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PERSPECTIVE

Brain–computer symbiosis

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Abstract
The theoretical groundwork of the 1930s and 1940s and the technical advance of computers in the following decades provided the basis for dramatic increases in human efficiency. While computers continue to evolve, and we can still expect increasing benefits from their use, the interface between humans and computers has begun to present a serious impediment to full realization of the potential payoff. This paper is about the theoretical and practical possibility that direct communication between the brain and the computer can be used to overcome this impediment by improving or augmenting conventional forms of human communication. It is about the opportunity that the limitations of our body's input and output capacities can be overcome using direct interaction with the brain, and it discusses the assumptions, possible limitations and implications of a technology that I anticipate will be a major source of pervasive changes in the coming decades.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

1.1. The communication problem

In their seminal articles *Man–Computer Symbiosis* [1] and *Augmenting Human Intellect* [2], Licklider and Engelbart highlighted the potential of a symbiotic relationship between humans and computers. Realizing that people spend most of their time on what essentially are clerical or mechanical tasks (i.e. the fundamental information processing bottleneck at the time they wrote their articles), they envisioned a future in which humans dynamically interact with computers such that the human devises the mechanical task to be performed, and the computer executes that task and presents the human with the results.

This vision capitalizes on the fundamental differences between the brain and the computer. The brain uses billions of cells in a massively parallel organization. Each cell represents a computing element that operates at low speeds. In contrast, a computer is comprised of billions of transistors that are mainly organized for sequential processing. Each transistor represents a computing element that operates at speeds millions of times faster than a computing element in the brain. One could thus say that the brain has a wealth of computational breadth (i.e., using parallel processing it can convert many inputs into many outputs) but little computational depth (i.e. it cannot process a long sequence of commands of a given algorithm). In contrast, a computer typically executes only a few algorithms at a time (i.e., it has little computational breadth), but can execute any particular algorithm at extremely high speed (i.e. large computational depth) (see figure 1 for an illustration of this issue). Each of these two approaches to computation naturally lends itself to different problems. For example, even two-year old toddlers are highly adept in spatial navigation, object recognition, motor planning and motor execution, and typically outperform advanced computers on these tasks. At the same time, computers are extremely efficient in computing the most complex functions with razor-sharp precision in very little time. This duality, and perhaps trade-off, between computational breadth and computational depth constitute maybe not the theoretical, but certainly the practical difference between the brain and the computer. This difference constitutes a mismatch between these two systems, which in the end hinders effective interactions. In the absence of modifying brain function to make them more similar to computers and of methods to make computers

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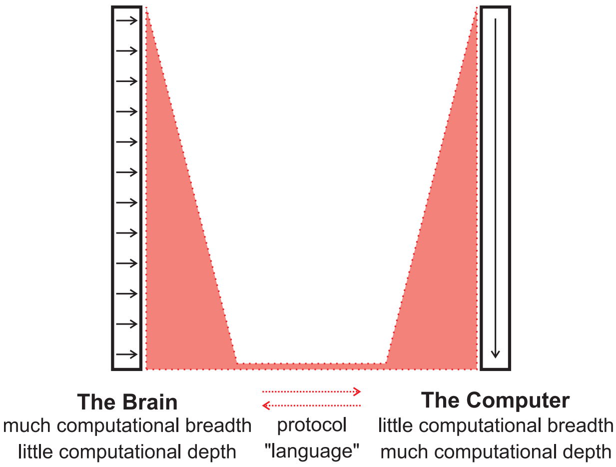

Figure 1. The systems problem. The brain can process information from many different sources in parallel (much computational breadth (horizontal arrows)), but is fairly slow in processing any particular algorithm (little computational depth). In contrast, the computer typically only processes information from few sources (little computational breadth), but is extremely fast executing any particular algorithm (much computational depth (vertical arrow)). In addition, the communication speed between the brain and the external world (indicated by the thin red communication pipe) is slow.

operate like human brains, this difference can still be useful. Donald Norman acknowledges the opportunities of these complementary approaches [3]:

> Machines tend to operate by quite different principles than the human brain, so the powers and weaknesses of machines are very different from those of people. As a result, the two together—the powers of the machine and the powers of the person—complement one other, leading to the possibility that the combination will be more fruitful and powerful than either alone.

