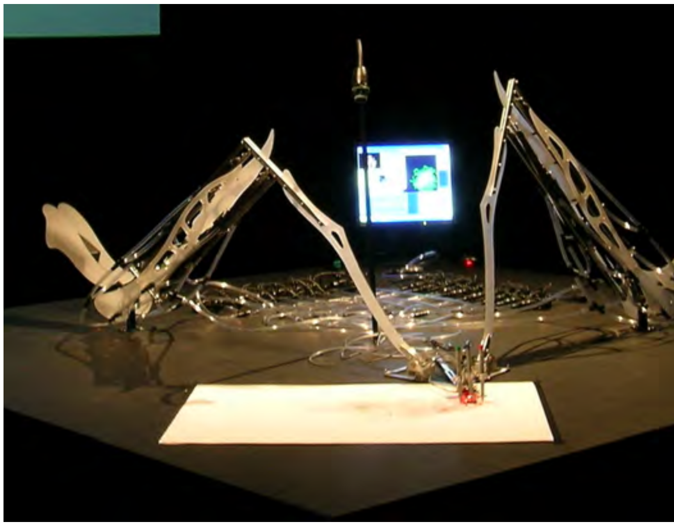
1 http://neuro.gatech.edu

2 http://www.fishandchips.uwa.edu.au/project.html



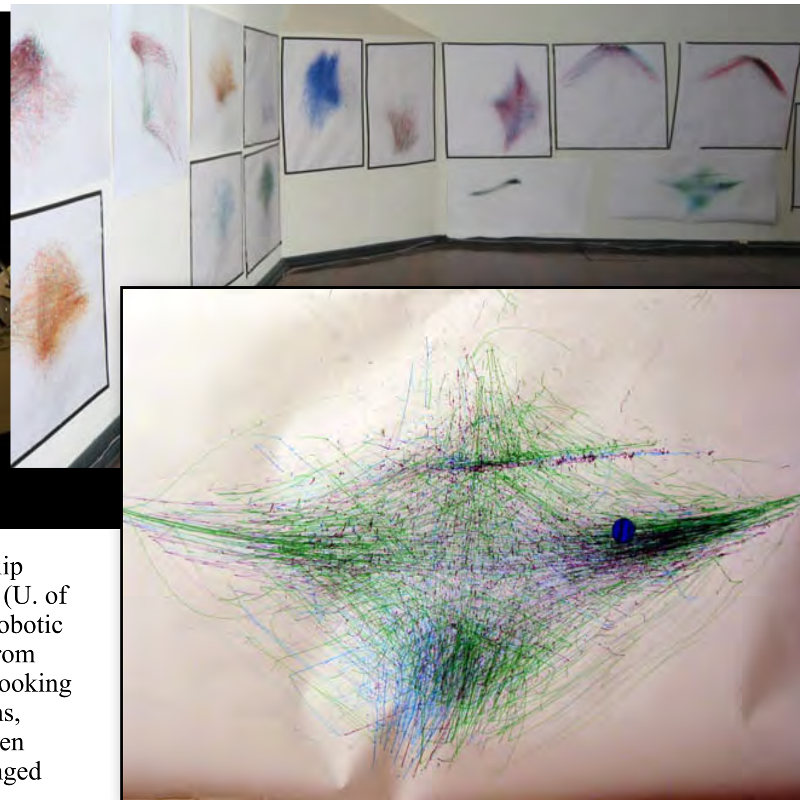


Figure 2. MEART, the Semi-Living Artist (left). Built by Philip Gamblen and Guy Ben-Ary, our collaborators in SymbioticA (U. of Western Australia, Perth). The pneumatically-driven pair of robotic drawing arms were controlled by recorded activity patterns from cultured neuronal networks in our lab in Atlanta. A webcam looking down at the drawing in progress sent back stimulation patterns, forming a closed-loop system whose body and brain were often thousands of miles apart. The drawings produced (right) changed dramatically from day to day, and culture to culture.

surprising. Like a classroom full of preschoolers, each network we hooked up as MEART's brain produced its own unique style of scribbles.

