Trends in Cognitive Sciences

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Opinion

Mind Reading and Writing: The Future of Neurotechnology

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Recent advances in neuroscience and technology have made it possible to record from large assemblies of neurons and to decode their activity to extract information. At the same time, available methods to stimulate the brain and influence ongoing processing are also rapidly expanding. These developments pave the way for advanced neurotechnological applications that directly read from, and write to, the human brain. While such technologies are still primarily used in restricted therapeutic contexts, this may change in the future once their performance has improved and they become more widely applicable. Here, we provide an overview of methods to interface with the brain, speculate about potential applications, and discuss important issues associated with a neurotechnologically assisted future.

Highlights

Advanced methods to record brain activity make it increasingly possible to access an individual's mental processes (i.e., to 'read their mind'). The information that is directly extracted from the brain can be used to control devices, artificial limbs, or obtain knowledge of (hidden) intentions.

Methods to stimulate the brain with electrical currents, optogenetics, and other methods are routinely used to probe causal relations in the brain and to restore dysfunctional neural circuits. These methods can also be used to 'write to the mind' (i.e., to feed information directly into the brain).

Neurotechnologies to read from, and write to, the brain might be combined in a single individual to create 'augmented cognition' with increased processing capacity and an enhanced cognitive repertoire. This potential methodology also raises some important ethical questions.

Neurotechnology between Science and Fiction

The possibility to influence the mind through advanced technology has long inspired science fiction writers and scenarists. The 1932 novel *The Affair of the Brains* [1] described multiple brains wired up to create a superintelligence that surpasses individual capacities. Movies such as *The Matrix* (1999) or the more recent *Black Mirror* series (2014) include similar ideas of neurotechnology mixed with virtual reality and artificial intelligence. In 1932, neuroscience was a relatively young field, but recent advances aimed at treating a variety of brain disorders have brought many of the once fictional technologies into the realm of science.

Symptoms of Parkinson's disease or psychiatric disorders, for instance, can already be greatly reduced with electrical stimulation of deep brain nuclei, while advanced **brain–computer interfaces** (BCIs, see Glossary) allow patients with paralysis to control a computer directly with their brain activity. While both our understanding of the brain and the availability of neurotechnologies increase, one may wonder what will be possible in the near and more distant future. In this opinion, we give an overview of the current status of neurotechnology and speculate about future developments. We first describe several techniques to extract information from the brain and transmit information to it. We then review recent and possible future applications that combine reading and writing and discuss how these developments may eventually lead to human cognitive enhancement. Several practical, ethical, and legal implications of directly interfacing with the human mind are also highlighted.

In the context of this opinion, we use the term 'mind' when reviewing how BCI users perceive imposed patterns of brain activity and how they intentionally control actuators. BCIs thereby provide insight into the relation between neuronal activity and psychological processes, although BCIs are also used to interface with nonconscious brain processes.

Reading the Mind

It is increasingly possible to record the activity of many nerve cells using invasive and non-invasive methods, gain access to ongoing thought processes, and 'read the mind' of humans

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and animals. Non-invasive methods to measure brain activity include **electroencephalography** (EEG), functional **magnetic resonance imaging** (fMRI) [2], and, more recently, **near-infrared spectroscopy** [3] (Figure 1A). Although the rate of information transfer is relatively small in EEG-based BCIs, it can be increased by using sensory stimuli that elicit recognizable features in the EEG signal, such as the steady-state visually evoked potential (Figure 1A) [4]. Using fMRI signals from early visual cortex, researchers can reconstruct the visual image that a participant perceives [5]. Importantly, with similar approaches, patients thought to be in a vegetative or minimally conscious state have been demonstrated to understand and respond to instructions [6–8]. When asked to imagine playing tennis, they activated their supplementary motor area (SMA), whereas their parahippocampal place area (PPA) was activated when they were asked to imagine walking around in their house [8].

An obvious limitation of using fMRI to measure brain activity is that subjects have to be in the scanner. BCI research aims to construct practical assistive devices that can help people with disabilities by directly interfacing with the brain (Figure 1B). In recent years, substantial progress has been made with invasive BCIs that require brain surgery. One important domain for invasive BCI is the assistance of people with paralysis, for instance by implanting subdural electrodes that lie over the cortex [9,10]. These electrodes provide a reliable, but relatively low-bandwidth readout of the local EEG. Higher bandwidths are obtained with electrode arrays that are inserted into cortex to record neuronal spiking activity. This approach makes it possible to decode the intention to move an arm or hand in a particular direction from spiking activity in motor and parietal cortices [11–13]. Monkeys could learn to use such a BCI to control a robotic arm and feed themselves without moving their own arms [12]. Furthermore, monkeys could regain control over their own arm when decoded movement intentions were used to electrically stimulate their pharmacologically paralyzed arm muscles [14]. Similar electrode arrays were also implanted in the parietal or motor cortex of patients with severe paralysis. Signals from these electrodes enable decoding of movement intentions [15,16] and they can be used to control a robotic arm for skilled movements, such as bringing a cup to their mouth [17]. In one patient, the recorded signals were used to control muscle stimulators, reinstating control of his own wrist and hand and allowing him to perform daily tasks [18]. These BCI methods aim to restore motor control by targeting brain regions representing low-level and higher-level motor commands. In principle, these methods are equally applicable to sensory and association cortices, where they could be used to read the neural codes related to what a subject perceives [19], attends [20–23], or will decide [22].