Forty-five years after Licklider and Engelbart articulated their visions, most of the impediments to a fruitful relationship with the machine that they described (i.e., largely technical or economic hurdles) have vanished. In the age of Internet search engines, vast digital libraries and large-scale mathematical simulations, we routinely work with computers in a highly interactive fashion—we devise the task, and the computer executes it and presents us with the results. Donald Norman calls this *People propose . . . and Technology conforms* [3]. Consequently, we have overcome this *information processing bottleneck*, that is, computers now perform many of humans' clerical tasks. However, this reveals the next source of inefficiency, i.e. a *communication bottleneck*: while the brain is fantastic at distilling input and concepts into plans and the computer's ability to execute these plans continues to improve, we are confronted with the increasing difficulty of communicating these plans with the low speed supported by our nervous system.[1]

Based mainly on classic methods developed by Shannon [5] and Fitts [6], numerous studies have evaluated the communication rates between humans and humans ([7], for review) and between humans and computers ([8], for review). These studies indicate that the external information transfer rates supported by the nervous system (i.e., the rates between humans and humans, or humans and computers) are very low and for communication methods (e.g., reading, speaking, Morse code, eye tracker, mouse or joystick movements) range from around 1 bit per second to not more than 50 bits s^{-1} (see figure 2). In addition, many people with certain neurological conditions (such as amyotrophic lateral sclerosis, muscular dystrophy, cerebral palsy, or brain stem stroke) are confined to communication rates that can be even lower. In contrast, computers cannot only communicate, but also store and process information at a rate exceeding 1 terabits s^{-1} [9]. In other words, even discounting the two orders of magnitude improvement in computing technology that is predicted by Moore's law for the next decade, there already is a 12 orders of magnitude difference between the external communication capacity of the nervous system and the external and internal communication and processing capacity of the computer. Moreover, while our motor system is highly adept at controlling movement of our limbs, those limbs have been optimized to address the challenges experienced by our ancestors, but not necessarily to address the complex challenges of today. For example, our hands and fingers are adequate for the manipulation of tools, but not necessarily optimal for communication.

The context-independent nature of this communication further impedes communication. Our brain has at its disposal highly complex semantic relationships that put the input to the brain into context. However, we need to use syntactic commands void of any semantics when we communicate to a computer, which makes communication less efficient [10].

The low communication rate between the brain and the computer, the constraints of our motor system, and the communication's highly syntactic and thus context-independent nature, constitute the most fundamental inefficiencies as well as the biggest potential for improvements in human efficiency on tasks that are constrained by this low speed and the physical limits of our bodily movements. For example, a jet pilot might have to execute a number of syntactic commands in sequence (e.g., turn left and then accelerate), when it would be more efficient to communicate a semantic command (e.g., follow a particular target). Human–computer interaction, an area within computer science, has been aware of these issues and has engaged in many efforts (such as context-aware software or the Semantic Web) that attempt to address them. Because the capacity to represent and relate information constitutes a major advantage of the brain over the computer (and we thus cannot easily reproduce these capacities in a computer), and because these efforts cannot address the low communication rate of our sensory and motor system, all current corresponding efforts are thus restricted to merely alleviate the symptoms of this fundamental communication problem.

This paper lays out a proposed solution to this problem that I expect to be realized in the coming decades. The expectation is that direct communication between the brain and the computer can overcome the low rate, context independence, and/or physical constraints imposed on current means of

[1] This idea is similar to the *Theory of Constraints* (e.g., [4]) that postulates that, for example in a manufacturing plant, total system output is limited by the slowest operation in the process.

