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ORIGINAL PAPER

Brain Machine Interface and Human Enhancement – An Ethical Review

Karim Jebari

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Abstract Brain machine interface (BMI) technology makes direct communication between the brain and a machine possible by means of electrodes. This paper reviews the existing and emerging technologies in this field and offers a systematic inquiry into the relevant ethical problems that are likely to emerge in the following decades.

Keywords Brain computer interface · Brain machine interface · Neuroethics · Bioethics · Electroencephalography · Neuromotor prosthesis · Autonomy · Privacy

Introduction

A few decades ago, implants that could interact directly with the central nervous system were mainly known in the world of science fiction. No longer. The last decade has seen astounding development in the technology known as *brain machine interface* (BMI) [1]. These implants connect the nervous system – via electrodes – to a machine, which makes communication between the two possible [2]. Today BMIs are used as treatments for profound deafness, Parkinson's disease and depression. Moreover, at the experimental stage, there are BMIs such as retina implants that can provide the blind with rudimentary visual orientation and, for the paralyzed, advanced prostheses maneuvered by neural control.

The potential effects of BMI technology on our society are substantial. This paper will argue that the deeply transformative effect that might result from a proliferation of BMI technology motivates public deliberation on these issues, and that the ethical issues are new and specific to this technology. While the ethical aspects of clinical and research practices have been addressed [3–6], the wider societal effects have not to an appropriate degree. In this area, the ethical issue of particular concern is the potential threat that BMI makes possible to autonomy and privacy, this paper will argue. In a longer perspective, individualism and the very nature of interpersonal relationships may be altered as a result of BMI applications. This discussion should avoid the mistakes of the discussion on genetic research, where much argument was based on fear of the unknown on one side, and wild optimism on the other. Biotechnology has not proven to be a quick fix for all health problems. Neither has the human workforce been replaced by armies of cloned drones. A cautious approach is therefore warranted when probing these issues. We should not expect BMIs to usher in a new era of transhuman enlightenment and universal happiness; neither should we fear becoming mindless cyborgs in a totalitarian community. Most of these fantasies and fears seem to be

K. Jebari (✉)
Kungliga tekniska högskolan (Royal Institute of Technology),
Stockholm, Sweden
e-mail: jebarikarim@gmail.com

based on science fiction rather than assessments of real and potential technologies. We should stay closer to reality and discuss the ethical implications of the existing and experimental BMI devices, but neither should we disregard the risks that are raised, nor only discuss issues of patient safety [7]. In particular, we should overcome our bias towards the status quo [8] and consider each BMI application in its own right, as suggested by Synofzik & Schlaepfer [9].

Although BMI devices can pose risks to privacy and autonomy, we should weigh that against the potentially very positive effects that this new technology may have. A balanced account must avoid both the reactionary appeal to "gut feelings" (also known as the "yuck factor") and the Utopian character of some transhumanist arguments [10].

Existing Brain Machine Interfaces

A brain machine interface is a direct communication pathway between a brain and an external device. The first BMIs were deployed to extract information from the brain about neural activity that correlates to thoughts, emotions, or other mental states. This information can then be used to allow the user to control machines with mere mental efforts, or to allow machines to adapt to the needs of the user. The most widely used BMI is *electroencephalography* (EEG), which consists of external sensors that record electrical activity produced by neurons in the brain [11]. Initially only used for diagnostic purposes, EEG is now used in a wide variety of simpler BMIs, due to its relatively low cost and non-invasiveness. Commercial applications of EEG include games and other recreational products that are controlled by thought commands. Emotiv Systems, a neuroengineering company headquartered in San Francisco, CA, has pioneered this market by releasing a game where the user can control the main character via an EEG device [12]. EEG is also used to collect information in neuromarketing, a field that studies consumers' cognitive and affective response to marketing stimuli [13].

Electrocorticography (ECoG) is the practice of using electrodes placed directly on the surface of the brain to record electrical activity from the cerebral cortex [14]. ECoG an invasive procedure that requires a surgical incision in the skull to implant the device, but after implantation, can be used outside the surgery room (extra-operative ECoG). However, because the electrodes are placed directly on the surface of the brain, ECoG yields much more information than EEG. The level of detail of the information transmitted permits subjects to play computer games (Pong, Space invaders) with sheer mental efforts. However, ECoG provides only superficial insights into the brain. Its activity is regulated by neuronal networks associated with different brain structures, some of them very deep inside the brain, such as the sub thalamic nucleus and the hippocampus. To decipher the activity of these deep structures, intracerebral electrodes have been developed. These are used for example to delimitate epileptogenic areas in epileptic surgery.