Someone's thoughts can also be decoded from the activity of so-called '**concept cells**'. These cells were discovered in the medial temporal lobe of patients implanted with electrodes to localize the brain regions that cause their pharmacologically intractable epilepsy [24]. Concept cells represent abstract concepts, such as a particular person or place, and become active when the individual sees a picture of the concept [25], thinks about the concept [26], or retrieves it from memory [27]. Given that these results were obtained by recording a single cell or a handful of neurons at any one time, there appears to be a great promise for the precision with which thoughts might be monitored if researchers could record the activity of larger numbers of concept neurons. The extraction of complex intentions could then be used to enhance BCI-based communication protocols that are currently tested in patients with locked-in syndrome [9].

In humans and monkeys, electrode arrays can record from up to a few hundreds of neurons at the same time. Recently developed high-density probes increase this number of simultaneously monitored neurons significantly [28], but advances in optical cellular imaging technology even

Glossary

Augmented cognition: expansion of the intrinsic processing capacity of the brain, for instance by providing external memory storage, or by tapping into external sources of information, such as the internet. These methods benefit from combined reading and writing operations for bi-directional communication.

Brain–computer interface (BCI): general term for any technology that communicates directly with the brain, either to extract information from it, or to inject information into it by means of brain stimulation [138].

Concept cell: neurons in the medial temporal lobe of the (human) brain that encode a highly specific abstract concept, such as a person or a building [24,25].

Deep brain stimulation (DBS): neurosurgical procedure in which electrodes are chronically implanted into the brain to allow stimulation of deep brain structures. The procedure is used as a treatment of treatment-resistant movement and neuropsychiatric disorders.

Deep neural networks: a class of machine-learning algorithms comprising multiple layers of processing units that extract and transform information at multiple levels of abstraction. By training the network on data with a known interpretation, the network learns a set of interpretation rules, which it can then apply to new data.

Electroencephalography (EEG): a non-invasive method to record the electrical activity of the brain with electrodes placed on the scalp.

Focused ultrasound stimulation (FUS): a non-invasive neuromodulation method that focuses a beam of high-frequency soundwaves to coincide at a particular location in the brain to influence neuronal activity.

Genetically encoded calcium indicators (GECIs): fluorescent proteins that indicate the level of calcium inside a cell or tissue with variations in fluorescence. The genes encoding GECIs can be transfected into cells or expressed in transgenic animals.

Magnetic resonance imaging (MRI): a non-invasive brain imaging method that uses a combination of go beyond this by several orders of magnitude (Figure 1C) [29]. Every action potential causes an influx of calcium into the neuron, which can be optically measured in neurons that express **genetically encoded calcium indicators** (GECIs) [30,31]. In mice, replacing part of the skull with a glass window permits recording from more than a million neurons in a single animal [29]. Although many studies use transgenic mice the neurons of which constituently express GECIs, engineered viruses can also be used to deliver a genetic construct that induces expression in nontransgenic animals. Similar viral delivery methods are already used in humans for gene therapy [32]. Notwithstanding the technical challenges related to virus technology, optical access to the tissue, and the application of high precision microscopes that will have to be overcome, these and other methods might make it possible to record from millions of neurons in a human in the future.

The interpretation of activity patterns from such large numbers of neurons can be challenging. Neural decoding approaches aim to extract information from neural activity and either reconstruct the event or stimulus that gave rise to it or predict the actions that will be evoked by it. While traditional linear decoding approaches are already relatively successful [33] and continue to be improved [34], recent advances in machine learning have yielded decoding approaches based on neural networks that extract even more information [35,36]. For instance, **deep neural networks** (DNNs) have been used to interpret activity patterns elicited by complex visual stimuli [37,38] and predict the activity of nerve cells to new stimuli with remarkable precision. In DNNs, lower layers generally represent simple features and higher layers conceptual information. These different layers of a DNN can be mapped onto different brain areas. Higher DNN layers can then be used to decode the semantic information on the user's mind, while lower layers provide access to lower-level percepts (Figure 1D) [38,39].

Advances in recording and decoding of neural activity may allow future researchers to read the human mind and reveal detailed percepts, thoughts, intentions, preferences, and emotions. BCIs for patients with paralysis will benefit from new methods to decode higher-order plans and abstract thoughts. However, they may also open the door for brain spying: the reading of thoughts without a subject's consent. Measures will have to be taken to ensure that BCIs do not violate an individual's privacy (Box 1).