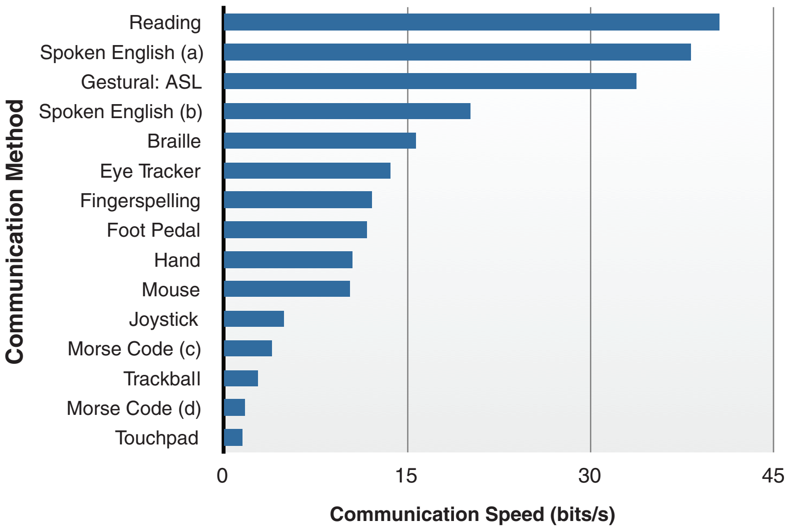

Figure 2. Comparison of communication rates between humans and the external world (sources: [7, 8]): (a) speech received auditorily; (b) speech received visually using lip reading and supplemented by cues; (c) morse code received auditorily; (d) morse code received through vibrotactile stimulation.

communicating between the brain and the computer. While this possibility has been contemplated in science fiction for some time (e.g., [11–18]), many studies over the past two decades have already demonstrated that non-muscular communication is possible and can, despite its early stage of development, already serve useful functions [19]. Thus, this paper is *not* science fiction. It is about realistic improvements to existing technology that will lead to a close and highly interactive relationship between the brain and the computer, and about the major implications of these developments.

1.2. Feasibility

As bold as the assertion of direct brain–computer communication may sound, its implementation, and all the powerful implications derived from it, merely rests on two assumptions. First, a direct interaction with the brain requires understanding of the *language* of the communication. The promise of this notion was most eloquently described by Ramón y Cajal about 100 years ago:

> To know the brain is the same thing as knowing the material course of thought and will, the same thing as discovering the intimate history of life in its perpetual duel with eternal forces, a history summarized and literally engraved in the defensive nervous coordination of the reflex, the instinct, and the association of ideas.

Second, it also requires a physical interface that can communicate the symbols of this language with the requisite clarity to and from the brain so that they can be understood the same way as if those symbols originated from within the brain.

1.2.1. Assumption 1: understanding the language. Many studies over the past decades have demonstrated that it is feasible to understand the *language* of the brain. (For the purpose of this paper, the term language refers to the set of brain signals that communicate information. A metaphor for these brain signals is the term *symbols* where each symbol is represented by an electrical, chemical, or metabolic signature, and is produced by communication primitives such as action potentials.) With these studies, it has become increasingly clear that mental faculties can be decomposed into a multitude of information-processing systems (which Minsky called *agencies* [20]) and that brain activity in these systems can be analyzed or modified to detect and change function in the associated mental faculties. For example, studies have shown that it is possible to stimulate motor or sensory areas to induce particular motor function or sensory perception (i.e. to communicate from the computer to the brain), and that it is also possible to analyze brain signals to decode motor function and sensory perception (i.e. to communicate from the brain to the computer).

Based solely on the language of the brain and its individual symbols, it thus appears feasible to interact with the brain on the basis of the mental faculties realized by these areas, even with the sensing and decoding technologies in use today. In other words, this suggests that it should be possible to decode, or produce, a clear and complete representation of the actually experienced or imagined visual, auditory, movement, language, olfactory, tactile, or taste sensations encoded by the symbols communicated within the brain. Because our plans can also be described in terms of such features [21–25], it should be possible to replace or augment the inadequate communication of an intent from the brain to the computer by an interpretation of this information, and to replace or augment the communication of these results back to the brain. (For the purpose of this paper, *intent* corresponds to the state of the brain areas that activate brain areas actually producing a particular behavior (e.g., executive functions in parietal lobe).)