Learning in Embodied Cultured Networks

Cultured neuronal networks, without a body and sense organs, are growing in sensory deprivation. Like a person put into solitary confinement in a dark cell, they go crazy. Without natural inputs, they develop activity patterns that resemble epileptic seizures, called network bursts. During these bursts of activity, the neurons fire pathological signals in synchrony, which make it difficult for the hybrots' sensory input to influence their behavior. We noticed that a culture that was being used to control MEART, after days of receiving stimulation fed back via the internet from its video camera eye, began to calm down, showing less and less epileptiform activity. We found we could quell the barrages of activity in all of our cultured networks by sprinkling low-frequency pulses of electricity across the network, delivered via the substrate electrodes. In some sense, this restored the natural level of background activity to the cultured networks, analogous to what an intact nervous system would receive from the animal's senses. Thanks to the burst-quieting background stimulation, networks no longer exhibited continuous seizure-like activity, and they were more responsive to artificial sensory input. This, in turn, made them more amenable to studying learning and information processing in vitro.

With the burst-quieting stimulation protocol, we were then able to reliably alter the behavior of embodied cultured networks with artificial inputs. We used patterns of electrical impulses to train a hybrot to navigate in a pre-specified direction. It was a simple task for a simulated animal controlled by a few thousand living brain cells, but a major advance for neuroscience. We now have a simple model biological system to study learning mechanisms, whose entire brain is laid out flat on a glass surface where one can easily watch it under the microscope while it is doing the learning.

Intact animals are used by many neuroscientists to study learning mechanisms, but their complexity makes it much harder to control all the variables in an experiment. Unlike behaving animals, whose constantly moving brains are hard to image under the microscope, hybrots have simple, stationary brains separated spatially from their robotic or computer-generated bodies. In the case of MEART, this separation was often thousands of miles. These experiments with *embodied cultured networks* have shown that an important aspect of the embodiment is for the neural-robotic system to be a closed loop. That is, the neural activity affects the robot's movement, the movement affects the robot's relation to its environment, the neuronal network receives new sensory input, and the sensory input then alters its neural activity, generating new movements, and so on. By actively sensing and interacting with our environment, humans can learn most effectively, and the same seems to be true for the hybrots.

To close the loop between cultured networks and computers, we had to build our own custom neural interfacing hardware and software. Others creating brain-computer interfaces for animal research closed the loop using natural sensory input via the animal's own visual system, instead of the electrical stimulation used to provide artificial sensory input to hybrots. The closed-loop neural interfacing technology we, and others have built for research purposes will help us understand basic mechanisms of learning and information processing in the brain, so we can begin to look for ways to improve it. This technology will form the basis of future devices designed to alter neural activity in humans, to enhance cognition in a variety of ways.

Cyborgs Walk Among Us

In the brains of thousands of patients, electrodes have been implanted for clinical treatments and diagnoses. Deep-brain stimulation (DBS) is being used to treat a number of neural disorders, such as Parkinson's disease and chronic pain, and even cognitive problems including depression, memory problems, and obsessive-compulsive disorder. Such devices are the descendants of pioneering research in the 50s by James Olds and Peter Milner, who found they could hijack the brain's natural reward circuits with electrical stimulation in certain regions, causing lab rats to become addicted to pressing levers to get small but intensely rewarding jolts of electricity. Because of the brain's incredible complexity, researchers and clinicians are still mapping out the effects of electrical stimulation of various brain circuits. The deep brain stimulators currently used are not much different from heart pacemakers, continually delivering pulses of electricity to normalize activity in some malfunctioning circuit. They are not very sophisticated, with only four electrodes, each one millimeter across, designed for stimulating but not recording neural activity. In contrast, the culture dishes we use in the Neurolab have 60 microelectrodes, each only 30 microns across (Figure 1), that can both record and stimulate with whatever complex stimuli we wish to deliver.

The brain stimulators of tomorrow will, like our multi-electrode array culture dishes, have large arrays of microelectrodes for more delicate, finessed stimulation that is tailored to a person's unique brain circuitry. Like our embodied cultured networks, they will be closed-loop, always monitoring ongoing neural activity and automatically adjusting their stimulation to meet the changing needs that arise from a person's varied activities and bodily states.

It is not hard to imagine taking brain stimulation from the clinic to something used routinely by normal people, to enhance their cognition. Like Olds' rats, we might try to reinforce behaviors that are productive and helpful in the modern world, by well-timed stimulation of our reward circuitry after accomplishing something of merit. Of course, the same potential for addiction that the rats faced will be a problem, as well as the potential for powerful brainwashing or other "mind control" scenarios.