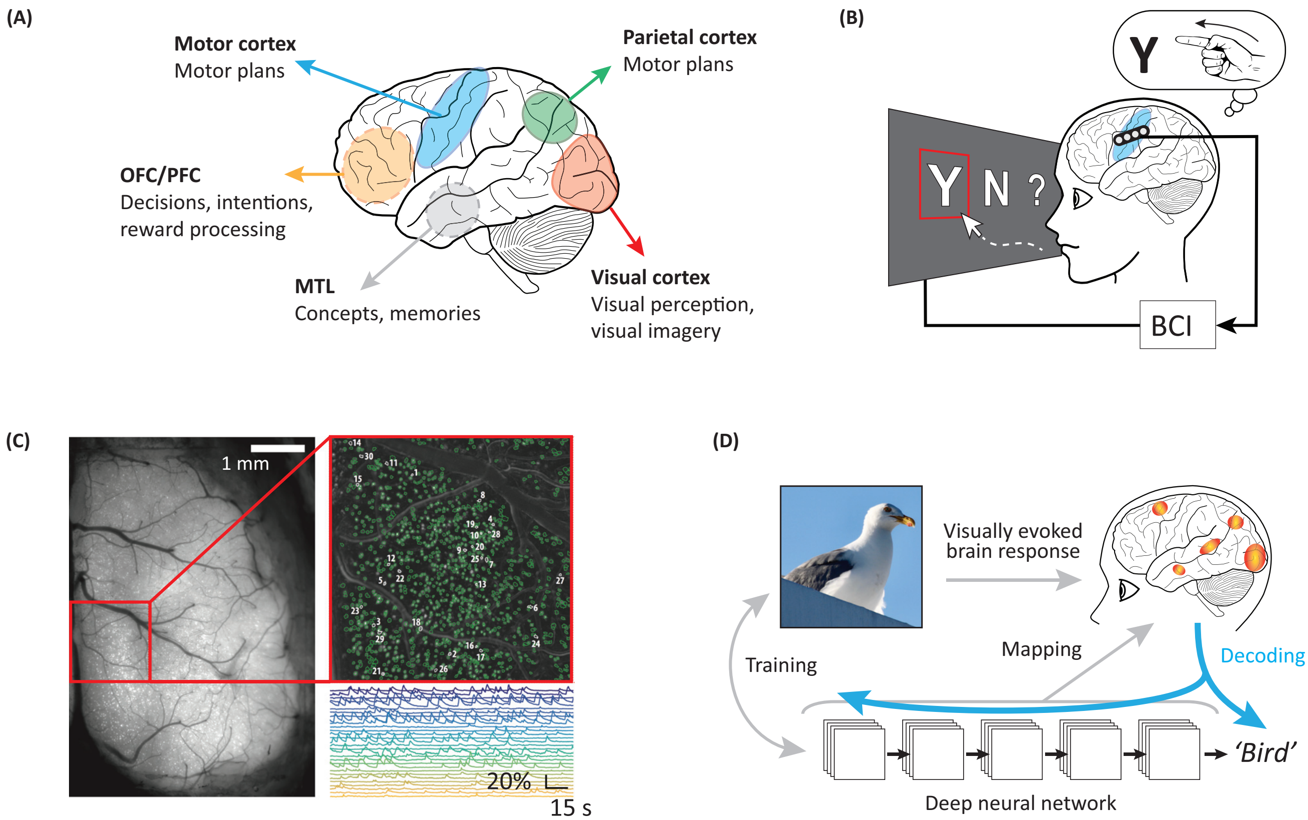
Writing to the Mind

The available technologies for influencing neural activity are rapidly expanding. Several non-invasive methods exist to influence brain activity, such as **transcranial magnetic stimulation** (TMS) [40], **transcranial direct current stimulation** (tDCS) [41], and **focused ultrasound stimulation** (FUS) [42]. However, the spatial resolution of these methods is limited and the exact manners in which they influence brain activity remain to be clarified. Here, we focus on invasive methods to precisely influence neuronal activity.

In the peripheral nervous system, cochlear implants that electrically stimulate the inner ear have become a mainstream treatment for deafness [43]. The first steps have also been taken to restore vision in patients with a damaged retina, either by electrical stimulation of surviving cells with retinal chips [44], or by chemical or **optogenetic stimulation** methods aimed at restoring the light sensitivity of the retina [45,46]. Progress has furthermore been made in equipping upper limb prostheses with an artificial sense of touch that can be directly transmitted to the remaining peripheral nerves with electrical stimulation [47].

Sometimes, artificial sensory information cannot be fed to the brain through the peripheral nervous system. This is, for instance, the case for blind individuals with too severely damaged

strong magnetic fields, electric field gradients, and radio waves to measure the composition of biological tissue and derive its structure or function.
Near-infrared spectroscopy (NIRS): a non-invasive brain imaging technique that uses light transmission and absorption to measure changes in blood oxygenation levels of (the outer parts of) the brain.
Optogenetic stimulation: technique in which light is used to control cellular activity [139]. It involves neurons that are genetically modified to express light-sensitive ion channels or pumps that can be opened or closed with light of specific wavelengths.
Transcranial direct current stimulation (tDCS): a non-invasive brain stimulation method in which a low constant direct current is applied to electrodes on the skull to evoke current flow in the underlying brain tissue.
Transcranial magnetic stimulation (TMS): a non-invasive brain stimulation technique that uses a changing magnetic field outside the skull to generate a relatively localized electric current in the brain via electromagnetic induction.