The language problem can be stated as the task of determining the symbols (i.e. brain signal features) that accompany actual or imagined actions or sensations, or intended plans for action. One should not be distracted by the dramatic problems that we face understanding how brain functions encode semantic relationships and use them to produce intent. For the purpose of removing the current communication bottleneck in many tasks, it is sufficient to understand the brain's intent and not necessary to understand the ways in which the brain produces this intent. At the same time, this limited understanding of brain function will ultimately limit the possible interactions between the brain and the computer. These limitations are discussed later in this paper in section 2.3.

1.2.2. Assumption 2: an adequate interface. An efficient physical interface between the brain and the computer would effectively measure and influence the electrical or chemical properties of the brain cells in proximity to the interface to measure or induce action potential or neurotransmitter activity (section 3 later in this paper describes several possible device technologies). Studies indicate that these different types of activity have different functions in the nervous system. Electrical activity in the brain (i.e. action potentials that are produced by the cell body and communicated from the cell's axon to other adjacent neurons) is mainly responsible for communication and information processing. Chemical properties typically communicate the results of past information processing so as to produce changes in the brain that optimize future processing. For example, increased neurotransmitter production triggered by increased electrical activity may start chemical signal cascades that eventually modify gene function that modify future cell behavior.

The interface problem can be stated as the task of designing a physical structure that can interact with requisite speed, safety and sensitivity with the brain using electrical and/or chemical means. This problem is, while a complex issue that will require considerable attention, ultimately an engineering problem with clearly defined mechanical, electrical, and chemical specifications that can be expected to be solved.

1.3. Breaking the bottleneck

Breaking the communication bottleneck by adding additional communication channels from the brain to the computer could have profound implications on the way we interact with and benefit from the computer. Additional information may increase the overall communication rate and thus could provide a mechanism to increase human efficiency. Alternatively, augmented awareness about the current state of the brain could make interaction with computers a more natural experience that in the end may not differ from the way we interact with and experience our own body. For example, we might simply focus attention to an Internet link to follow it rather than producing complicated motor commands to move and click a mouse, or we might merely feel that a particular menu selection is not appropriate rather than having to learn the same by reading text on a screen. In summary, the processes that transform our intent into the actions necessary to achieve it could become simpler if we had better access to the current state of the brain.

The concept of the perfect interface that allows humans to interact with computers without performing complex arbitrary procedures has long been a matter of discussion in the usability community. Donald Norman described this concept as follows:

> A device that knows about its own environment and that of its user could transparently adapt to the situation, leading to the idea of the invisible computer as discussed by Weiser [26]. This in turn is a step toward a disappearing interface as demanded by Norman [27].

The following sections review the current state of the two requirements that are necessary to realize this vision, i.e., understanding the language of the brain and the physical interface.

2. The language of the brain

Given a suitable physical interface, one may use two different languages to communicate with the brain. First, one may communicate using the same symbols that the brain uses during its normal function (i.e., decoding information from or inducing information into the brain). Using this approach, the communication process between the brain and the computer could be faster and more efficient (because the brain's intent does not have to be translated into motor commands); it could also augment conventional communication with the context defined by information derived from the brain (see figure 3). Second, one may communicate with the brain by establishing a new mutual language, i.e. by defining a set of symbols that is not normally used by the brain to communicate information, or by associating a set of existing symbols with a new meaning (e.g., associating the amplitude of the mu rhythm in the electroencephalogram with velocity of cursor movement). This procedure creates a new communication channel that does not rely on the brain's normal output pathways of peripheral nerves and muscles [19]. Because this option does not involve our body's sensory and/or motor systems, it renders the communication process between the brain and the computer independent of the constraints of the replaced conventional system(s), and could thus be useful to people with motor disabilities, or to people who are otherwise limited by their body's communicative abilities (such as surgeons whose eyes provide them with an inadequate picture and whose hands do not have the accuracy and degrees of freedom that would allow them to perform as desired).

