Brain-Machine Interfaces as Commodities: Exchanging Mind for Matter

Journal:	*The Linacre Quarterly*
Manuscript ID	LQR-20-0017.R2
Manuscript Type:	Essay
Keywords:	Bioethics, Theology and bioethics, Brain-Machine Interface, Neuroscience, Brain-Computer Interface, enhancement, Human dignity, Commodification

Abstract:	Brain-machine interfaces (BMIs), which enable a two-way flow of signals, information, and directions between human neurons and computerized machines, offer spectacular opportunities for therapeutic and consumer applications, but they also present unique dangers to the safety, privacy, psychological health, and spiritual wellbeing of their users. The sale of these devices as commodities for profit exacerbates such issues and may subject the user to an unequal exchange with corporations. Catholic health care professionals and bioethicists should be especially concerned about the implications for the essential dignity of the persons using the new BMIs.

Brain-Machine Interfaces as Commodities:

Exchanging Mind for Matter

Brain-machine interfaces (BMIs), also referred to as brain-computer interfaces (BCIs), are electronic devices that enable detection of activity in the brain or nervous system, direct the operation of computerized machines or devices, and often send signals back to the brain in order to generate further outcomes. BMIs offer a host of applications, both therapeutic and consumer oriented, but they also pose unique problems for the safety, privacy, and psychological identity of the user. The status of BMI devices as commodities also places the users in a decidedly unequal position relative to the manufacturers and retailers of the equipment and software. These issues, along with concern for the spiritual engagement of users with technologies that significantly impact their minds and experience of embodiment and ensoulment, make development of BMIs a topic that should be of particular interest to Catholic theologians and healthcare professionals.

BMI technology

One might describe BMI technology as a combination of four processes: neuronal signal acquisition, signal preprocessing, feature extraction through computer analysis, and classification of data (Gonfalonieri 2018). Many BMI technologies also include “writing” data back to the brain, thereby stimulating selected neurons to initiate brain functions or motor functions or send signals to a computerized machine, isolated computer, or other digital device. Signal acquisition, or detecting neuronal activity in the brain or peripheral nerves, may be achieved in several ways. The most common of the less-invasive technologies is EEG (electroencephalogram), which measures electrical activity in the brain, but fMRI (functional magnetic resonance imaging) or FNIRS (functional near-infrared spectroscopy) are also used frequently to measure blood flow that corresponds to neural activity. DARPA, the research agency within the U.S. military, is also working with commercial entities to explore the use of non-invasive technologies such as ultrasound waves, optical tomography to measure optical path-length changes, and magnetometers (DARPA 2019). The technologies vary in their effectiveness, accuracy, speed, location, and spatial extension when recording brain activity.

Invasive technologies for signal acquisition involve placing nodes attached to electricity-conducting wires inside the skull or near peripheral nerves in healthy portions of amputated or otherwise severed limbs. The Utah Array uses 100 such nodes in the skull, and as many as five may be used at a time. Well-known entrepreneur Elon Musk's company Neuralink has developed an invasive technology with as many as 3,000 electrodes rapidly sewn into the surface of the brain (Samuel 2019; Tournas and Johnson 2019; Musk 2019). Musk claims to be aiming for clinical trials in humans in 2020 (Gaunt and Collinger 2019). Synchron has tested (with further clinical trials underway) a technology in a human patient that simply places a stent into the back of the neck to measure changes in blood oxygenation with near-infrared light (Synchron n.d.). Using 16 electrodes, the system can record activity in about 1,000 neurons in the motor cortex (Corbyn 2019). Some technologies utilize neuronal signals acquired outside the brain. Osseointegration connects electrodes that are anchored through the bone (Ortiz-Catalan et al. 2014), and robotic prostheses may be operated through muscle reinnervation that assists amputees with retargeted, healthy nerves (Kuiken 2019; Scully 2019).

DARPA and its commercial and university participants have had varied success with non-invasive technologies like pairing ultrasound and magnetic waves and genetically altering cells so that neurons will respond more reliably to magnetic fields (Tullis 2019). One group of researchers is developing a technique of “sonogenetics” by which selected viruses are inserted into brain cells to genetically alter them for greater sensitivity to ultrasound signals (Ibsen et al. 2015; Chalasani 2019). Facebook is hard at work to create fMRI headsets and augmented reality glasses for applications including thought-generated speech, controlling digital devices, remote typing, and communicating with others in a virtual environment (Regalado 2019; Samuel 2019[2]; Facebook 2019; Moses et al. 2019).

With the development of EEG technology that operates through more comfortable dry connections to the surface of the skull, Facebook and other companies are racing to develop non-invasive technologies that can be worn in headsets and goggles for a variety of consumer purposes, with some therapeutic implications. The company Emotiv is already selling relatively affordable headsets and earbuds that can decode and analyze brain signals with machine learning software and transmit data via wireless signals to be stored in the cloud (an Internet-based, broad network of computers) (Emotiv n.d.). NextMind has developed a back-of-the head device that enables thought-controlled manipulation of computers that respond to the user’s visual actions; humans have been able so far to complete tasks like changing a TV channel or crack the code on a safe (NextMind n.d; Pardes 2020).

Integration with artificial intelligence

BMI technology relies on a device-embedded computer that operates at various levels of artificial intelligence (AI). These computerized machines are controlled by complex algorithms developed by the manufacturers, typically utilizing a “neural network,” which is an abstract computer model that identifies relevant signals from neurons, “maps” them by pairing them with desired outputs, and represents the interactions in a multi-level structure of possible combinations. To improve a neural network, the model will be tested or "trained" with actual data from the subject's brain. Recently, some scientists have been able to identity more stable activity patterns underlying common movement skills, and this will allow them to predict patterns rather than constantly re-interpret the rapid firing of individual neurons (ScienceBlog 2020). The military is working on models that identify common patterns across individuals so their devices can follow more predictable signals from pre-selected neurons without relying on the inflow of data from just one individual (Powers 2017). On the other hand, some researchers are helping AI-operated computerized devices to recognize certain typical states in discrete individuals to enhance the efficiency of adapting neural nets to the unique characteristics of that person (Powers 2017).

Machine learning (ML) is a form of artificial intelligence in which a machine's algorithms adapt over time in response to actual machine experience (signals, movement, or external stimuli) and data analysis. During continued use, the algorithms should change repeatedly until they most accurately translate neuronal signals into the desired and expected actions of the device. Model-based reinforcement learning is an enhanced process whereby the computer learns from its trial-and-error experiences to build a model of experiences, adaptations, and results, and then uses this model to more efficiently "choose" actions when faced with new situations. Another variation called neuromodulation allows adaptation in a brain-machine interface of the input-output sequence programmed when decoding individual neuronal signals; instead of adapting the modeled linkages between signals as with model-based reinforcement learning, the programmed response to each individual signal also changes as the machine learns through experience (Won, et al. 2020).