Thorough analysis of the neural patterns provided by ECoG has led to the possibility of *neuromotor prostheses* (NMPs). Experimental devices tested on non-human animals allow EEG to be used in NMPs that can replace or restore lost motor functions by routing movement-related signals from the brain to computers or machines. These are essentially arrays of electrodes that detect and register electrical activity (action potentials) via an electrode in direct contact with or close to one or more neurons. A digital sensor is programmed with the patterns of neural activity associated with various common motions, such as "move left arm up" and so on. These prostheses are mainly developed for therapeutic purposes, and motor control is still rudimentary [15]. However, the main problem with these devices is the invasiveness of the implant and the likely long term rejection related to glial scarring of the brain tissue. A possible way to deal with this problem is to employ a coating of carbon nanotubes around the microdevices. These may prevent the rejection of the implant [16].

BMIs that primarily feed information to the brain or alter neural activity by means of electrical impulses have been deployed in a wide variety of applications. In this category of implants we find *cochlear implants* and *visual prostheses* [17]. These implants restore lost sensory perception by "translating" digital sensory data (from a microphone or a camera) to neural impulses that are transmitted to the brain. Whereas early cochlear implants could only convey sound to a limited degree, new "hi-fi" implants allow for listening to music and make it possible for the user to discern specific voices in loud rooms [18]. Visual prostheses are much less developed. However, even here some progress is being made. A research group at

Stanford University has developed a system for visual prosthesis that includes a subretinal photodiode array and an infrared image projection system mounted on video goggles. The resulting prosthesis provides stimulation with a frame rate of up to 50 Hz in a central 10◦ visual field, with a full 30◦ field accessible via eye movements. Pixel sizes are scalable from 100 to 25 μm, corresponding to 640–10 000 pixels on an implant 3 mm in diameter [19].

Other widely used implants include *deep-brain stimulation* (DBS), also referred to as "brain pacemakers," and *spinal cord stimulation* (SCS). These involve the surgical implantation of a medical device in the brain or the spinal cord, respectively. These devices stimulate neural activity by electrical impulses. DBS and SCS have showed remarkable success in the treatment of certain types of chronic pain, Parkinson's disease (by targeting the subthalamic nucleus), dystonia (globus pallidus pars interna), and essential tremor (thalamic ventralis intermedius) [20]. In the last few years, DBS has been expanded for use in the treatment of major depression, epilepsy and obsessive compulsive disorder [21, 22]. However, sometimes these implants have side effects in the form of unexpected behavior, such as outbursts of rage, sexual obsession or obsessive gambling, depending on the placement of the implant and the neural configuration of the patient [23, 24]. These side effects are not yet fully understood, but illustrate the potential of electrical stimuli of the central nervous system [25]. DBS and SCS could in theory be used to induce or block specific emotional responses in unaware or unwilling subjects. However, DBS is at the moment only useful for affecting pathological conditions and not for the modulation of emotional states. Although DBS can neutralize abnormal brain activity, the effects of DBS on normal human brains is so far unknown and experiments to investigate them are not ethical in human patients, since the implant is so invasive.

It is very important to discern the difference between normal and pathological brain physiology. Whereas abnormal brains provide an easy target to focus on, the normal brain is much more difficult to decipher and to date very difficult to manipulate. Are we likely to see a more widespread use of DBS? Perhaps. This procedure is still risky and expensive and only seems justified when medical benefits are substantial, as Synofzik and Schlaepfer plausibly argue [9]. But as the size of the implant is reduced, and expertise in its use and implantation is refined, it may be used for the treatment of a wider array of psychological and psychosomatic disabilities or impairments, such as anorexia nervosa and obesity [26, 27]. However, it is unlikely to reach widespread use for non-medical (recreational or other) purposes, unless safety is dramatically improved and costs fall considerably.

Experimental Technologies

At an experimental stage, we find BMI technology converging with the recent advancements in artificial intelligence (AI), a field in computer science that aims to create systems that can perceive and learn from their environment [28]. The main idea is to link the brain to machines that can act on our thoughts but also learn from our behavior, and then act independently, foreseeing our needs [29]. For example, some existing neuroprosthetic arms are controlled by the patient's thoughts in a quite crude way, crude in the sense that they require full attention and a great deal of effort. Experimental neuroprostheses are equipped with sophisticated sensors that mimic the constant sensory feedback to the brain from real organs. With an internal computer equipped with the appropriate AI, these prostheses co-adapt with the user, forming a "symbiotic" relationship [30]. This opens up huge potentials not only for the field of neuroprosthetics, but also for our daily interactions with machines.