2.1. Using the brain's existing language

2.1.1. Decoding information from the brain. Many studies over the past decades have demonstrated that information from sensory or motor systems in the brain can be decoded to retrieve details about currently perceived sensations and executed movements, or even about the currently imagined sensations or movements. Examples have been described in the somatosensory system, visual system, auditory system, olfactory system, motor system and language system.

Somatosensory cortex represents a somatotopic map of particular sensory modalities such as temperature or touch. This map is commonly referred to as the homunculus model that was first described by Penfield (see [28]). Stereotypical stimuli, such as touch of a particular finger, result in specific activity changes (measured as changes in the frequency of discharge of neural action potentials) in the corresponding area of the cortex. Decoding information from these areas in

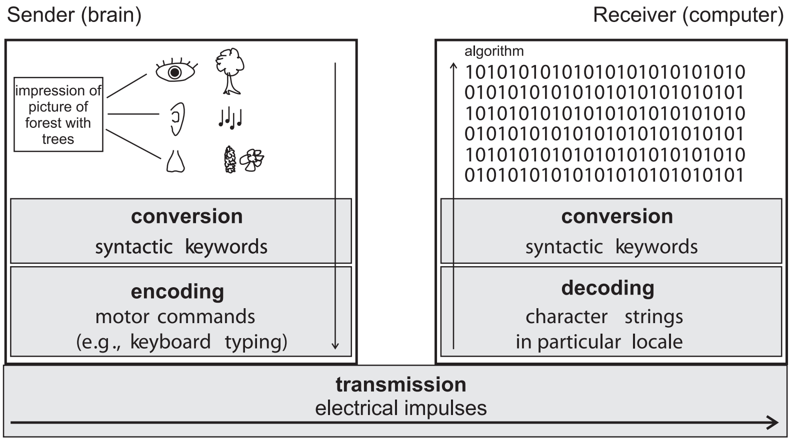

Figure 3. The communication process. Semantically rich representations in the brain are translated into syntactic keywords, void any semantics and encoded into motor actions that are transmitted and detected by a computer. The reverse process takes place in the computer without restoration of the original semantic relationships.

the brain would give the computer a detailed picture of the brain's current actual or imagined sensory experiences.

In the visual system, different areas of cortex represent the luminosity and color of visual input (i.e. a *retinotopic* map). In addition, starting with the work of Hubel and Wiesel (see [29]), neuronal assemblies have been found to be responsive to, and thereby *encode*, complex visual stimuli such as lines at particular orientations, certain shapes, or even faces (see [30, 31]). Decoding such information would afford the computer a comprehensive understanding of perceived or imagined visual images (e.g. [32]) and their higher-level semantic properties.

In auditory cortex, areas appear to be mapped to tones of different frequencies (i.e. a *tonotopic* map). In addition, Knudsen and Konishi identified an area in the midbrain of owls that contain cells (i.e. *space-specific neurons*) that encode the particular spatial location of a sound (see [33]). Decoding information from auditory cortex could thus communicate to the computer actual or imagined pitch and location information.

The olfactory system is able to discriminate different odors. It contains receptors that are preferentially responsive to particular smells. By measuring responses from assemblies of cells, many odors can be clearly distinguished [34, 35].

The motor system is very similar to other systems in the sense that features that are adjacent in a particular feature domain (e.g., such as position, direction, or velocity of hand movements) have representations that are spatially adjacent to each other in cortex. Since at least the late 1960s it has been known that the firing of motor cortical neurons is correlated with muscular force and other movement parameters (e.g. [36–43]). Furthermore, subsequent studies showed that appropriate decoding algorithms can accurately predict the position and velocity of limbs [44–48] or eyes [49, 50] in non-human primates. These studies confirmed a directional sensitivity of motor cortical neurons that is known as *cosine tuning*: cells fire fastest if the direction of limb movement equals their preferred direction, and fire slowest if the limb is moved in the opposite direction. Interestingly, a similar relation has been described between the direction of eye movements and cell discharge in the paramedian pontine reticular formation (see [51]), the mesencephalic reticular formation (see [52]), and the internal medullary lamina of the thalamus [53]. Moreover, increasing evidence strongly supports the hypothesis that, as in the systems described previously, imagined movements have brain signal signatures that are similar to those associated with actual movements [32, 54–58]. Furthermore, studies also indicate that particular parts of cortex not only encode particular aspects of actual or imagined movements (such as the particular direction of an actual or imagined hand movement), but also more general aspects of movement planning (such as the brain's intent to move a hand to a particular location prior to translation of this plan into actual motor commands (e.g. [24])). Using this information, a computer could execute commands based on specific or abstract movement plans.