By delivering complex patterned stimulation to the brain through arrays of microelectrodes, as we now do routinely in our embodied cultured networks, we could artificially exercise or train certain brain circuits. This might first be used to aid recovery from stroke or head trauma, by strengthening weakened circuits, or re-mapping neural function to work around the damage. Michael Merzenich and others have demonstrated how plastic the cerebral cortex is, even in adults. They have developed therapeutic behavioral training video games that normalize signal processing in dyslexic children and improve memory in the aged.[3] These computer programs require diligent effort, and constant attention to the training, to be successful. One can imagine activating the same brain circuits, not through the eyes and ears, but via artificial stimulation. Once it becomes common and reliable to improve damaged brain circuits with electrical stimulation, it may be employed by normals to enhance their existing capabilities. Complex, patterned stimulation can serve as artificial sensory input, endowing us with new types of senses or amplifying those we already have. Perhaps even information or new skills could be artificially learned, much faster or with less effort than the traditional way of learning by seeing, hearing, and doing.

Micro-doses to Alter Brain Activity

Thanks to the fact that part of neurons' natural communication is electrical (the action potential), electrical stimulation has proven to be very useful for studying and influencing the brain, as described above. But other components of neurons' natural communication (neurotransmitters) are chemicals. Influencing brain function with chemicals is nothing new, especially in the modern world where caffeine, alcohol, and tobacco are ubiquitous. Advances such as closed-loop drug delivery, like an insulin pump that injects insulin as a function of changing glucose levels, will allow more sophisticated control of brain function and enhancement.

Present-day drugs for treating disorders of the brain are a blunt instrument. We may wish to target only a tiny subset of the brain's 100 billion neurons, yet all of them (and the entire body)

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[3] http://www.scilearn.com/

are bathed in the drug. Clever chemists are designing neuroactive pharmaceuticals with fewer side effects and better targeting, but the most effective drugs of the future will be those delivered by devices implanted in the brain. These will release well-timed tiny doses only to the specific circuits that we wish to influence. In fact, the brain itself is already wired to do this. There are a number of modulatory brain regions that release minute but very effective amounts of an endogenous drug, such as dopamine, endorphins, or norepinephrine, onto very specific brain circuits to effect changes in their function. These are the neuromodulators that wake us up, change our mood, get us moving in an emergency, and help us remember important things. Neuro-active drugs of the future will be delivered in a similar manner, in small, well positioned doses via microscopic devices implanted in the brain. As with electrical stimulation, this will be done in closed-loop fashion, with the release of a drug being triggered by some physiological measurement, to ensure continually appropriate, personalized modulation of brain function. They will also be under some degree of voluntary control by the “implantee”.

Magnetic Stimulation of the Brain

By sending magnetic pulses into the brain, its activity can be altered, in a similar fashion to electrical stimulation, but without the need to implant anything. Trans-cranial magnetic stimulation (TMS) is presently moving from being a research tool to a clinical treatment. The TMS devices being used are cumbersome figure-8 coils of wire resembling big Mickey Mouse ears when held behind a person’s head. They can only excite one brain region at a time, a few millimeters across. They cannot presently reach brain structures beneath the outer few centimeters of the brain. Their side effects are substantial, including discomfort in the scalp, potential hearing loss due to their loud clicking, and seizures induced occasionally and unpredictably. Despite all this, TMS is being used to successfully treat depression in some patients. With better coil design and pulse sequences, TMS could potentially stimulate any part of the brain non-invasively, causing the release of desirable endogenous neurochemicals or altering ongoing activity in a manner similar to DBS.

Electrical, chemical, and magnetic means to improve brain function are all at a very rudimentary stage, but have tremendous promise to be much much more useful by moving to more sophisticated technologies and techniques.[4] We are at the infancy of our technological sophistication, analogous to space travel in the 1800s. Jules Verne envisioned a rocket to the moon as a hollow projectile full of space men, shot from a very large cannon. What it actually took to get to the moon was much more complicated and required many cycles of refinement (Figure 3).