Trends in Cognitive Sciences

Figure 1. Mind Reading. (A) Different mental processes can be decoded from brain activity in a range of areas (colors). Motor plans can be decoded from sensorimotor cortex (S1/M1) [140] and posterior parietal cortex (PPC) [141], visual percepts and visual imagery from primary visual cortex and other visual areas (V1+) [142], and decisions, intentions, and reward from prefrontal (PFC) and orbitofrontal cortex (OFC) [143–145]. In the medial temporal lobe (MTL), 'concept cells' represent abstract concepts, such as individuals and landmarks [24]. (B) Neural activity associated with imagined hand movements can be decoded from sensorimotor cortex and used by a brain–computer interface (BCI) to move a cursor, allowing patients with paralysis to communicate by selecting letters on a screen [9]. (C) In rodents, it is possible to optically read the activity of up to 1 million neurons [29]. Cells in the cortex (left) are labeled (green; top right) and their activity can be monitored (bottom right). (D) If deep neural networks (DNNs) are trained to classify images, the lower layers represent simple features and higher layers represent conceptual information. With an additional training step, the DNN can also be used to decode information from activity patterns across many neurons or voxels in functional magnetic resonance imaging (fMRI). Higher DNN layers can now be used to determine semantic information present in the picture, and lower layers to reconstruct the visual input that gave rise to the activity pattern (blue arrows) [38,39]. Adapted from [29] (C).

retinas or optic nerves. For these patients, researchers have had the longstanding dream to directly impose activity patterns onto the visual cortex with electrical stimulation [48–52]. Pioneering studies during the 1960s and 1970s implanted stimulation electrodes over the surface of the visual cortex [48,49], while later work used intracortical electrodes [50] to activate a sparse subset of neurons a few tens of micrometers around the electrode [53]. In primary visual cortex, which contains a 2D map of the visual field, stimulation evokes the perception of little spots of light (called phosphenes) at the corresponding position in this map, with sizes ranging from a pinpoint to a nickel at arm's length [50,54]. A visual cortical prosthesis would use multiple electrodes and stimulate patterns of neurons to build rudimentary visual percepts, pixel by pixel, or phosphene by phosphene (Figure 2A). In higher visual cortical areas, microstimulation elicits or biases more specific percepts, such as motion or depth from stimulation in area MT/V5 [55,56], and the shape of faces [57,58] or the spatial layout of scenes from stimulating the temporal cortex [59,60]. Similarly, for patients lacking a functional auditory

Box 1. Practical and Legal Aspects of Neurotechnology

Non-invasive brain-reading methods, such as fMRI, are used by neuromarketing companies to guide product development and advertising [122]. While fMRI might also detect lies and deception [123,124] better than conventional polygraph tests [125], its reliability is debated [126,127]. The potential reading of unconscious or hidden brain information for commercial purposes or criminal justice cases should be evaluated both legally and ethically.

Benefits of invasive BCIs should be carefully weighed against their risks and costs. For patients who regain impaired functionality, these benefits are large, but for healthy humans aiming to enhance their mental capacity, they are considerably smaller. Allowing machines to access our brain also raises issues of mental ownership [128], liability [129], privacy, and safety [130,131].

Any application that interprets or uses brain activity requires some understanding of the neural code. For relatively simple brain functions, such as perception or movement generation, important aspects of this code are known [132], but for more complex mental operations, such as memory or abstract thought, they are not. Recent progress with deep neural networks in machine learning suggests that it might even be possible to extract information from brain activity patterns without explicit knowledge of the neural code [37]. However, such algorithms need to be trained on independent data with known information content, which limits their real-time applicability.

Let us assume that neurotechnology advances to a point where safe and high-bandwidth brain interfaces become available for which the nontherapeutic benefits outweigh the risk and discomfort associated with required surgical procedures. For whom should such technology be available? With substantial costs, availability might be limited to governmental organizations, such as the department of defense, and the happy few that can afford it. This could cause a dichotomy in society between those that can afford neurotechnology and those that cannot.

Are humans responsible for augmented decisions? New laws should define the legal status of mental processes and assign liability in case things go wrong [129]. A recent review suggested that human rights need to be expanded to incorporate cognitive freedom. In this view, every human should have a basic right to not have their mental processes read out from neural activity without explicit approval (right to mental privacy); to not have anyone or anything interfere with their neural computations (right to mental integrity); and to not have their personality or mental identity altered, such as by implanting false memories (right to psychological continuity) [128].

nerve, a new approach in the central nervous system targets the cochlear nucleus in the brainstem [61,62]. Discriminable tactile sensations have also been evoked by stimulation of the somatosensory cortex of nonhuman primates [63]. Future prostheses could aim to conjointly activate multiple brain areas to evoke richer, more detailed sensations. For instance, low-level percepts elicited in lower areas could be complemented with semantic features elicited in the higher areas.

