Special Section: Technology and the Body:
Linking Life and Technology

Design and Engineering Ethics Considerations for Neurotechnologies

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Society has already seen multiple potential futures of neurotechnologies through the multifaceted lens of science fiction. We do not know which of those futures we will come to live, but the strong force in society's evolutionary process will likely continue to be the insight and oversight developed by the bioethics community, pushing and being pushed by the advances of technology, improvements in medical care, and market competitiveness.

Today's neurotechnologies are capable of only simple physical interactions with our brains, but it is easy to speculate that today's low-level devices will lead to significant advances in our understanding of neural function and our ability eventually to extract, synthesize, and inject high-level thought and perception processes through computer interfaces. In one possible future, computers themselves will manipulate knowledge and interact with each other as human brains do. How will the relationship between neurotechnology and humans then change? How will we deal with the societal aspects (rights, equality, free-will, ownership, passports, religion, morality) of cyborgs and robots? Although these questions are the domain of the future of neuroethics, can today's bioethics evolve and serve our multicultural society as the advances unfold? The current state of neurotechnologies and currently debated ethical issues can inform us in approaching the future we are designing for ourselves.

Neurotechnologies

Today's neurotechnologies can be divided into three main categories: neuroprostheses, internal direct brain interfaces (DBIs), and external direct brain interfaces. A derivative category, neurorobotics, which is a robotic extension of an internal or external direct brain interface, will be discussed separately.[1]

Neuroprostheses are devices that contain sensors and/or actuators, implanted in or communicating with the brain, to replace neural and sensory function. Cochlear and retinal implants, as well as hypocampus memory mediation chips in a rodent model, are recent examples.

Internal direct brain interfaces share with neuroprostheses the fact that they are implanted in the body and connect directly with biological neural structures.

The author thanks the "Ethical Dimensions in Neuroscience" Program of the Stanford University BioX Interdisciplinary Initiative and the Stanford Center for Biomedical Ethics for supporting this work.

Cambridge Quarterly of Healthcare Ethics (2007), **16**, 303–307. Printed in the USA.
Copyright © 2007 Cambridge University Press 0963-1801/07 $20.00
DOI: 10.1017/S0963180107070338

https://doi.org/10.1017/S0963180107070338 Published online by Cambridge University Press

However, Internal DBIs do not replace neural function; they sense it through electrodes and potentially stimulate the brain to provide information to it. For example, the Cybernetics Braingate™ cortical implant is a 2-mm × 2-mm array of 100 electrodes that has been implanted in nonhuman primates and several human subjects in the motor cortex and several other cortical regions.[2] Each of the electrodes senses electrical activity (action potentials) from one or a small number of neurons in direct contact with or in proximity to the electrode. A digital signal processor records and is programmed to find patterns in the electrical activity recorded from numerous electrodes that correlate with actions the subject is asked to perform. Once trained, subjects can make simple actions such as "move arm up" and "move arm left" to drive a cursor on a screen or move a robotic arm. Depending on where the chip is implanted, it has also been shown that it is only necessary to think about moving one's arm up, not actually doing it, to elicit a temporo-spatial brain activation pattern that can be used to drive a cursor or robot, a first step to being able to record a measure of intentionality.[3]

Another type of internal DBI is the electrocorticogram (ECoG), used principally for epilepsy research and treatment. An ECoG electrode array is implanted on the surface of the cortex near the suspected focus of epilepsy seizures. Once found, the focus can then be surgically removed to alleviate symptoms.

Deep brain stimulation (DBS) electrodes are implanted in the basal ganglia to improve quality of movement of persons who have Parkinson's Disease. Electrode stimulation is controlled by a pacemaker-type device commonly placed subcutaneously under the collarbone. This device is also being studied for control of psychiatric conditions.

External direct brain interfaces rely on sensing through the skin of electrical activity related to nerve impulses. For example, electroencephalogram (EEG) electrode arrays can be mounted on caps to capture temporo-spatial patterns of electrical activity over the skull, but because the interelectrode spacing is approximately 1 cm, and because the electrodes are at least a skull's thickness from cortical activity, only the pattern from an entire region consisting of thousands or millions of neurons can be captured.[4] Still, subjects can be trained to modify normal brain wave activity, for example the μ-wave, to provide a signal that can be captured and turned into a command, such as driving a cursor or selecting a specific target on screen.