Stimulating neurons with light

A glimpse into the type of revolutions we can expect in brain control in the 21st century is provided by optogenetics. This term, unheard of before 2006, refers to a neural stimulation technique that is becoming a very popular research tool in neuroscience. It has the potential to

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[4] For a detailed review of the state of the art in brain-enhancing technology, see: M. D. Serruya and M. J. Kahana (2008) "Techniques and devices to restore cognition" *Behavioural Brain Research* 192:149-165

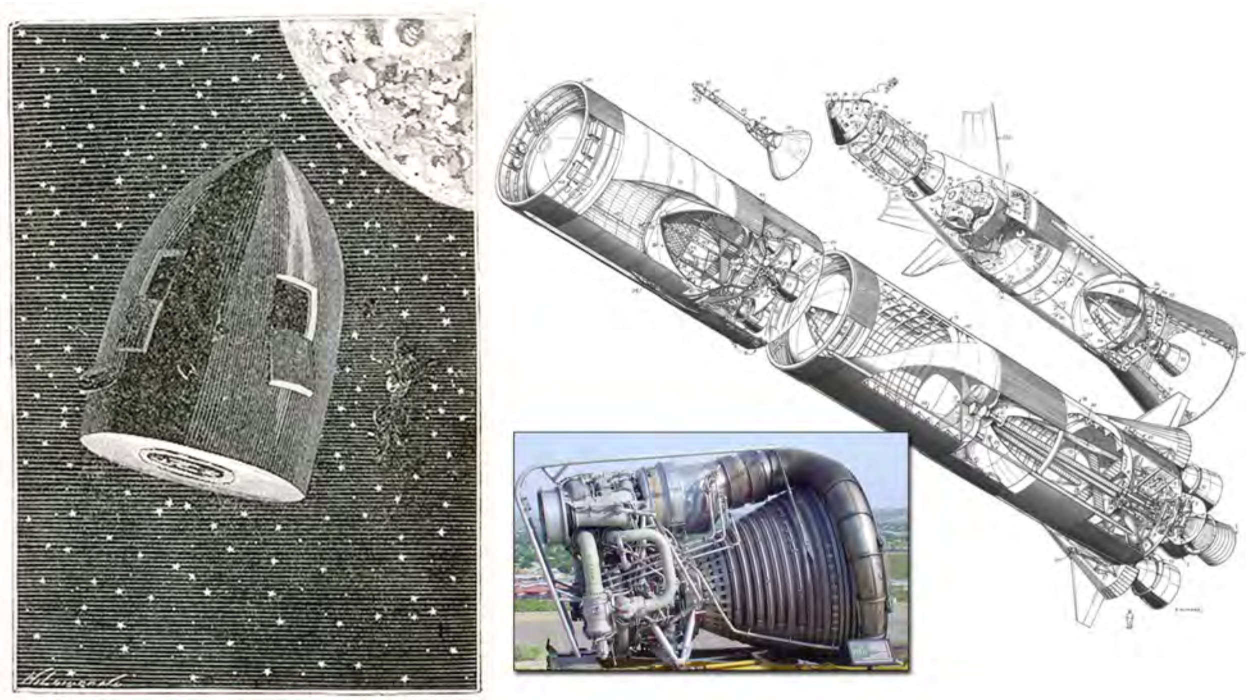

Figure 3. Jules Verne's conception of a moon rocket: a hollow bullet, 1874 (left), compared to the incredibly complex Apollo Saturn V rocket, 1969 (right, and closeup of its rocket engine in inset) used to transport astronauts to the moon.

make electrical and magnetic stimulation of the brain obsolete. By splicing a gene from certain light-sensitive algae or bacteria into a neuron's DNA, the neuron can be switched off and on at will, with light. These pieces of genetically-engineered DNA, or optogenetic constructs, can be inserted into brain cells' chromosomes using a virus as the vector, to carry the gene into the cell and do the gene splicing operation. (Such viral vectors have been disabled to prevent them from replicating.) Karl Deisseroth and Edward Boyden have shown that mouse brain circuits transfected with optogenetic vectors can be activated by light delivered through fine fiber optics. They have developed optogenetic constructs that can cause neurons to be activated with one color of light, and inhibited by another color. One of the most powerful aspects of this gene-therapy approach to altering neural function is that it can be targeted to very specific cell types. The brain has many different types of neurons that serve different purposes. Electrodes and magnetic pulses tend to activate all of them indiscriminately. However, with optogenetics, scientists can selectively activate or inhibit a genetically-defined population of neurons. Fiber optics can be thinner than a human hair (less than 0.1 mm; a DBS electrode is ~ 1 mm in diameter) so the pool of activated neurons can also be spatially defined. Glass fibers are more biocompatible than implanted metal electrodes, which can cause an immune reaction and become encapsulated by scar tissue that reduces their effectiveness.