As machines get smarter and BMI technology develops, it is natural to assume that these technologies will converge. It is of particular interest to note the surprising plasticity of the brain. Even an adult or aging brain is able to "rewire" itself to new conditions. Studies of cochlear implants illustrate how the brain can adapt to better interact with BMIs [31]. With a corresponding ability in intelligent machines, BMIs could allow us unprecedented levels of control not only in mechanical limbs, but also in vehicles, home utilities and tools.

A similar development seems likely to take place in the field of sensory neuroprostheses. A human eye is not a "dumb" object that simply channels visual data to our brains. The retina performs advanced and complex image processing to provide the brain with relevant and accurate visual input. The visual implants of today are far from that, more similar to digital cameras than to the complex sensory tools that our eyes are.

However, research on equipping artificial retinas with some degree of "intelligence" is advancing rapidly. By applying filters and image processing, these smart implants can yield far better visual representations than "dumb" implants [32]. These "intelligent" BMI devices open new possibilities for future development. Until now, cochlear implants and retinal implants have only been of interest to deaf and blind people, respectively. The sensory information provided is still vastly inferior to that provided by healthy eyes and ears. And without the use of AI and sophisticated computing, they are likely to remain so. With the convergence of AI and BMI however, these applications have the potential to be superior to our biological sensory equipment, in the sense that artificial eyes and ears may provide sensory input from infrared or ultraviolet light as well as sounds not audible to human ears [33]. When this threshold is crossed, the commercial prospects of these technologies may be considerable.

DBS will potentially follow a similar development path. The first DBS models were, by modern standards, quite crude. In the development stage there are several DBS applications that include quite sophisticated sensory equipment that measures the levels of neurotransmitters such as dopamine and glutamate and thus adapt the strength and frequency of the electrical stimuli [34]. This may prove highly valuable from the perspective of patient safety.

Of particular interest are those BMIs that create a connection between at least two brains via a BMI device. This allows communication, control or shared sensory information. Although these devices are still in an experimental stage, they are feasible and do not rely on any major breakthroughs. Consider a research project financed by DARPA, a research agency of the US Department of Defense [35]. The project in question, *Silent Talk,* involves the use of EEG "to allow user-to-user communication on the battlefield without the use of vocalized speech through analysis of neural signals" [36]. The basic principle is simple. The brain generates word-specific signals prior to sending electrical impulses to the vocal cords. These signals of "intended speech" are analyzed and translated into distinct words which are wirelessly transmitted as digital signals to a corresponding device in another brain. This translates the signals back to neural activity. Silent speech technology has already been successfully tried [37]. If successfully deployed in the battlefield, it is not unlikely that this technology may be commercialized, as other military innovations have (the Internet, formerly ARPANET, was developed by DARPA). Another military innovation with commercial potential is the "Cognitive Technology Threat Warning System", BMI binoculars that can respond to a subconsciously detected threat. This could vastly increase detection range and increase vision field to 120° [38]. As Kotchetkov et al point out, while these Other DARPA financed BMI experiments of a potentially dystopic nature involve the remote control of organisms. Experiments with rats show how BMIs could be used to remotely control animals' actions and behavior. This could be achieved by directly manipulating motor control centers, a somewhat heavy-handed approach. A more subtle approach consists in triggering the reward center in the brain by releasing dopamine when "right" choices are made [39]. DARPA is financing experiments that involve using sharks for naval reconnaissance. The sharks have BMIs that allow an operator to steer them toward a chosen target [40]. It may be worth mentioning that DARPA is known for sometimes funding projects that are speculative with little scientific rigor. Whether or not these projects will result in anything tangible remains to be seen.

The rapid development of BMI technology is likely to converge with the inexorable improvement of computing power. Modern mobile phones have more capacity than personal computers had a decade ago. A decade from now, devices small enough to be surgically implanted in the brain could have considerable computing power, if we are to believe Moore's law.[1] What this convergence may produce is impossible to tell. Perhaps progress will be obstructed by an unforeseen obstacle. But internal computers that connect brains to the internet, devices that monitor neural conditions and other ideas that seem like pure fiction today may very well be fact sooner than we think.