Robotic prosthetics and exoskeletons

Scientists have been creating BMI prostheses since the 1990s, but the technology has changed rapidly in the past several years. In 2019, Carnegie Mellon University scientists announced development of a mind-controlled robotic arm that operated through EEG technology rather than brain implants and could accurately follow a computer cursor (College of Engineering, Carnegie Mellon University 2019). Other BMI technologies use supernumerary robotics to append new, additional limbs to a person's body in order to accomplish tasks – from lifting and grasping to travelling – more efficiently and effectively. A brain controlled third arm has been developed and tested to enhance not only the physical dexterity of the wearer but to also develop cognitive skills such as musical rhythm (Gopinath and Weinberg 2016).

Researchers have also enjoyed success with new sensor and artificial skin technologies that allow a prosthetic user to enjoy tactile sensations through the robotic limb in BMI devices (Hruska 2019). Microstimulation of residual nerve fibers allowed the user to grip fragile objects more accurately and distinguish their size and softness. Prosthetic legs have been created that have sensors on the insole of the foot and inside the knee, connected with electrodes implanted in the user's thigh (Petrini 2019). Researchers are quickly gaining ground in developing artificial skin that can cover robotic machines, including prostheses, and can more accurately sense contact, temperature, acceleration, and proximity to objects (Technical University Munich 2019). One type of artificial skin sends electronic signals 1,000 times the speed of the human nervous system (Lee et al. 2019).

An exoskeleton is an external machine structure that supports the body and enhances limb movement. French researchers have created a BMI exoskeleton that allowed a tetraplegic to move all four limbs through intentional signals from his brain (Wilson 2019). Other researchers have demonstrated greatly improved performance for a BMI exoskeleton by training users to rely less on strategic thoughts and more on the motor imagery (McFarland and Wopaw 2018).

Communication, Visual, and Affective Applications

In 2019, five people with epilepsy were able to send brain signals to their lips, tongue, jaw, and larynx that caused a BMI to produce verbal phrases as intended (Regalado 2019[2]). The BMI was surgically implanted in their skulls. Other researchers were able to decode spoken responses to questions in real time, gaining speed by first identifying brain activity that indicated which predefined question was heard by the subject (Moses et al. 2019). Stanford University scientists have expanded the possibilities by generating speech through a BMI that instead focused on a region of the gyrus involved in hand and arm movements (Stavisky et al. 2019).

One BMI device, with an invasive array attached to the back of the user's skull, allowed a blind woman to see very low-resolution shapes and colors (Juskalian 2020). In 2019, researchers used EEG detection of brain signals, magnetic communication of the signals, and pulses of light as cues to enable three persons to collaborate on a task (Martone 2019). Even with "noise" deliberately interfering with the magnetic signals, one person was able to receive thought-initiated directions from two others, perceive the accuracy of their signals, and solve basic problems.

A wide variety of applications for "affective BMIs" involve detecting or influencing users' emotions or moods (Steinert and Friedrich 2020). One researcher's EEG-based system is highly accurate in identifying positive and negative states (Wu et al. 2017). Some devices can identify the user's moods and adjust the content of a novel or game in response (Brouwer et al. 2015; Andujar et al. 2015).

Technical problems

Despite increasingly rapid progress, BMI devices face a host of potential problems. Surgically implanted devices can cause scar tissue, infections, and damage to micro-vasculature with potential hemorrhaging. We don't know yet if BMI devices, especially those that access thousands of neurons, will alter the neurons or their interactions in some unintended way. It has already been demonstrated that deep brain stimulation (DBS), now a common technology for stimulating portions of the brain, experiences infections and device failures, perhaps exceeding 4% of cases (Zhang et al. 2017). Removal or replacement of invasive BMI devices will also require further surgery.

The integration of AI and machine learning into BMIs, while greatly enhancing the devices' capabilities, can be problematic. Most importantly, it is difficult to gain or retain insight into the decisions made by an AI-driven device when those decisions are based on highly complex, changing, and voluminous data signals, not to mention the millions of changes to algorithms that may be made as the device is trained. DARPA is exploring ways for AI to generate real-time explanations for its output and actions, aiming to produce information that increases persons' trust in the reliability of robotic systems (Gao et al. 2019). An explanation of what happens is not, however, an explanation of why, and translating such data into easily understood and simplified statements is very difficult for the use of developers, let alone the end-users.

BMI devices with AI and wireless technology will be vulnerable to hacking from persons who seek to interfere with the devices' operations, manipulate them, or access information. The U.S. Food and Drug Administration has warned about serious vulnerabilities in internet-connected medical devices of all types, and has specifically identified problems with pacemakers (U.S. Food and Drug Administration 2019). With a BMI device, one study found that hackers might cause the user to unwittingly spell incorrect words (Zhang et al. 2020).

User identity and autonomy

Users of any device that coordinates with and partially extends bodily functions, especially those associated with the brain, may wrestle with its implications for their identity and social interactions (Haselager 2013). The experience of patients treated with DBS is illustrative, for some such patients have experienced damage to their personal identities as well as impulse-control issues like hypersexuality or excessive gambling, apathy, or a confused sense of agency (Drew 2019; Klein et al. 2016; Volkmann et al. 2020). The psychological issues for DBS patients were not only deteriorative, but also occurred during restoration of their prior perceived identities (Gilbert et al. 2017). Such problems may extend to a host of issues of personal integrity in BMIs (Lavazza 2018). When persons lose limbs and wear prostheses, their psychological health and social relations depend significantly on the level of difficulty with the prosthesis (Gallagher and MacLachlan 1999). Some wearers may conceptually blur the lines between the object and their self, perceiving merely a fluid process of bodily "re-territorialization" (Middleton 2017).

Because BMIs decode, influence, and interact with a person's mental acts and intentions, the physical and moral autonomy of the user might be questioned. This is especially a problem when "offloading computations" from the brain to a BMI that independently alters and adapts algorithms in a continuous yet invisible process. A user might experience doubt about whether the device or the person is in control of decisions as mundane as moving a computer cursor in a particular direction or as momentous as harming another person through the movements of a prosthetic arm or exoskeleton. With affective BMIs, uncertainty about the authorship or implications of emotional states can interfere with the user's experience of their own intentions and reasoning, or even their actions toward others.

Beyond moral responsibility, there may be profound legal questions about liability that our current laws are unable to adequately disentangle (Nakar et al. 2015; Grübler 2011; Weinberger and Greenbaum 2016). It may be possible, for example, to use BMI devices to determine if a suspect or court witness is lying (Monaro et al. 2017). Regarding liability, to what extent is the user responsible for training and concentrating on the operation of the BMI device, or even for choosing to use the device in the first place? Legal cases involving harm caused by devices integrated with AI have so far tended to place blame on the user, who appears to be a "liability sponge" in contrast to the manufacturer and others involved in an incident (Hao 2015).

Commodification of BMIs

Estimates of the commercial market for BMIs vary considerably, with one report expecting a global market size of $2.67 billion in 2026 (Reports and Data 2019). Medical purposes for BMIs may reach close to 80% of total commercial production as an aging population and neurodegenerative diseases drive most of the increase (Juniper Research 2019). The market value of the global limb prosthetics industry is expected to reach $2.7 billion by 2024, with an annual growth rate of 5.8% CAGR (Zion Market Research 2019). For robotic prosthetics specifically, in 2016 the global market size was around $790 million (Grand View Research 2017).