Reading Brain Activity With Light

Also at a very experimental stage are genetic constructs for *probing* neural activity with light. In this case, DNA from jellyfish that produce fluorescent proteins is joined with DNA coding for the voltage-sensitive ion channels that neurons already have. Now, for a neuron transfected with this construct, when the channels sense neural activity, the color of the attached fluorescent protein changes slightly. These voltage-sensitive fluorescent proteins could be co-transfected with the optogenetic constructs described above, to allow implanted fiber optics not only to modulate neural activity, but also to read out ongoing activity or the responses to optical stimulation.

There are other, less invasive ways to read brain activity with light shone through the scalp, thanks to the way blood in active brain regions changes color as it becomes de-oxygenated. This near-infrared spectroscopy is presently very limited in both spatial and temporal resolution, but with improvements in optics and signal processing, it will become increasingly useful. As with electrodes that can both stimulate and record neural activity, two-way optical brain interfaces will enable closed-loop systems with continual fine-tuning of their effects to optimize function.

Changing Human Nature

We all know from personal experience that we are a “different person” after we have had our favorite psychoactive beverage, such as coffee, tea, or alcohol, for example. There is no doubt that pharmacology can be (and often is) used to change our level of happiness, our productivity, or our sociability. Some day, we may develop genetic engineering to cause more permanent changes in human nature. Much closer on the cognitive enhancement horizon are neuroengineering-based means to alter how we feel, behave, and interact. How will brain interfacing technology make the transition from clinical therapies to cognition-enhancing tools for all of us? Given the thousands of patients already having their brains electrically stimulated to treat various disorders, some are bound to notice some positive, cognition-enhancing side effects. Paul Cosyns, a deep-brain stimulation investigator in Belgium, relates this anecdote from one of the patients that was implanted to relieve her obsessive-compulsive disorder: "Well, Dr. Cosyns, when I'm at home doing my regular things, I'd prefer to have contact two (of the 4 electrical contacts on her DBS implant), but if I'm going out for a party where I have to be *on* and, you know, I'm going to do a lot of socializing, I'd prefer contact four because it makes me revved up and more articulate and more creative."[5] This patient is clearly using her DBS for the “off-label” benefits she has discovered by fiddling around with the controls.

The surgery for DBS is complicated and not without risk of injury or infection, so few today would elect to undergo this procedure just to feel more “revved up, articulate and creative”. But consider how far refractive eye surgery has advanced in the last few years, from a delicate, risky operation with long recovery and poor outcomes, to an outpatient procedure that, thanks to advances in closed-loop lasers and robotics, is very fast, safe and extremely effective. The wide variety of elective cosmetic surgery procedures carried out with few or no worries about death or permanent damage are another likely indicator of where neurotechnology is headed. It is inevitable that closed-loop brain interfaces, whether optical, electrical, or both, will follow this

[5] President’s Council on Bioethics, June 25, 2004. http://bioethics.georgetown.edu/pcbe/transcripts/june04/session6.html

path, to help more disabilities in more people with fewer complications. The more we hear about lab experiments or clinical trials of brain interfaces with cognitive enhancing effects, the more demand there will be to turn these into elective procedures for normal people. When there is money to be made, surgeons are quick to open up new types of clinics. Expect “Brain Implants On Demand” shops in your neighborhood before too long, right between the Lasik and cosmetic surgery boutiques.

Conclusion

There are many technologies and techniques for altering brain function, some still laboratory curiosities, some being used actively in the clinic, but all with a long way to go before they are sophisticated in the way our interplanetary spacecraft are. Where they will take humanity is very hard to predict, because by altering brain function, we may fundamentally alter human nature. It is exciting to imagine these technologies making the transition from clinical treatments for diseased and disabled people, to enhancements for all of us. This is as inevitable as space travel was for Jules Verne. We must begin now to plan for it, and to anticipate the ways it will benefit, or potentially harm humanity. By doing so, we are more likely to create a future in which our brains allow us to function more effectively and interact more harmoniously, in step with the modern world.