Writing information directly to higher order cortices of, for example, the parietal and temporal cortex, will require both a detailed understanding of how complex thoughts are encoded in brain activity and the technical capabilities to evoke such refined activity patterns (Box 1). A possible downside of stimulating higher brain areas is that activation of these regions may exert direct control over a subject's emotional state [64] and behavior. Control over behavior is evident in the motor cortex, where stimulation elicits both simple and more complex movements [65,66], but it is also possible to trigger complex behaviors in other brain structures [67]. For example, a recent study using optogenetic stimulation of the amygdala in mice demonstrated the possibility to activate behavioral programs, such as the pursuit and attacking of prey [68]. Similarly, feeding, drinking, and sexual behavior of rodents and other animals can be steered by stimulation of the hypothalamus and surrounding regions [69–73], with more recent studies starting to dissect the underlying circuits using optogenetics [74,75]. Higher cognitive functions, such as attention and memory, can also be influenced. For example, stimulation of the superior colliculus, parietal cortex, or frontal eye fields [76–78] modulates spatial attention. These brain regions contain maps of visual space and stimulation summons attention to the spatial region that is represented by the activated cells. Furthermore, the classic work of

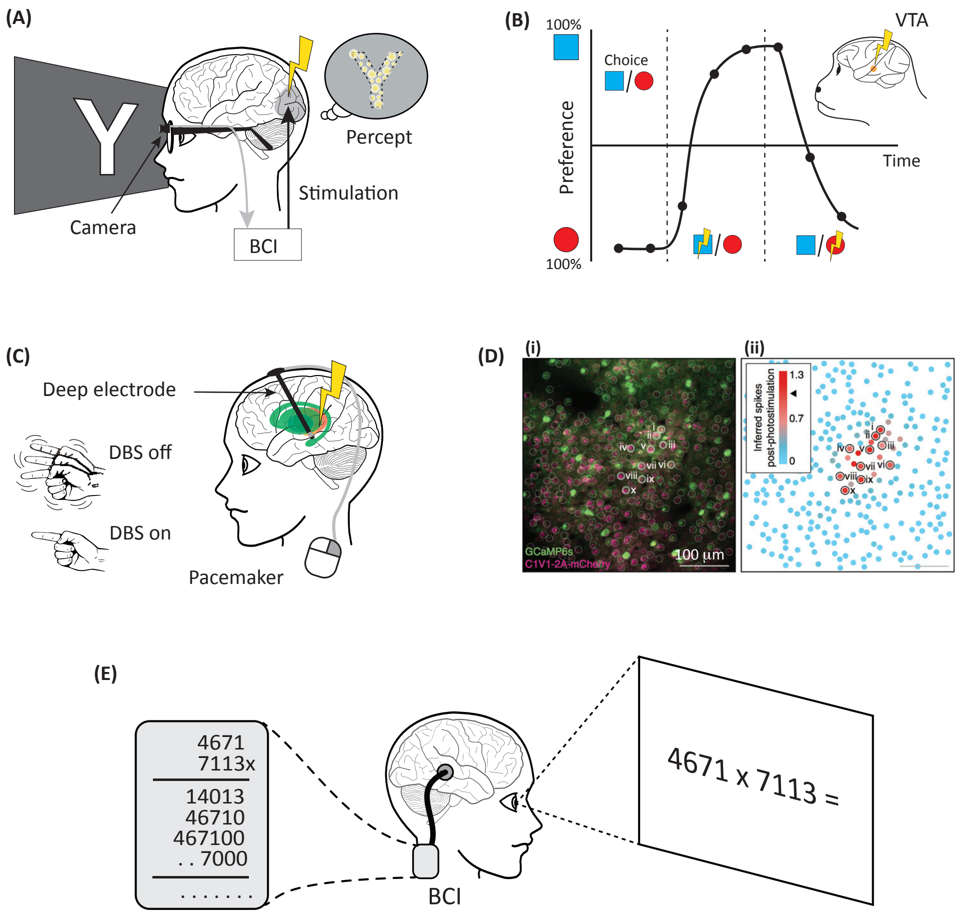


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Figure 2. Mind Writing. (A) Visual prostheses can evoke visual percepts directly in the brain. Visual information is captured by a camera mounted on a pair of glasses, processed by a brain–computer interface (BCI) and translated into stimulation patterns that are inserted into cortex through multielectrode arrays. Each stimulation electrode evokes a phosphene, the percept of a small dot of light. Together, selected stimulation electrodes create groups of phosphenes that can be positioned to convey meaningful visual input. (B) Stimulation of the ventral tegmental area (VTA) biases decisions in macaques [85]. When given the choice between two equally rewarding stimuli (blue square/red circle), monkeys develop a preference for one of the two (e.g., the circle). If the nonpreferred stimulus is paired with VTA stimulation, their preference quickly switches to the target associated with stimulation. (C) In deep brain stimulation (DBS), a stimulation electrode is implanted into deeper parts of the brain, usually the basal ganglia, and current is delivered by an implanted pacemaker. In Parkinson's disease, DBS of the subthalamic nucleus eliminates essential tremor [146]. (D) Simultaneous calcium imaging and optogenetic stimulation demonstrates how it is possible to evoke precise activity patterns. Simultaneous stimulation of ten cells in the mouse barrel cortex [(i) i–x] evokes responses in all stimulated cells (ii). (E) Future BCIs might expand our limited working memory capacity to enhance mental operations, such as the multiplication of two four-digit numbers. Panel D adapted, with permission, from [97].