High prices and relatively low reimbursement rates for limb prosthetics among insurers may dampen the rate of growth for robotic prosthetics sales, as such products can be priced at $100,000 or more. Those costs may fall, however; a company called Brain Robotics announced in 2018 development of an electromyography-enabled prosthetic hand that is expected to sell for under $5,000 (Johnson 2018). The number of potential consumers of prosthetic BMIs may expand dramatically with the prevalence of diabetes and an aging population with more cases of osteoarthritis.

The commercial exchange involved in a user's purchase of a BMI device is unique in regard to the sensitivity of privacy and identity issues related to one's brain functions. In order to receive the machine and access the manufacturer's software updates and ongoing maintenance, the user will need to pay money (sometimes with assistance from an insurance entity) and grant significant access to their brain signals and patterns. The incalculable and transcendent nature of the value of mental data may cause it to be under-appreciated by users who are eager to obtain the functional benefits of BMI devices. Subsequent loss of the brain-machine connection could be psychologically damaging; will poorly counseled consumers be aware of the risk of repossession of a BMI prosthetic during financial disputes or the manufacturer's bankruptcy (Bologna 2020; Drew 2019)?

It remains to be seen what legal rights the user will retain in regard to liability, disputes, data ownership, and privacy, but service contracts and privacy statements from software and electronic device manufacturers as well as providers of various internet-based services often skew heavily against the users, if only in their intelligibility (Kulenkamp 2020). Published research has indicated that over 90% of consumers do not read terms of service contracts that they consent to (Guynn 2020). The willingness and capability of BMI manufacturers to override consumer protections in a highly lucrative market may not support much peace of mind for users and their healthcare providers. For years, implantable device manufactures have enjoyed various protections from lawsuits by users (Bailey 2010), and it is unclear if these protections will also extend to BMI producers.

BMI developers and future retailers may be overly eager to derive a near-term profit from their efforts, sacrificing consumer safety. The data provided so far from Neuralink neglects to share such information as rates of infection or compatibility of materials with human tissue (Kent 2019). Owner Elon Musk is listed as the sole author of a recently published paper detailing Neuralink's new technology, and the associated research has not been published in peer-reviewed studies (Musk 2019). Concerns about transparency among commercial BMI efforts resembles controversies that previously surrounded DBS technologies (Erickson-Davis 2012).

Privacy concerns and issues of brain data ownership will be amplified by the role of the user as the intentional agent and producer of the data acquired, stored, analyzed, and repeatedly used to adapt the algorithms that guide BMI output. Who then has a right to determine the use of brain signal data, especially when it informs large-scale studies, further development of BMI software and training of machines, or sharing with researchers and other developers? Does the user as initial producer of the data have a financial or property claim on profitable development of AI that is derived from it? The United States Patent and Trademark Office (USPTO) has taken these questions seriously in requests for public comments regarding copyrights and patents (Department of Commerce 2019).

Much of the research on BMIs, while funded by commercial entities and government agencies, occurs in universities where the culture and interest of researchers is to share datasets widely. The most robust protection of privacy in data sharing, however, is a multi-layer series of data “silos” that segment encrypted information that is controlled at individual, application, corporate, and industry levels. The privacy interests of individual users are therefore pitted against the interests of powerful research, educational, corporate, and even state institutions. One might consider the experience in 2019 with Microsoft’s MS Celeb database, which a watchdog organization discovered was distributing facial recognition data of ordinary citizens to corporate and state entities, including the aggressive surveillance programs in China (Song 2019). Facebook has recently been subject to historic fines for social media privacy violations and facial recognition technology abuse (Federal Trade Commission 2019).

Although BMIs currently focus on accessing brain signals specific to narrowly defined tasks or perceptions, rapid advancements in neurology and BMI technologies indicate that BMI devices may one day access further brain signal data for expanded purposes. How far can the technology take us, and how much control will users have over the information gained from BMI operations? For example, patterns of neuronal signals may indicate health concerns, emotions, cognitive impairments, or conditions such as pregnancy that are beyond the scope of a device’s intended applications (Schwartz 2019). Many potential applications for BMIs open opportunities for neuromarketing, data sharing, and state coercion. It may be possible to predict individual intentions, as has been achieved in a limited way through fMRI (Soon et al. 2013; Haynes et al. 2007). Our democratic system could be put into disarray with identification or prediction of persons’ political attitudes through neural patterns (Schreiber et al. 2013).

If such data is collected, decoded, and stored by a device, then shared with a manufacturer, software developer, or researcher, it may reach an unwanted third party or hacker, whether intentionally or not. Some social media companies currently treat nearly all the data shared by their users with friends as inputs to sophisticated, targeted advertising that is not always desired or in the best interests of the users. Facebook, for example, has been accused of recording users' emotions through manipulation of news feeds and of detecting teenagers' need for a "confidence boost" to assist advertisers with targeted pitches (Levin 2017).

Even when aggregated data cannot be attributed to individuals by third parties, sharing that data may be decidedly against their interests as a group. Insurance companies, for example, might learn to raise premiums for a class of BMI users by identifying and correlating certain health risks with that population, or researchers might label that population as more likely to commit a crime. This tendency can be seen in other industries; there is already heavy interest in finding such correlations based on genetic data, including data gathered through ancestry or other tests sold to consumers (Kaiser 2019; Gard et al. 2019).

Will BMI technology advance to a point where corporations can influence or even plant thoughts in the users' brains, and how will users maintain control over such applications when the algorithms in AI and their constant adaptation in machine learning are so obscure? Some BMI devices already "write" signals back to the brain, assisting a user, for example, with responsive movement of a robotic prosthesis or stimulating reminders to take medications when an epileptic is in danger of a seizure. Researchers have demonstrated that just one hour of training with a BMI causes significant alterations in their brain's structure and function, thereby creating opportunities for therapeutic treatment for conditions like strokes but also the eventual capacity – as neurologists expand their understanding of the human brain – for targeted stimulation of movements, images, moods, memories, or even simple thoughts (Nierhaus et al. 2020). One company has created a device that enables remote control of neural circuits in the brain through light signals and drug deliveries, a small brain implant, and a smartphone interface (University of Washington Health Sciences 2019). Researchers have demonstrated wireless remote control of rats' movements through an EEG-enabled BMI (Andrews 2020).

As profit-oriented entities, commercial manufacturers of BMI devices might focus more on the interests of wealthy consumers. Currently marketed myoelectric prostheses may cost $50,000 or more (Sharington 2017), and robotic exoskeletons are more complex and therefore unlikely to cost any less when operated with BMI technology. Surgery for invasive devices will be a significant cost in itself; bilateral surgery for DBS, for example, currently runs from $30,000 to $100,000 (Parkinson's Foundation 2019). BMI devices that are intended for sophisticated and highly accurate decoding of neuronal patterns will be constantly upgraded for decades as neuroscience advances, reducing the likelihood that those commercial products will be available from a wide variety of cost-competing retailers. The markets for expensive, individualized health treatments are already distorted by medical tourism that undermines competition in certain countries like the United States. Potential regulation by government agencies, liability exposure for manufacturers, and the increasing availability of skilled, lower-paid developers in foreign countries may encourage relocation of BMI companies to more hospitable and profitable environments.