The language system also consists of a number of different areas with different functional characteristics. For example, Broca's area is responsible for the production of spoken language (i.e. motor programs for controlling speech sounds); Wernicke's area is responsible for the comprehension of language (i.e. the interpretation of spoken and written words); visual cortex is involved in processing written language; and motor cortex is responsible for the production of speech sounds (i.e. for controlling vocal muscles). In addition, there is recent evidence that even the representation of syllables and phonemes is encoded in brain signals (see [59, 60]). A computer could use this information to learn about the spoken or imagined words produced by the brain.

Finally, the capacity to decode information from the brain has even been extended into personal experiences such as sympathy and empathy (e.g. [61, 62], respectively). Moreover, as mentioned above, it is becoming increasingly evident that the brain signals that accompany *imagined* movements, sensations and feelings are, while smaller, similar in characteristics to signals that accompany *actual* movements, sensations and feelings. This opens the possibility that one could not only decode or produce actual, but also imagined, experiences.

In summary, many studies have shown that the activity in particular mental faculties can be decoded to determine the nature of actual or imagined movements and sensations.

These studies have typically analyzed only one mental faculty in isolation, and many have been conducted in animals for practicality or safety issues. This prohibits realization of the promise set forth in this paper. Thus, the challenge at hand is to remove these practicality and safety issues so that comprehensive study of a number of faculties simultaneously becomes possible.

2.1.2. Inducing information into the brain. The same way that information from the brain can be used to determine the state of many different agencies in the brain, similar information could be induced into the brain using the same understanding of the symbols and the language of the brain's internal communication. Even 60 years ago, the eminent scientist Vannevar Bush, then Director of the Office of Scientific Research and Development, hypothesized in *As We May Think* [63] about such a possibility:

> By bone conduction we already introduce sounds into the nerve channels of the deaf in order that they may hear. Is it not possible that we may learn to introduce them without the present cumbersomeness of first transforming electrical vibrations to mechanical ones, which the human mechanism promptly transforms back to the electrical form?

It took until recently for this vision to become reality, but auditory prostheses are already in widespread use (e.g. [64]). These prostheses work by introducing into the auditory nerve ([65] for review) or auditory cortex (e.g. [66]) electrical impulses that encode pitch information similarly to, albeit currently somewhat cruder than, those encoded by the electrical impulses produced by a healthy cochlea. Advances are also made toward interfacing more complex systems, such as the visual system with the retinal implant [67–70].

In summary, there is no reason to believe that current systems could not eventually decode or produce sounds or visual images rivaling in clarity those produced by our own body apparatus. This could at least be partially achieved simply by engineering sensor and stimulator devices with an appropriately large number of electrodes. Given this development, it also appears feasible and practical to extend these systems to interact with all movements, sensations and emotions using a single device. While this possibility opens up many new avenues for restoration or augmentation of motor and sensory function, it also raises several ethical issues, which are outlined in section 6 later in this paper.

2.2. Establishing a new language: brain–computer interfaces

The second option for interacting with the brain is by establishing a new mutual language, i.e., essentially creating a new communication channel that does not rely on the brain's normal output pathways of peripheral nerves and muscles [19]. While this new language is based on the same neural communication primitives (such as action or field potentials) used by the brain in its internal communication, the symbols or function of this language may be different. Over the past two decades, a variety of studies have evaluated this possibility. They assessed whether brain signals recorded from the scalp, from the surface of the brain, or from within the brain could provide new augmentative technology that does not require muscle control (e.g. [46, 71–82]) (see [19] for a comprehensive review). These brain–computer interface (BCI) systems measure specific features of brain activity (i.e., the symbols of this communication that are typically mutually established between the brain and the computer) and translate them into device control signals.