A neurorobot is a system that typically involves an electromechanical device (robot) connected to a human or animal controller, or its converse, a biological system whose neural functions are partially taken over by a synthetic controller with sensor and/or motor connections. A human cyborg would be a neurorobot, as would a rat or flying insect whose brain receives signals from external vision sensors to steer its course. Although animal-level neurorobots are not fiction anymore, cyborgs are still in our future and will invite increasing bioethics scrutiny as the level of abstraction of neural processes increases and the level of interaction with humans evolves.

Bioethics Considerations

The ethical issues for the neuroprostheses of today are actively pursued by ongoing neuroethics research,[5] because the technologies involved are being

https://doi.org/10.1017/S0963180107070338 Published online by Cambridge University Press

used with people who have a disability or disease and for whom the neurotechnology represents a potential improvement in quality and length of life. As the other papers in this Special Section elucidate, there are compelling, urgent bioethics matters with these technologies involving access, multiculturalism, and issues of personhood, among others.

From the available literature on bioethics applied to various technologies, some of the main ethical questions that can be foreseen as particularly relevant to DBI–robotics are the following:

- **Control**: If a chip is implanted in a human's brain, will that person be in sole control of the inputs and outputs or may there be an outside agent, perhaps even a distributed system on the Internet, to determine information flow? Although we as a society have the benefit of science fiction to have been exposed to the specter of this issue already, the reality, when it arrives, will be more complex, with outcomes decided by the courts and the private sector, mediated by the available neurotechnology.
- **Observability**: Closely linked to the previous issue, how can the design and actions of the technology itself reveal its intentions in informing or controlling the human who uses it? In our society, we reveal our intentions to others through our behavior, gestures, and communication. When technology has the fundamental capacity to inject a layer of nonhuman reasoning to our thought processes, how can that be made apparent to the technology user, and, equally importantly, how can others affected by such bionic behavior be informed and protected?
- **Functional improvement**: The debate over the use of assistive technology and pharmacology for people with disabilities as well as for able-bodied persons to enhance "normal" function[6] is not specific to neurotechnologies, and the same arguments pertain. However, implicating brain function raises significantly the power of the technology to disrupt society through the introduction of cognitive superhumans or cyborgs.[7]
- **Agency**: Asimov's three (plus the zeroth) laws of robotics[8] touch on the relationships between humans and machines sharing the planet. However, at what point does a robot's higher intelligence, if realized, require humans to give robots rights in society? How might artificial intelligence have to include artificial morality? Do we need to have "Kantian" as well as "utilitarian" interaction chips, and perhaps "Christian," "Islam," and "Hindu" morality overlays? Although this might appear to be more an issue for future humanoid robots, the same arguments will surface when direct brain interaction has the power to modify or control human behavior. What defines who is a human and who (or what) is not? Can we invent a "Moral Turing Test"[9] to guide us in making such a decision?

Although such questions may seem to become problems only far into the future, the exponential graphs of Ray Kurzweil[10] predict that our generation will have the computer power to make confronting such issues mandatory.

On a higher plane, as neuroprostheses and DBIs mature to levels of cognitive interaction with the brain that are still in the realm of science fiction today, bioethics will need to evolve as well to provide guidance for them. Nanoethics and roboethics,[11] to name two, have emerged as subspecialties adjoining bio-

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ethics to focus on two specific technology sectors. Although the ethical issues may appear at first glance to be divergent, it has also been argued[12] that nano-, bio-, info-, and cognitive sciences are the essential building blocks of a new unified area—the so-called NBIC convergence, in which the ethical issues collapse to a more consistent set and can and should therefore be studied together. Although there will always be a need to discuss the ethics related to a specific robotics or nanotechnology or other area, it may indeed not be worth it to do so, because fundamentally these support technologies will be part of many of the newer systems that are invented, developed, and deployed in the years to come to reduce the effects of disease and disability and improve the quality of life for all.

Conclusions

Even though the fields of philosophy and psychology have developed great theories over the past centuries that help explain how people think and interact, there is still no end to the debate about which of these theories is "right," or even if there can be a "right" theory. Current neurotechnologies can only interact with the brain at very prosaic and well-understood levels such as simple movements (e.g., left, right) and single-modality sensing, and the ethical issues are mostly tractable. However, as the technologies are being developed to mimic higher levels of human thought, how can one reduce what are still theories to real practice as software and hardware, and how do we achieve any consensus on what might be the "right" approach? Bioethics of the future will have to grapple with this type of meta-challenge, as if the challenges of advanced neurotechnologies were not enough.

Notes

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