A key stakeholder population, but not always the most lucrative for retail purposes, is comprised of persons with disabilities. Given the 1 billion persons with defined disabilities worldwide (World Bank 2019) and the wide variety of potential applications for BMI devices, especially regarding mobility and cognitive functions, the market for commercial producers could be huge. Somebody needs to pay for the BMI devices, however, and this will depend on reimbursement from insurance companies and the political will of governments to provide supportive public benefits or insurance regulations. With an almost 10% unemployment rate for disabled persons in the U.S. (Kang et al. 2018), alleviating the economic impact of the non-working disabled population with BMI devices may be an incentive that advocates can use to gain more public support.

Consumer applications for entertainment or non-therapeutic purposes may, however, generate greater demand from the wider population. Facebook is investing hundreds of millions, or even billions, of dollars in BMI technology primarily for consumers to operate personal and entertainment-oriented digital devices with their minds (Facebook 2020). One might imagine brain-control over smart home applications, intra-brain communication and game playing enhanced with virtual reality systems, or even the extinction of finger-dependent keyboards. Elon Musk seems most enthused – and quite serious – about developing Neuralink's technology for a transhumanist future where human beings are intimately tied in through their brains to the immense store of information and analytical capacities of computer networks (Samuel 2019). On the other hand, while the companies and universities financed by DARPA are making useful advances in the benefits of BMI technology for paraplegics and epileptics, will those efforts and the funding continue when military functions for BMI become more reliably operational?

Regulating BMI manufacturers, AI developers, and their downstream end-users may be desirable, but also very difficult. Attempts at codifying broadly defined consumer rights in regard to BMI are underway in the Organisation for Economic Cooperation and Development (OECD) and United Kingdom Royal Society (OECD 2019). To be effective, regulations will need to be specific to the technology, adapt to new BMI applications, and lead to the implementation of compelling incentives and sanctions. The participants in developing and manufacturing BMI devices, however, are highly diverse, ranging from designers of electrodes to innovators in surgical methods. Participants in BMI manufacture are not like the medical industry, which is at least populated by medical professionals who have a partial mission of public service and established norms and institutional sanctions. A review of more than eighty ethics reports on AI, for example, was long on principles but short on moral and legal imperatives that can be in some way enforced (Mittelstadt 2019).

Regulatory agencies like the FDA face difficulties in "pacing," or trying to keep up with rapidly developing technologies that quickly exceed the scope and specificity of regulations as the definitions of technologies, applications, and agents change. Commercial entities may force the FDA into extended legal battles that neutralize regulations until they are no longer relevant. Regulations can also unintentionally benefit the companies most likely to violate them; Europe's General Data Protection Regulation (GDPR) mandate for statistics reporting, for example, has been criticized for encouraging advertisers to flock to largest technology companies that were the targets of the legislation (Kostov and Schechner 2019). One possibility is for regulatory agencies to focus on the practices and outcomes from companies rather than individual products, but such an approach can fail in addressing the inherent problems with technologies themselves, such as the potential for psychological damage from BMI-AI integration. The FDA has experimented with such an approach in its Pre-Cert program (U.S. Food and Drug Administration 2019[2]).

Further considerations for Catholics

In a letter to the Pontifical Academy of Life titled *Humana Communitas*, Pope Francis declared that AI-powered robotics "touches the very threshold of the biological specificity and spiritual difference of the human being" (Francis, 2019). The Academy concentrated on robotics in its 2019 Assembly and has extended its robotics conversation into AI in February 2020. The president of the Academy, Archbishop Vincenzo Paglia, also warned that "Some perspectives at times surprise us with their audacity, their creativity, their potential, but also with the diversity of anthropological approaches that they express" (Pentin 2019). He was no doubt referring, in part, to secular bioethicists that apply mainly instrumentalist criteria in evaluating the ethics of technologies ranging from genetic engineering of embryos to the use of AI in medical systems and diagnosis.

Consideration of BMIs with enhancement and even therapeutic goals might over-emphasize the importance of extending human bodies and minds. Extension can be a metaphorical or functional representation of the way machines seem to expand the body's presence in space, including the ethereal world of the Internet, or in physical and mental action. Theorist Ernst Kapp famously portrays technical objects as projections of human organs into the external world (Kapp 2018), while Andy Clark's and David Chalmers' "extended mind thesis" suggests that technical artifacts and electronic media create a semi-determining environment that forms the mind when integrated into its cognitive functions (Clark and Chalmers 1998).

While providing important insights into the interaction of technical artifacts and systems with human persons, such secular representations can reinforce a false sense of dualism in human nature. Either the mind is extended, or the body, or both, but it is not a picture of the vitally unified, partly transcendent person acting in the world. This is what enables the transhumanists to imagine the preservation of personhood while somehow "uploading" the conscious mind into a merger with an electronic network of computers or overcoming bodily death by recording neuronal structures and patterns in a digital format. It also reinforces a popular fascination with the science fiction fantasy (or tragedy) of an essential union between machine and human body into a "cyborg".

As Catholics, however, we understand that the person is a unity of body and soul, not primarily an interaction of body and brain-instantiated mind. "The human body shares in the dignity 'of the image of God': it is a human body precisely because it is animated by a spiritual soul, and it is the whole human person that is intended to become, in the body of Christ, a temple of the Spirit" (Catholic Church 1997, 367). In the theology explained by Thomas Aquinas, the soul is not an independent substance or separate kind of matter, but the form of the human body (Aquinas 2017, I, Q75-76); following Aristotle's interpretation, that form is what helps define the material substance, the human body, into its nature as a rational person. The human mind is therefore not an addition to or self-subsistent captain of the human body, but instead the intellect is a power of the soul that strives ultimately toward perfection in the knowledge of God found in the afterlife. Secular emphasis on extension of the mind or of the body can otherwise pose an imagined obstacle to Christian wisdom about the person as a dignified child of God with a purpose far greater than instrumental mastery over nature.

As a body-soul unity with essential dignity, the patient legitimately calls to us to apply BMI technologies for therapeutic purposes in their care. Many BMIs are however designed for applications that primarily enhance capabilities or entertain. The Congregation for the Doctrine of the Faith has warned us about blind enthusiasm for enhancement of human persons in the context of genetic therapies: "The key to man's dignity does not lie in his autonomy or in his reason, in his ability to decide for himself or in creating his own universe: it is found rather in his reality as a human person, the only earthly creature that God has wanted for its own sake, the man 'formed' by God, into whose nostrils God breathed the 'breath of life'" (Congregation for the Doctrine of the Faith 2008, 11,a). We also must be careful to balance the risks and benefits of any therapy in a proportionate manner (United States Conference of Catholic Bishops 2018, §31). With all the significant dangers of BMIs for autonomy, moral responsibility, psychological integrity, and social withdrawal, and all the spectacular temptations of entertainment and instrumental applications, the user of a BMI will want to reflect deeply on whether a BMI device will further their purpose in virtue, worship, and ultimate felicity in the vision of God.