These studies show that direct communication with the brain is possible and that, despite its early stage of development, simple language, and consequently relatively modest communication rates (i.e., no more than 25 bits min^{-1} or 0.41 bits s^{-1} [83]), it might already serve useful purposes for paralyzed individuals who cannot use conventional technologies. To people who are locked-in (e.g. by end-stage amyotrophic lateral sclerosis, brainstem stroke, or severe polyneuropathy) or lack any useful muscle control (e.g. due to severe cerebral palsy), a current BCI system could give the ability to answer simple questions quickly, control the environment, perform slow word-processing, or even operate a neuroprosthesis or orthosis [84–86]. While the communication rate of present BCI systems is modest, it is almost as fast as certain communication methods (such as the Morse code) and only two orders of magnitude lower than the fastest external communication rate supported by our nervous system (see figure 2).

2.3. Issues and limitations

Direct communication with the brain will eventually be limited by five issues that relate to the difficulty of establishing the language of communication.

The first issue relates to the *calibration procedure* that determines the symbols of this language. This procedure utilizes an understanding of the mental faculties to be decoded (i.e. a reference task such as actual or imagined motor movements, speech, etc) to establish the relationship between the reference task and signals from the brain. For example, current techniques may use linear regression to determine the linear relationship between particular brain signal features (such as amplitudes in certain frequency bands at relevant locations) and a particular output parameter (such as the direction of hand movement). Thus, this calibration procedure can only be performed if such a reference exists, and therefore will be impossible for mental faculties that do not correspond with measurable actions. This issue has been recognized for a long time in philosophy where it is known as the *reference problem* [87].

The second issue relates to the stability of the brain's existing language. The brain is not a static processing unit but rather undergoes continuous adaptations in response to external and internal influences. In other words, the particular symbols that the brain uses to represent and communicate information can be expected to change over time. This will require adaptations in the computer and/or more continual calibration procedures.

The third issue is what could be called the *language identification paradox*. Because a strong theoretical basis (and thus, a mathematical model) for the brain's internal communication currently does not exist, any calibration procedure needs to rely solely on mathematical techniques (e.g., machine learning) to establish the relationship between a reference action and all possible symbols (i.e., brain signal features). As the number of possible symbols in the language and the number of reference tasks increase with better sensor technologies, the determination of this relationship will, paradoxically, also become more difficult. Thus, with current mathematical techniques and current understanding of the brain's internal communication, this issue will result in an increasing demand for more data from an increasing number of reference actions, and hence soon become impractical. Thus, advances in sensor fidelity will eventually also demand advances in mathematical techniques (e.g. [88]) and/or better understanding of the brain's internal communication.

The fourth issue is that the communication system may be falsely activated by existing tasks (e.g., actual movements) that also produce symbols of this language. As an example, a communication system that is controlled by imagined hand movements may also be activated by actual hand movements (which typically produce similar neural signatures). This issue may limit the utility of this type of communication for control tasks that would augment (rather than replace) bodily actions.

The fifth and final issue relates to communication that relies on a new language. Establishing a new language requires, by definition, mutual adaptation of the brain and the computer. The more complex the syntax and taxonomy of the new language, the longer this training process will become. Practical considerations will eventually limit this time and thus the complexity of the language.

3. The interface

Efficient communication between the brain and the computer requires a physical interface that supports rapid bidirectional communication with a large number of sites in the brain, that is clinically safe, and that can communicate symbols that are indistinguishable from the brain's internal communication. While there is currently no technique that can satisfy all of these requirements, several promising avenues for further research exist. The following three sections describe available techniques, future developments and potential issues.