Penfield demonstrated that electrical stimulation of the temporal lobes elicited vivid recollections of memories of a patient's past [66,79].

If it is the goal of a sensory prosthesis to elicit percepts without infringing on the user's autonomy, sensory brain regions appear to be the most suitable stimulation target. However, some BCI applications aim to influence behavior instead. One example is the aim to increase eating in patients with anorexia nervosa [80]. In such cases, influencing the activity of the relevant higher-order brain regions can be considered. A versatile method to indirectly influence behavior is the activation of neurons that process rewards and punishments [81–83]. Researchers can reinforce desired behavior of mice and monkeys by activating dopamine neurons in the ventral tegmental area or nucleus accumbens [84–87] (Figure 2B), and inhibit undesired behavior by activating circuits that mediate aversion, for example in the lateral habenula [88,89]. However, applying these methods to humans requires careful consideration of costs and benefits, because they may interfere with the freedom to make one's own choices (Box 1).

The therapeutic potential of brain writing is exemplified by the success of **deep brain stimulation** (DBS) in treating symptoms of Parkinson disease [90] (Figure 2C). Clinical trials have also explored DBS for the treatment of psychiatric disorders, such as depression [91,92] and obsessive-compulsive disorder (OCD) [93]. Current stimulation patterns for DBS are relatively crude because of the large surface areas of the contact points of the electrodes, but future technical developments may increase this precision and enhance the therapeutic benefits while reducing the risk of adverse effects [94,95].

Brain-writing methods may also capitalize on optogenetics and make specific cell populations sensitive to light [96]. Combined with innovative methods of light application, such methods allow activation of specific subsets of individual neurons [97] (Figure 2D). These methods currently rely on bulky two-photon microscopes that are impractical for clinical use. However, wearable single-photon microscopes have already been developed [98], and it is conceivable that increases in the precision, quality, and bandwidth of optical methods will enhance their therapeutic potential in the near future.

Reading and Writing Combined

Powerful new BCI applications may include both reading and writing operations. The advantage would be that writing operations can be made conditional upon the current state of the brain. For example, this approach has been used to increase control over a robotic arm by reading movement commands from the motor cortex, and sending haptic feedback signals from the robotic arm directly to the somatosensory cortex with microstimulation [99]. These writing operations provide feedback about the touched objects and increase the precision of control over the robotic arm.

Closed-loop DBS, for which stimulation depends on concurrently monitored brain activity, is another illustration of the utility of combined brain reading and brain writing. In Parkinson's disease, for instance, oscillations in the local field potential of the subthalamic nucleus (STN) give real-time information of a patient's clinical state [100,101]. These oscillations can be used to control the settings of the electrical stimulator and limit stimulation to only those time periods when interference is necessary [102]. This limitation increases battery life and reduces the occurrence of potential adverse effects. Similar applications are considered for OCD. Here, symptom provocation both induces theta oscillations (3–8 Hz) in the striatum and medial frontal cortex (mFC), and increases frontostriatal functional connectivity [103]. Future DBS applications might use these oscillations as a trigger signal for stimulation. With increasing knowledge about the specific neuronal activity patterns associated with obsessive thoughts, future devices might even detect such thoughts and trigger stimulation when appropriate.

Closed-loop brain stimulation is also used to detect the early onsets of epileptic seizures in monitored brain activity and interrupt them with electrical stimulation of, for example, the anterior thalamus or deep cerebellar nuclei, before the seizures become generalized [104–106].

Recently, similar approaches were used to detect brain states associated with poor memory and to respond to them with stimulation of the temporal cortex to improve memory encoding [107].

Augmented Cognition

Methods to read from, and write to, the brain have generally been developed to aid patients. The idea of enhancing the cognitive abilities of healthy individuals has remained firmly within the domain of science fiction. However, despite our still limited understanding of the neuronal mechanisms of cognition [108], the time is now ripe to consider both the potential and downsides of '**augmented cognition**' driven by directly interfacing with the brain. Elon Musk, a prolific entrepreneur who recently started a BCI company, has suggested that such a research program is necessary for humans to keep up with advances in machine intelligence. Machines have already started to surpass human intelligence in several domains [109,110]. Computer programs beat the best human players in games such as chess, Go, and Jeopardy [111,112], while advances in deep neural networks endow machine vision systems with several capabilities that are at least on par with human vision [113]. Let us briefly put present technical limitations aside and assume that future researchers will develop safe methods to read from, and write to, millions of neurons in the human brain. Could this technology indeed be used to improve cognition, and if so, how? Would such technology even be desirable?