The sale of BMIs as commodities only exacerbates this dilemma. As Pope Francis has warned, a "technocratic paradigm" in the contemporary culture applies the instrumental rationality of technology – a dominant mentality that prioritizes evaluation of the efficiency, utility, and efficacy of means over an appraisal of the ends – to the abuse of dignified persons as mere objects for achieving secular goals (Francis 2015, §101-114). This technocratic paradigm is most prevalent in the drive for consumer acquisition and corporate greed for excessive profits (Francis 2015 §109, 144, 203). This is the logic of accumulation and exchange, similar to the concept of Martin Heidegger's "standing reserve" whereby things and human beings become mere fodder for a self-propelling economy of production and marketing (Heidegger 1993).

Medical professionals and bioethicists will have a hard time convincing patients of the crucial distinction between therapeutic care for the person, enabled radically through BMI devices, and instrumental or frivolous use of BMIs with potentially dangerous technologies. The patient must not subject their invaluable integrity as a person to the highly unequal and manipulative exchange of the mind, or even the soul, with a BMI manufacturer. The proliferation of BMI devices, as never before, places medical and bioethics counselors squarely in the middle of a deeply personal, ideological confrontation between the spiritual and secular goals of each human patient. Although medical professionals, counselors, and bioethicists necessarily have very practical objectives in mind, whether it is the process of healing a patient or interpreting the implications of principles of beneficence and informed consent to more mundane medical decisions, the profound questions associated with BMIs call for what Roberto Dell'Oro refers to as "an elemental attunement to the deeper sources of life, over, or against, the ethos we super-impose upon them, thus clogging what is primal with constructions of our own making" (Dell'Oro 2019). The quandary of BMI development, use, sale, and consumption is at its heart the fundamental dilemma of our hyper-technological age.

References:

Andrews, Bill. 2020. "Mind-Controlled Rats Are Now a Thing" *Discover* 41, no. 1: 38.

Andujar, Marvin, Chris S. Crawford, Antinus Nijholt, France Jackson, and Juan E. Gilbert. 2015. "Artistic Brain–Computer Interfaces: The Expression and Stimulation of the User's Affective State" *Brain–Computer Interfaces* 2, no. 2–3: 60–69.

Aquinas, Thomas. 2017. *Summa Theologiae*. "New Advent." Accessed Feb. 8, 2020. http://www.newadvent.org/summa.

Bailey, Ryan and Kristin E. Schleiter. 2010. "Testing Manufacturer Liability in FDA-Approved Device Malfunction" *Virtual Mentor* 12, no. 10: 800-803.

Bologna, Giacomo. 2020. “A Company Repossessed and Returned a Vet's Prosthetic Legs. He Still Can't Use Them” *Mississippi Clarion Ledger*, Jan. 9, 2020. https://www.clarionledger.com/story/news/politics/2020/01/09/mississippi-veteran-caught-u-s-medical-system-after-legs-taken/2784777001.

Brouwer, Anne-Marie, Maarten Hogervorst, Boris Reuderink, Ysbrand van der Werf, and Jan van Erp. 2015. “Physiological Signals Distinguish between Reading Emotional and Non-Emotional Sections in a Novel” *Brain-Computer Interfaces* 2, no. 2–3: 76–89.

Catholic Church. 1997. *Catechism of the Catholic Church, 2nd ed.* Vatican: Libreria Editrice Vaticana.

Chalasani, Sreekanth. 2019. “The New Field of Sonogenetics Uses Sound Waves to Control the Behavior of Brain Cells” *Real Clear Science*, Aug. 13, 2019. https://www.realclearscience.com/articles/2019/08/13/the_new_field_of_sonogenetics_uses_sound_waves_to_control_the_behavior_of_brain_cells_111071.html.

Clark, Andy and David J. Chalmers. 1998. "The Extended Mind” *Analysis* 58, no. 1: 7-19.

College of Engineering, Carnegie Mellon University. 2019. "First-Ever Successful Mind-Controlled Robotic Arm without Brain Implants." *Science Daily*, June 19, 2019. https://www.sciencedaily.com/releases/2019/06/190619142542.htm.

Congregation for the Doctrine of the Faith. 2008. *Instruction Dignitas Personae on Certain Bioethical Questions*. Vatican: Libreria Editrice Vaticana.

Corbyn, Zoë. 2019. "Are Brain Implants the Future of Thinking?" *The Guardian*, Sep. 22, 2019. https://www.theguardian.com/science/2019/sep/22/brain-computer-interface-implants-neuralink-braingate-elon-musk.

DARPA. 2019. "Six Paths to the Nonsurgical Future of Brain-Machine Interfaces." Accessed Feb. 8, 2020. https://www.darpa.mil/news-events/2019-05-20.

Dell'Oro, Roberto. 2019. "On the Ultimate That Is the First: Thinking Beyond (Bio)ethics" *Gregorianum* 100, no. 3: 621-647.

Department of Commerce. 2019. "Request for Comments on Intellectual Property Protection for Artificial Intelligence Innovation" *Federal Register* 84, no. 210: 58141.

Drew, Liam. 2019. "The Ethics of Brain–Computer Interfaces" *Nature* 571: S19-S21.

Emotiv. n.d. Accessed Feb. 8, 2020. https://www.emotiv.com.

Erickson-Davis, Cordelia. 2012. "Ethical Concerns Regarding Commercialization of Deep Brain Stimulation for Obsessive Compulsive Disorder" *Bioethics* 26, no. 8: 440-446.

Facebook. 2019. "Imagining a New Interface: Hands-Free Communication without Saying a Word." https://tech.fb.com/imagining-a-new-interface-hands-free-communication-without-saying-a-word.

Facebook. 2020. "Imagining a new interface: Hands-free communication without saying a word," March 30, 2020. https://tech.fb.com/imagining-a-new-interface-hands-free-communication-without-saying-a-word/.

Federal Trade Commission. 2019. "FTC Imposes $5 Billion Penalty and Sweeping New Privacy Restrictions on Facebook," July 24, 2019. https://www.ftc.gov/news-events/press-releases/2019/07/ftc-imposes-5-billion-penalty-sweeping-new-privacy-restrictions.

Francis. 2015. *Laudato si', On Care for Our Common Home*. Vatican: Libreria Editrice Vaticana.

Francis. 2019. *Address to Participants in the Plenary Assembly of the Pontifical Academy for Life, February 25, 2019*. Vatican: Libreria Editrice Vaticana.

Gallagher, Pamela and Malcolm MacLachlan. 1999. "Psychological Adjustment and Coping in Adults with Prosthetic Limbs" *Behavioral Medicine* 25, no. 3: 117-124.