Ethical Considerations

The pace of the development of various BMI applications outlined in this paper justifies efforts to outline

[1] Moore's law describes a long-term trend in the history of computing hardware, in which the number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years.

the ethical issues that may arise from the use of these applications. One issue worthy of some consideration concerns emotions of disgust that implants sometimes evoke, and the potential for social ostracism. Another concern relating to BMI and other enhancement technologies is the claim that the normalization of less controversial technology may lead to the acceptance, in the future, of more controversial technologies. This is sometimes labeled the slippery slope argument. Finally we have the argument from equality, the idea that enhancement technologies exacerbate and cement social inequalities. While these issues are important and interesting, they will not be considered here. The slippery slope argument, concerns about equality and the argument of the (alleged) wisdom of repugnance have been the focus of much academic debate, and are relatively well explored [41]. Instead I would like to focus on more pressing concerns that have not been addressed to a full extent: privacy and autonomy. The main reason of my focus is that the ways in which technological innovations may affect autonomy and privacy has not yet been adequately understood. This is partly due to the rapidly changing potential of this technology, but also because these notions are elusive and poorly understood. In particular, we need to understand more fully how erosions in privacy may affect people's sense of being able to lead autonomous lives. Although some effort has recently been made to explain how information technology and ubiquitous access to the Internet may undermine privacy and autonomy, these efforts have not fully explored the possibilities of BMI to extend the scope and reach of this technology in a substantial and significant way. My general outlook is that the problems these issues pose could be dealt with some regulation, rather than with outright bans of this technology.

Privacy

As BMI technology aims to extract information from the brain to manipulate machines, there is an obvious concern that some of this information could be transferred beyond the person's control, for instance to advertisers, employers or governments. All these, and others perhaps, have an interest in acquiring information about an individual's thoughts and feelings. The potential uses of such information might include increased productivity in the workplace and smarter advertising.

For example, EEG could be used to greatly increase the efficiency of the mapping of consumer behavior and choice. The information obtained would be highly valuable information for advertisers, who seek to make advertisements smarter and more targeted. With Internet access, some of this information could easily be collected from recreational users of EEG computer games and home appliances. Advertisers are already experimenting with smart cameras that relay real-time information about emotions that consumers convey by their facial expressions [42]. If neural implants could be used to transmit information about neural activity to advertisers, this kind of advertising could be far more accurate. Some kind of information extraction about their users' thoughts and feelings for commercial purposes could make recreational BMI products affordable for a wider segment of consumers, so there is an obvious incentive for innovators to design commercial BMI devices that are able to collect the relevant neural data. The current trend, where technological advancement causes shifts in privacy norms rather than norms directing this development could be further aggravated by commercial BMI products.

Another privacy concern is the potential for employers to use surveillance technology to monitor employees in order to maximize their productivity. For example in Japan, video analysis software allows employers to monitor the smiles of employees. As Hansson and Persson convincingly argue, employees ought to have a prima facie right to privacy. However, this right could be overridden by other moral considerations, in particular if these considerations have been explicitly outlined in the work contract [43]. Some kind of surveillance may thus be justifiable, but would employers utilize BMIs to monitor employees' thoughts and feelings, if possible? If privacy is important to preserve, then arguably nothing could be more private than our thoughts and feelings. BMIs could in theory make these public or accessible to institutions and organizations that could use this information for purposes that are not necessarily in the public interest. It is therefore of crucial importance that we deliberate on how to regulate BMI technology in order to protect our privacy.

However, a consistent definition of "privacy" has yet to be agreed on. Some philosophers claim that privacy can best be described in terms of other rights, such as the right not to be harmed, and the right to property [44]. Other, more recent accounts define privacy as control over access to certain information [45]. Arguably, the extraordinary nature of the intrusion of some BMI applications is qualitatively different from previous surveillance. No other technology can possibly access subjective experience in the manner that BMI could. Although speculative, this is a possibility that can't be ruled out. A discussion on whether or not control over access is sufficient to preserve privacy, as well as a discussion on what "control" actually requires, may be urgent.

We should in particular keep in mind that notions about what constitutes a privacy infringement not only differ between cultures, but also seems to differ between generations [46]. Any plausible account of privacy must take into consideration rapidly changing social norms, and accommodate those people do not find it disturbing at all that others may obtain information about them that was previously considered very private. Social networking sites and personal online diaries show how technological innovations drive change in social norms concerning the definition of what is private. How commercial EEG devices might further transform modern notions of privacy remains to be seen. However, we should expect a significant impact if this technology becomes commercially widespread.