We highlight a few domains where future BCI devices might enhance cognition, but we admit that our short list is far from complete. A first domain to consider is working memory. Human cognition is limited by the amount of information we can maintain while performing a task [114,115]. Consider, for example, how difficult it is for most of us to multiply two four-digit numbers. We typically solve this task by writing down intermediate results on a piece of paper, which is thus essentially used as external memory. A BCI system could connect neurons to an external memory store in a computer, allowing users to offload intermediate computational results with a brain-reading operation and access them later with a brain-writing operation when necessary (Figure 2E). External memory could enhance human cognition in other domains as well, for example by permitting entirely new problem-solving strategies that take advantage of the expanded memory. It is even conceivable that (parts of) complex computations might be offloaded to an external processor giving users direct access to the final answer. In our example, the final result of the multiplication could, for instance, be written to the brain. The possible scope of hybrid computations, with parts taking place in the brain and other parts in an assistive device, are likely to expand when our understanding of the neuronal codes for abstract thoughts in the human brain increases. Furthermore, the enhancement of long-term memory would help us with our generally poor recollection of past events. A BCI could record a user's experiences or thoughts and store them externally, where they might be retrieved days, months, or even years later with the same amount of detail they were recorded with. Associations between concepts, such as between faces and names or between environments and events, could also be maintained externally.

In an extension of the types of sensory neuroprosthesis already in use, BCIs could also increase the depth of sensory processing, supplement it with relevant information, and help prioritize the most relevant parts of it (Box 2). BCIs that read sensory codes and write to motor-planning regions might even enable users to carry out tasks that would normally require extensive training (the main character in the movie *The Matrix* uses such functionality to download a control program to fly a helicopter). Entirely new forms of communication might be possible through neurotechnology if the thoughts of one person could be made accessible to another person in their native neural format or other form [116]. With an advanced understanding of the

Box 2. Augmented Vision

In visual perception, only a few of the objects in any given scene can be attended at once. Attended objects are processed up to the semantic level, whereas nonattended objects are filtered out at earlier processing stages [133]. A BCI with access to early sensory representations could process unattended items to a deeper level and direct the user's attention to them if it labels them important. For example, if a driver fails to notice a dangerous situation (e.g., a crossing pedestrian), a BCI could detect the dangerous situation, summon attention, and direct it to the danger, and avoid a collision. With access to experiences from many users combined, BCIs might even learn to detect important situations that, on average, occur only once in a lifetime.

The use of collective experiences might be possible through a link with the internet. Such connectivity could give a user's brain direct access to seemingly endless amounts of information. The users could ask for information with a brain-reading operation while the retrieved information could be uploaded using a brain-writing operation. For example, neural activity evoked by looking at faces might be used to perform a search on the internet and provide the user with a name that belongs to the face (Figure I). Clearly, such applications would need to demonstrate an advantage over conventional internet use on a computer or smartphone, but it is not inconceivable that search engines could develop codes that make direct internet access from the brain more efficient. However, such technology will need to define levels of sharing, similar to the mechanisms that are currently implemented on social media platforms, such as Facebook. This will allow users to keep some of their experiences and thoughts private, share some within defined user groups, and broadcast others to an entire user community.

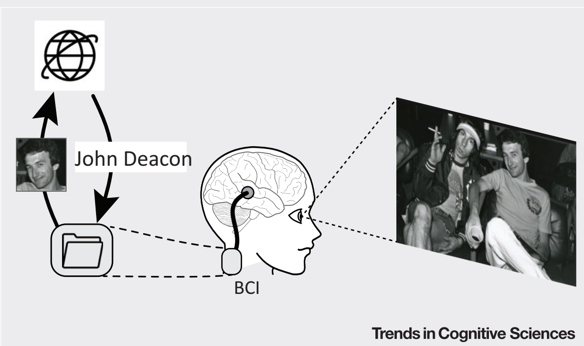

Figure I. Augmented Vision. With access to the internet, brain–computer interfaces (BCIs) could assist a user by retrieving information relevant for the current situation, for example, about visible faces.

neural code, such BCI telepathy could communicate complex or abstract concepts more efficiently and in more detail than traditional communication means, such as speech and writing. However, in such a scenario it will be essential that users can choose what information they share and what they keep private.

It is an important philosophical question how BCIs impact a user's conscious experience. Will processing steps that take place outside our brain feel like they are part of our own thoughts or will they evoke a sense of 'externalness'? Take the example of multiplying two numbers. Is it necessary for a user to go through all steps for the subjective experience of doing the calculation or would it suffice to simply write the outcome to their brain? Theoretical models of consciousness [117,118] argue that the possibility of sharing conscious experiences between brains and computers should strongly depend on the bandwidth and type of connectivity. While the belief that consciousness is tied to the biological substrate of the brain is common, the boundary conditions for consciousness to emerge inside or outside a brain are not known [119]. Important insights have been obtained from research in patients with split brains, where cutting fiber connections between the two hemispheres caused conscious experience to be split [120], at least transiently. However, recent research suggests that consciousness 'reunites' over time after the surgical procedure [121]. Could a similar reorganization of consciousness occur if part of the processing is done externally?