Gao, Feng, Hangxin Liu, Xu Xie, Siyuan Qi, Yixin Zhu, Yingnian Wu, Hongjing Lu, and Song-Chun Zhu. 2019. "A Tale of Two Explanations: Enhancing Human Trust by Explaining Robot Behavior" *Science Robotics* 4, no. 37.

Gard, Arianna M., Hailey L. Dotterer, and Luke W. Hyde. 2019. "Genetic Influences on Antisocial Behavior: Recent Advances and Future Directions" *Current Opinion in Psychology* 27: 46-55.

Gaunt, Robert and Jennifer Collinger. 2019. "Brain-Machine Interfaces Are Getting Better and Better – And Neuralink's New Brain Implant Pushes the Pace" *The Conversation*, June 19, 2019. http://theconversation.com/brain-machine-interfaces-are-getting-better-and-better-and-neuralinks-new-brain-implant-pushes-the-pace-120562.

Gilbert, Frederic, Eliza Goddard, John Noel M. Viaña, Adrian Carter, and Malcolm Horne. 2017. "I Miss Being Me: Phenomenological Effects of Deep Brain Stimulation" *AJOB Neuroscience* 8, no. 2: 96-109.

Gonfalonieri, Alexandre. 2018. "A Beginner's Guide to Brain-Computer Interface and Convolutional Neural Networks" *Towards Data Science*, Nov. 25, 2018. https://towardsdatascience.com/a-beginners-guide-to-brain-computer-interface-and-convolutional-neural-networks-9f35bd4af948.

Gopinath, D. and G.A. Weinberg. 2016. "Generative Physical Model Approach for Enhancing the Stroke Palette for Robotic Drummers" *Robotics and Autonomous Systems* 86: 207–215.

Grand View Research. 2017. "Robotic Prosthetics Market Size, Share & Trends Analysis Report by Technology (Microprocessor Controlled, Myoelectric Prosthetics), by Extremity (Lower Body, Upper Body Extremity), by Region, and Segment Forecasts, 2018 – 2025." Accessed Feb. 8, 2020. https://www.grandviewresearch.com/industry-analysis/robotic-prosthetics-market.

Grübler, Gerd. 2011. "Beyond the Responsibility Gap: Discussion Note on Responsibility and Liability in the Use of Brain–Computer Interfaces." *AI & Society* 26, no. 4: 377–382.

Guynn, Jessica. 2020. "What You Need to Know before Clicking 'I Agree' on That Terms of Service Agreement" *TechXplore*, Jan. 29, 2020. https://techxplore.com/news/2020-01-clicking-terms-agreement.html.

Hao, Karen. 2019. "When Algorithms Mess Up, the Nearest Human Gets the Blame" *MIT Technology Review,* May 28, 2019. https://www.technologyreview.com/s/613578/ai-algorithms-liability-human-blame.

Haselager, Pim. 2013. "Did I Do That? Brain–Computer Interfacing and the Sense of Agency" *Minds & Machines* 23: 405–418

Haynes, John Dylan, Katsuyuki Sakai, Geraint Rees, Sam Gilbert, Chris Frith, and Richard E. Passingham. 2007. “Reading Hidden Intentions in the Human Brain” *Current Biology* 17: 323–328.

Heidegger, Martin. 1993. “The Question Concerning Technology”, in *Martin Heidegger: Basic Writings*, edited by D. F. Krell, translated by W. Lovitt. London: Routledge.

Hruska, Joel. 2019. “‘Luke Skywalker’ Robotic Prosthesis Allows Amputee to Feel Again” *Extreme Tech*, July 29, 2019. https://www.extremetech.com/computing/295794-luke-skywalker-robotic -prosthesis-allows-amputee-to-feel-again.

Ibsen, Stuart, Ada Tong, Carolyn Schutt, Sadik Esener and Sreekanth H. Chalasani. 2015. “Sonogenetics is a Non-Invasive Approach to Activating Neurons in Caenorhabditis Elegans” *Nature Communications* 6: 8264.

Johnson, Heather R. 2018. “An Affordable Prosthetic Hand” *Medical Device and Diagnostic Industry*, May 25, 2018. https://www.mddionline.com/affordable-prosthetic-hand.

Juniper Research. 2019. “Brain Machine Interfaces and Neuromodulation: Market Summary and Key Takeaways.” Accessed Feb. 8, 2020. https://www.juniperresearch.com/resources/infographics/brain-machine-interfaces-neuromodulation-statist.

Juskalian, Russ. 2020. “A New Implant for Blind People Jacks Directly into the Brain” *MIT Technology Review*, Feb. 6, 2020. https://www.technologyreview.com/s/615148/a-new-implant-for-blind-people-jacks-directly-into-the-brain.

Kaiser, Jocelyn. 2019. “A Judge Said Police Can Search the DNA of 1 Million Americans without Their Consent. What’s Next?” *Science*, Nov. 7, 2019. https://www.sciencemag.org/news/2019/11/judge-said-police-can-search-dna-millions-americans-without-their-consent-what-s-next.

Kang, Janie-Lynn Kang, Megan Dunn, and Andrew Blank. 2018. “Labor Force Characteristics of People with a Disability” U.S. Bureau of Labor Statistics. Accessed Feb. 8, 2020. https://www.bls.gov/spotlight/2018/labor-force-characteristics-of-people-with-a-disability/home.htm.

Kapp, Ernst. 2018. *Elements of a Philosophy of Technology: On the Evolutionary History of Culture*, edited by Jeffrey West Kirkwood and Leif Weatherby, translated by Lauren K. Wolfe. Minneapolis: University of Minnesota Press.

Kent, Chloe, Verdict Medical Devices. 2019. “Neuralink: Unpacking the Hype around Elon Musk’s Brain-Computer Interface.” Accessed Feb. 8, 2020. https://www.medicaldevice-network.com/features/neuralink-fact-fiction.

Klein, Eran, Sara Goering, Josh Gagne, Conor V. Shea, Rachel Franklin, Samuel Zorowitz, Darin D. Dougherty and Alik S. Widge. 2016. “Brain-Computer Interface-Based Control of Closed-Loop Brain Stimulation: Attitudes and Ethical Considerations” *Brain-Computer Interfaces* 3, no. 3: 140-148.

Kulenkamp, Emily. 2015. “What do donuts and equipment service contracts have in common?” *Becker’s Hospital CFO Report*, Oct. 3, 2015. https://www.beckershospitalreview.com/finance/what-do-donuts-and-equipment-service-contracts-have-in-common.html.

Kostov, Nick and Sam Schechner. 2019. “GDPR Has Been a Boon for Google and Facebook” *Wall Street Journal*, June 17, 2019. https://www.wsj.com/articles/gdpr-has-been-a-boon-for-google-and-facebook-11560789219.

Kuiken, T.A.. 2009. “Targeted Muscle Reinnervation for Real-Time Myoelectric Control of Multifunction Artificial Arms” *Journal of the American Medical Association* 301, no. 6: 619-628.