Autonomy

Individual autonomy is commonly defined as an individual's awareness of and influence over his or her own desires, values, emotions and the formation of these mental states. It also argued that coherence and the lack of internal conflict in one's attitudes is also significant for our autonomy. A person whose first order desires and second order desires are not aligned is thus less autonomous than a person who likes liking the things he or she likes. According to this notion of autonomy, it is not an all-or nothing quality. Autonomy can be used to refer both to the global condition and a local notion. Addicted smokers for example are autonomous persons in a general sense but unable to control their desires regarding smoking. It may be plausible, in some cases, to consider levels of general autonomy, which may vary according to the general ability of an individual to form coherent and stable desires and dispositions. It is also important to distinguish between basic and ideal autonomy. Ideal autonomy could be described as a state of mind with coherent desires and values, and complete control over and acceptance of these desires and thoughts. Perhaps the fictional character in the Star Trek television series, Mr. Spock, comes close to this notion. While ideal autonomy is perhaps unattainable for most people, it is described by many political and moral philosophers as an intrinsically valuable state. On the other hand, basic autonomy implies the level of general autonomy minimally required to be regarded as a competent person. Any plausible notion of basic autonomy should imply that most mentally sane adults are at least basically autonomous [47]. This notion is supported by the alleged connection of autonomy with moral responsibility, protection from paternalism and the right to participate in the political discourse. Anyone opposed to the idea that people should not be treated as children or animals, or believes that people are responsible for their acts must assert that most people have at least basic autonomy. Thus, the notion of most people have at least basic autonomy seems to be coherent with modern common-sense notions and values. This at least shifts the burden of proof to those who deny that most people are basically autonomous.

DBS could be used to inhibit emotional states that are undesired by the individual, such as depression, obsessive and compulsive behavior, aggression and jealousy. Since these emotions (when undesired) restrict autonomy, inhibiting them would expand autonomy to a corresponding degree. This is analogous to pharmacological treatments; they give people the opportunity to be the kind of person they would like to be. These potential benefits should not be underestimated. The limitations to autonomy that depression and mental illness impose are significant, and a possible treatment that promises to substantially reduce the occurrence of these modern epidemics should be taken seriously. The potential for extending individual autonomy could be greater still. DBS could in theory be used to *create,* and not only to inhibit, emotional responses. If used consciously and by the recipient of the stimulation, this would yield considerable control over a wide variety of mental states. This improved control over our desires and preferences could greatly enhance our autonomy, by aligning our first order preferences to our second order preferences. We could for example desire healthy food instead of junk food, love decent people instead of violent criminals and create an appreciation of works of art that our loved ones appreciate.

On the other hand, DBS could be used by a third party to manipulate our emotions and desires, for example, by making us enjoy things that we would not otherwise consider enjoyable. This indicates a potential ambiguity in the use of this technology, since DBS could also be used by employers to alter their employees' thoughts and feelings. This is unlikely to happen in the near future, due to the invasiveness, costs and lack of widespread skill on how to make such implants. However, as DBS becomes more widespread, as this paper has concluded is to be expected, costs and risks will plunge and in a longer perspective, productivity-enhancing DBS seems like a real prospect. A cashier could be made happier and more friendly, a police officer could have his aggressions blocked, a doctor could be made more caring and empathetic, and a solider could be transformed into a callous and detached person. These seem like obvious cases of autonomy infringement.

However, if used consciously and in full awareness of the consequences by employees, this technology is not necessarily morally repugnant. If certain mental faculties are required for a certain task, say a rudimentary ability to control rage, and a prospective employee lacks this faculty, would it be so questionable for this person to install a device in order to acquire this faculty? And in which relevant manner does this differ from other ways of acquiring or eliminating some psychological trait? Consider the following example:

> Addicted police: Harry is a police officer. After the tragic death of his wife, he becomes depressed and starts drinking. As his condition deteriorates, he becomes a liability to his colleagues and is a risk to himself and the citizens he tries to serve and protect. The head of department demands that, as a condition for keeping his job, he must attend therapy, and possibly accept medication. By doing so, Harry changes his previously dangerous behavior and can retain his job.

Assuming there is nothing morally objectionable in this example, we should conclude that were Harry to be treated with DBS instead of conventional therapy and antidepressants, his autonomy would not have been curtailed. Of course if someone's feelings would be altered without prior consent, this would indeed constitute a severe incursion in that person's autonomy. But this does not differ from the case where employers would force or deceive employees to take some medication, by for example mixing Prozac in their drinking water. To that extent, BMI does not seem to pose a greater threat to autonomy than other mood altering interventions, such as antidepressants, stimulants, sedatives or certain forms of psychotherapy.

Concluding Remarks

BMI technology has the potential to affect many aspects of everyday life. This paper has described the various existing and experimental innovations in this field, and highlighted some ethical concerns. I conclude that we should focus on how the proliferation of this technology may undermine but also enhance our privacy and autonomy. These risks are not fundamentally new, but in certain ways similar to those posed by information technology and mood enhancing drugs. The potential threats can be substantially reduced if the right regulations are implemented. These regulations should not, however, overlook the potential of autonomy enhancement that some applications of BMI may offer. The need for an assessment of how regulation could ensure that this technology does not violate our most cherished values is evident.

Conflicting Interests None.

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