Concluding Remarks

The benefits of novel technologies that read from and write to the brain are evident when they restore impaired functions in patients. With recent advances in neuroscience and engineering, it is likely that we will soon see more sophisticated sensory prostheses and more efficient BCIs for the control of prosthetic limbs or computers. In the longer term, these applications may have farther-reaching consequences. It is of scientific interest to ask how such methods can be used to augment the cognitive functions of healthy individuals. Future BCI applications for augmented cognition face a high bar because smartphones and computers already enhance cognition in a non-invasive manner. Similarly, car manufacturers develop systems that detect dangerous situations, while self-driving cars may take away the necessity of learning to drive altogether. A limitation of these technologies is the bandwidth of human–computer interactions: it takes time to either type messages or comprehend what is displayed on a computer screen. Cognitive enhancements through BCIs will be most effective when they increase the bandwidth of information transfer from and to the brain.

Further development of BCI applications will first focus on alleviating disabilities and impairments. The question of whether to apply BCI for cognitive enhancement in healthy humans will become pertinent once the capabilities of patients with BCI devices start to surpass those of healthy individuals and many questions will have to be addressed before that time arrives (see Outstanding Questions). This leap from coarse neurotechnological assistance to sophisticated cognitive enhancement will not only rely on technological advances. A detailed understanding of the neural code in all its complexity is perhaps even more important. When communicating directly with the brain, it is crucial that the amount of information that is 'lost in translation' is kept to a minimum and unwanted modifications of perception, thoughts, and actions are avoided.

Finally, since many neurotechnological advances come with an implicit potential to infringe on an individual's autonomy or privacy, it would be responsible to discuss the possible ethical and legal implications before we are confronted with them (Boxes 1 and 3). This might be the right time to have that conversation.

Box 3. Ethical Consequences of Neurotechnology

There are important ethical challenges for the implementation of mind-reading and mind-writing techniques in medicine and beyond. Although higher level mind-reading or writing applications are not yet clinical practice, they are already heavily debated among ethicists and neuroscientists. A special issue of the *American Journal of Bioethics* (AJOB) *Neuroscience* entitled 'On predictive brain devices' (2015) illustrates this debate, with the main article stating that 'The inclusion and combination of predictive, advisory and automated functionalities involving permanent monitoring of brain activity in real time creates unprecedented ethical challenges, and may introduce the need for conceptual analysis that is novel.' [134].

Careful consideration of the ethical consequences of neurotechnology in humans is imperative [135]. Mind reading can lead to concerns about privacy. The user should be able to control who has access to the data. Other issues concern the user's autonomy. For example, the combination of mind reading and writing creates an autonomous loop inside the brain that is not intentionally controlled by the patient. Hence, it could interfere with a person's autonomy and alter their sense of human identity and personhood. This concern is particularly relevant for patients with psychiatric disorders whose autonomy and identity are already compromised by their disease. Therefore, it may be necessary to expand the current ethical-medical framework with specific guidelines for studies involving high-level mind reading and writing [136].

The ethical debate could take advantage of the experiences of patients [137], and develop standardized and validated tools to assess the impact of devices on the sense of autonomy. The collection of data from patients could help to identify unknown ethical issues and to design research guidelines to protect the privacy and autonomy of the recipients of future neurotechnological devices.

Outstanding Questions

How much understanding of the neural code is required for augmented cognition? While we currently have basic knowledge of how some relatively simple cognitive functions (e.g., perception) are organized in the brain, we are still far removed from understanding the neurobiological basis of other functions (e.g., complex planning and abstract thoughts).

Are the potential neurotechnological cognitive enhancements for healthy humans worth the risks of having technology connected directly to the brain? The impact of imagined technology is inherently difficult to predict. The risks of surgical procedures involving the brain do not yet outweigh the benefits of augmented cognition for healthy humans, but, in the future, risks may decrease, while the potential for benefits might increase.

How will augmented cognition influence 'mental ownership'? Physical prostheses can be mentally adopted by their owners to feel as an integral part of the body. Will a similar adoption apply to cognitive processes outside the brain? Will consciousness gradually expand to include a BCI, and what are the consequences of connecting the thought processes of multiple people together, for instance through the internet?

How can mental privacy be protected in the face of augmented cognition? This is especially relevant if BCIs of different people would connect to each other, or to the internet. With all its benefits, the internet has also brought us computer viruses, hacking, spam e-mail, phishing, and ransomware. The scenario of having someone hack into the brain, steal memories, and ask a ransom for them is currently entirely science fiction, but these issues should be addressed before the technical possibilities arise.

What are the ethical implications of advanced neurotechnology for cognitive freedom and human autonomy? With increasing possibilities of directly interfacing with the brain comes a strong need for discussion and guidelines.

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