Lavazza, Andrea. 2018. “Freedom of Thought and Mental Integrity: The Moral Requirements for Any Neural Prosthesis” *Frontiers in Neuroscience* 12: 82. https://www.frontiersin.org/articles/10.3389/fnins.2018.00082/full.

Lee, Wang Wei, Yu Jun Tan, Haicheng Yao, Si Li, Hian Hian See, Matthew Hon, Kian Ann Ng, Betty Xiong, John S. Ho, and Benjamin C. K. Tee. 2019. “A Neuro-Inspired Artificial Peripheral Nervous System for Scalable Electronic Skins” *Science Robotics* 4: 32.

Leigh, Sang-won, Harpreet Sareen, Hsin-Liu Kao, Xin Liu, and Pattie Maes. 2017. “Body-Borne Computers as Extensions of Self” *Computers* 6, no. 1: 12.

Levin, Sam. 2017. “Facebook Told Advertisers It Can Identify Teens Feeling 'Insecure' and 'Worthless'” *The Guardian*, May 1, 2017. https://www.theguardian.com/technology/2017/may/01/facebook-advertising-data-insecure-teens.

Martone, Robert. 2019. “Scientists Demonstrate Direct Brain-to-Brain Communication in Humans” *Scientific American*, Oct. 29, 2019. https://www.scientificamerican.com/article/scientists-demonstrate-direct-brain-to-brain-communication-in-humans.

McFarland, Dennis J. and Jonathan R. Wolpaw. 2018. “Brain–Computer Interface Use Is a Skill That User and System Acquire Together” *PLoS Biology* 16, no. 7.

Middleton, Alexandra. 2017. “Reterritorialization of the Body: Ethnographies of Emergent Biotechnologies” *Anthropological Quarterly* 90, no. 1: 267–276.

Mittelstadt, Brent. 2019. “Principles alone Cannot Guarantee Ethical AI” *Nature Machine Intelligence* 1: 501–507.

Monaro, Merylin, Luciano Gamberini, and Giuseppe Sartori. 2017. “The Detection of Faked Identity Using Unexpected Questions and Mouse Dynamics” *PLOS One* 12, no. 5.

Moses, David A., Matthew K. Leonard, Joseph G. Makin, and Edward F. Chang. 2019. “Real-time Decoding of Question-and-Answer Speech Dialogue Using Human Cortical Activity” *Nature Communications* 10: 3096.

Musk, Elon, Neuralink. 2019. “An Integrated Brain-Machine Interface Platform with Thousands of Channels” *Journal of Medical Internet Research* 21, no. 10.

Nakar, Sharon, Sara Weinberger, and Dov Greenbaum. 2015. “Legal and Social Implications of Predictive Brain Machine Interfaces: Duty of Care, Negligence, and Criminal Responsibility” *AJOB Neuroscience* 6, no. 4: 40-42.

NextMind. n.d. Accessed Feb. 8, 2020. https://www.next-mind.com.

Nierhaus, Till, Carmen Vidaurre, Claudia Sannelli, Klaus-Robert Mueller, and Arno Villringer. 2020. “Immediate Brain Plasticity after One Hour of Brain–Computer Interface (BCI)” *Journal of Physiology* Nov. 2019: 1-17.

OECD. 2019. “Recommendation on Responsible Innovation in Neurotechnology.” Accessed Feb. 8, 2020. https://www.oecd.org/science/recommendation-on-responsible-innovation-in-neurotechnology.htm.

Ortiz-Catalan, Max, Bo Hakansson, and Rickard Branemark. 2014. “An Osseointegrated Human-Machine Gateway for Long-Term Sensory Feedback and Motor Control of Artificial Limbs” *Science Translational Medicine* 6, no. 257.

Pardes, Arielle. 2020. “Mind Control for the Masses—No Implant Needed” *Wired*, Jan. 2, 2020. https://www.wired.com/story/nextmind-noninvasive-brain-computer-interface.

Parkinson’s Foundation. 2019. “Parkinson’s Disease: Deep Brain Stimulation: A Practical Guide for Patients and Families.” Accessed Feb. 8, 2020. https://www.parkinson.org/sites/default/files/attachments/Deep-Brain-Stimulation-Guide-Parkinsons.pdf.

Pentin, Edward. 2019. “Assessing the Ethical (and Unethical) Implications of Artificial Intelligence” *National Catholic Register*, April 2, 2019. http://www.ncregister.com/daily-news/assessing-the-ethical-and-unethical-implications-of-artificial-intelligence.

Petrini, Francesco M. 2019. “A Prosthetic Leg That Attaches to Nerves Feels Like Part of the Body” *New Scientist*, Oct. 2, 2019. https://www.newscientist.com/article/2218474-a-prosthetic-leg-that-attaches-to-nerves-feels-like-part-of-the-body.

Powers, Benjamin. 2017. “The Military Has a Plan for Human Brain Waves” *Medium*, Oct. 4, 2017. https://medium.com/@bnpowers8/the-military-has-a-plan-for-human-brain-waves-170c57956e9f.

Regalado, Antonio. 2019. “Facebook is Funding Brain Experiments to Create a Device That Reads Your Mind” *MIT Technology Review*, July 30, 2019. https://www.technologyreview.com/s/614034/facebook-is-funding-brainexperiments-to-create-a-device-that-reads-yourmind.

Regalado, Antonio. 2019[2]. “Scientists Have Found a Way to Decode Brain Signals into Speech” *MIT Technology Review*, April 24, 2019. https://www.technologyreview.com/s/613421/scientists-have-found-a-way-to-decode-brain-signals-into-speech.

Reports and Data. 2019. “Brain-Computer Interface Market by Product (Non-Invasive BCI, Invasive BCI, Partially BCI, Others), By End User (Medical, Military, Others), By Application (Healthcare, Smart Home Control, Communication, Entertainment & Gaming) and Segment Forecasts, 2017–2026.” Accessed Feb. 8, 2020. https://www.reportsanddata.com/report-detail/brain-computer-interface-market.

Royal Society. 2019. “iHuman: Blurring Lines between Mind and Machine.” Accessed Feb. 8, 2020. https://royalsociety.org/-/media/policy/projects/ihuman/report-neural-interfaces.pdf.

Samuel, Sigal. 2019. “Elon Musk Reveals His Plan to Link Your Brain to Your Smartphone” *Vox*, July 17, 2019. https://www.vox.com/future-perfect/2019/7/17/20697812/elon-musk-neuralink-ai-brain-implant-thread-robot.

Samuel, Sigal. 2019[2]. “Facebook is Building Tech to Read Your Mind. The Ethical Implications Are Staggering” *Vox*, Aug. 5, 2019. https://www.vox.com/future-perfect/2019/8/5/20750259/facebook-ai-mind-reading-brain-computer-interface.

ScienceBlog. 2020. “Decoding Hidden Brain Conversations to Advance Neuroprostheses.” Jan. 10, 2020. https://scienceblog.com/513403/decoding-hidden-brain-conversations-to-advance-neuroprostheses.

Scully, Ruby Prosser. 2019. “A Prosthetic Leg that Attaches to Nerves Feels Like Part of the Body” *New Scientist*, Oct. 2, 2019. https://www.newscientist.com/article/2218474-a-prosthetic-leg-that-attaches-to-nerves-feels-like-part-of-the-body.

Schreiber, Darren, Greg Fonzo, Alan N. Simmons, Christopher T. Dawes, Taru Flagan, James H. Fowler, and Martin P. Paulus. 2013. “Red Brain, Blue Brain: Evaluative Processes Differ in Democrats and Republicans” *PLoS ONE* 8, no. 2.

Schwartz, Oscar. 2019. “Mind-Reading Tech? How Private Companies Could Gain Access to Our Brains” *The Guardian*, Oct. 24, 2019.

https://www.theguardian.com/technology/2019/oct/24/mind-reading-tech-private-companies-access-brains.

Sharington, Grace. 2017. "The Cost of Prosthetic Limbs: For Some Families, Diagnosis is Only the First Hurdle" Jordan Thomas Foundation. Accessed on Feb. 8, 2020. https://jordanthomasfoundation.org/true-cost-prosthetic-limbs.

Song, Victoria. 2019. "Microsoft Quietly Pulls Its Database of 100,000 Faces Used by Chinese Surveillance Companies" *Gizmodo*, June 6, 2019. https://gizmodo.com/microsoft-quietly-pulls-its-database-of-100-000-faces-u-1835296212.

Soon, Chun Siong, Anna Hanxi He, Stefan Bode, and John-Dylan Haynes. 2013. "Predicting Free Choices for Abstract Intentions." *Proceedings of the National Academies of Science* 110, no. 15: 5733–5734.

Stavisky, Sergey D., Francis R. Willett, Guy H. Wilson, Brian A. Murphy, Paymon Rezaii, Donald T. Avansino, William D. Memberg, Jonathan P. Miller, Robert F. Kirsch, Leigh R. Hochberg, A. Bolu Ajiboye, Shaul Druckmann, Krishna V. Shenoy, and Jaimie M. Henderson. 2019. "Neural Ensemble Dynamics in Dorsal Motor Cortex during Speech in People with Paralysis" *eLife*, Dec. 10, 2019. https://elifesciences.org/articles/46015.

Steinert, Steffen and Orsalya Friedrich. 2020. "Wired Emotions: Ethical Issues of Affective Brain–Computer Interfaces" Science and Engineering Ethics 26, no. 1: 351-367.

Strom, Stephanie. 2019. “Algorithm May Improve Brain-Controlled Prostheses and Exoskeletons” *TechXplore*, Nov. 19, 2019. https://techxplore.com/news/2019-11-algorithm-brain-controlled-prostheses-exoskeletons.html.

Synchron. n.d. Accessed Feb. 8, 2020. https://www.synchronmed.com/stentrode.

Technical University Munich. 2019. “Biologically-Inspired Skin Improves Robots' Sensory Abilities” *TechXplore*, Oct. 10, 2019. https://techxplore.com/news/2019-10-biologically-inspired-skin-robots-sensory-abilities.html.

Tournas, Lucille M. and Walter G. Johnson. 2019. “Elon Musk Wants to Hack Your Brain” *Slate*, Aug. 5, 2019. https://slate.com/technology/2019/08/elon-musk-neuralink-facebook-brain-computer-interface-fda.html.

Tullis, Paul. 2019. “The US Military is Trying to Read Minds” *MIT Technology Review*, Oct. 16, 2019. https://www.technologyreview.com/s/614495/us-military-super-soldiers-control-drones-brain-computer-interfaces.

United States Conference of Catholic Bishops. 2018. *Ethical and Religious Directives for Catholic Health Care Services, 6th Ed.*

University of Washington Health Sciences. 2019. "Scientists Can Now Manipulate Brain Cells Using Smartphone" *ScienceDaily*, Aug. 5, 2019. https://www.sciencedaily.com/releases/2019/08/190805143525.htm.

U.S. Food and Drug Administration. 2019. "FDA Informs Patients, Providers and Manufacturers about Potential Cybersecurity Vulnerabilities for Connected Medical Devices and Health Care Networks that Use Certain Communication Software." Accessed Feb. 8, 2020. https://www.fda.gov/news-events/press-announcements/fda-informs-patients-providers-and-manufacturers-about-potential-cybersecurity-vulnerabilities.

U.S. Food and Drug Administration. 2019[2]. "Digital Health Software Precertification (Pre-Cert) Program." Accessed Feb. 8, 2020. https://www.fda.gov/medical-devices/digital-health/digital-health-software-precertification-pre-cert-program.

Volkmann Jens, Christine Daniels, and Karsten Witt. 2020. "Neuropsychiatric Effects of Subthalamic Neurostimulation in Parkinson Disease" *National Review of Neurology* 6, no. 9: 487-498.

Weinberger, Sara and Dov Greenbaum. 2016. "Are BMI Prosthetics Uncontrollable Frankensteinian Monsters?" *Brain–Computer Interfaces* 3, no. 3: 149–155.

Wilson, Clare. 2019. "A Mind-Controlled Exoskeleton Helped a Man with Paralysis Walk Again" *New Scientist*, Oct. 3, 2019. https://www.newscientist.com/article/2218863-a-mind-controlled-exoskeleton-helped-a-man-with-paralysis-walk-again.

Won, Min, Enming Song, Jonathan T. Reeder, and John A. Rogers. 2020. "Emerging Modalities and Implantable Technologies for Neuromodulation" *Cell* 181, no. 1: 115-135.

World Bank. 2019. "Disability Inclusion." Accessed Feb. 8, 2020. https://www.worldbank.org/en/topic/disability.

Wu, Shiyi, Xiangmin Xu, Lin Shu, and Bin Hu. 2017. "Estimation of Valence of Emotion Using Two Frontal EEG Channels" In *2017 IEEE International Conference on Bioinformatics and Biomedicine*, 1127–1130.

Zhang, Jing, Tao Wang, Chen-cheng Zhang, Kristina Zeljic, Shikun Zhan, Bo-min Sun, and Dian-you Li. 2017. "The Safety Issues and Hardware-Related Complications of Deep Brain Stimulation Therapy: A Single-Center Retrospective Analysis of 478 Patients with Parkinson's Disease" *Clinical Interventions in Aging* 12: 923-928.

Zhang, Xiao, Dongrui Wu, Lieyun Ding, Hanbin Luo, Chin-Teng Lin, and Tzyy-Ping Jung. 2020. "Tiny Noise Can Make an EEG-Based Brain-Computer Interface Speller Output Anything" *arXiv*, Feb. 6, 2020. https://arxiv.org/abs/2001.11569.

Zion Market Research. 2019. "Global Artificial Limbs Market Will Reach USD 2,758 Million by 2025." Feb. 18, 2019. https://www.globenewswire.com/news-release/2019/02/18/1733678/0/en/Global-Artificial-Limbs-Market-Will-Reach-USD-2-758-Million-By-2025-Zion-Market-Research.html.