3.1. Currently available technologies

A variety of methods for monitoring brain activity currently exist, and could in principle provide the basis for direct communication between the brain and the computer. These include, besides electrophysiological methods (i.e. electroencephalography (EEG), electrocorticography (ECoG), or recordings from individual neurons within the brain), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and functional near-infrared imaging (fNIR). However, MEG, PET, fMRI and fNIR are currently technically demanding and expensive. Furthermore and more problematically, PET, fMRI and fNIR, which give a measure of brain activity based on metabolic activity, have limited temporal resolution and are thus less amenable to rapid communication. Non-invasive and invasive electrophysiological methods (i.e. EEG, ECoG and single-neuron recordings) are at present the only methods that can measure and in part alter brain activity with the requisite speed.

Non-invasive electrophysiological methods use electrodes on the scalp to record the electroencephalogram (EEG) [19, 71–77, 89–94]. EEG is convenient, safe and inexpensive, but has low spatial resolution [95, 96] and is susceptible to artifacts from sources outside the brain. Furthermore, non-invasive methods can typically only be used to measure brain function (i.e. communicate from the brain) but not directly alter brain activity (i.e. communicate to the brain).[2] In summary, EEG signals can provide the basis for safe and uni-directional communication of limited resolution. At present, the degree of potential improvement in fidelity, in particular those that can be achieved in relatively uncontrolled situations, is unclear.

Invasive methods use microelectrodes implanted within the cortex to record single-neuron activity [45, 46, 80, 81, 97–100]. While intracortical microelectrodes can detect or alter communication between individual brain cells, their widespread implementation is currently impeded mainly by the difficulties in maintaining stable long-term recordings [101, 102], by the substantial technical requirements of single-neuron recordings, and by the need for intensive continual expert oversight. In summary, intracortical microelectrodes combine good signal fidelity with limited practicality. At present, the degree of potential improvement in practicality are unclear.

While it may eventually be feasible to use implanted microelectrodes to record from a large number of individual neurons practically and safely over long periods, this is currently (and probably for the foreseeable future) not possible. This appears to be problematic, because many scientists have assumed that only action potential or field potential recordings from small groups of neurons can accurately reflect detailed aspects of actions (e.g., such as the direction and speed of hand movements, the position of individual fingers, or different phonemes in speech). Recent studies have provided strong evidence that this notion is not justified; that, in fact, decoding of detailed aspects of motor or speech function is possible, in humans, using electrocorticographic (ECoG) signals recorded from the surface of the brain.

ECoG has higher spatial resolution than EEG (i.e., tenths of millimeters versus centimeters [95]), broader bandwidth (i.e. 0–500 Hz [103] versus 0–50 Hz), higher characteristic amplitude (i.e., 50–100 μV versus 10–20 μV), and far less vulnerability to artifacts such as EMG [95] or ambient noise. At the same time, because ECoG does not require penetration of the cortex, it is likely to have greater long-term stability [104–107] and to produce less tissue damage and reaction than intracortical recordings.

Using ECoG, a recently published report [108] demonstrated that it is possible to decode the position and velocity of hand movements in humans. More importantly, it showed that the accuracy of that decoding was comparable to what has previously been demonstrated only by studies using intracortical microelectrodes in monkeys. This finding, i.e., that field potential activity recorded from the surface of the brain can be as informative for relevant questions as single-unit activity recorded from within cortex, is further supported

[2] One exception is transcranial magnetic stimulation (TMS), which has low spatial specificity and can be uncomfortable in its use. Another exception is biofeedback of brain activity, which can be used to alter behavior.

by ongoing work [108, 109] that extends these encouraging findings to finger movements and speech.

In sum, traditional non-invasive and invasive techniques currently have, and likely for the foreseeable future will continue to have, issues with robustness, fidelity, and/or practicality. At the same time, it is reasonable to anticipate that, with appropriate engineering improvements, ECoG recordings could combine robustness and fidelity with clinical practicality.

3.2. Future development

As described above, at present only traditional electrophysiological methods (i.e. EEG, ECoG, and single-neuron recordings) have the characteristics and maturity necessary for comprehensive investigations in this area. However, a number of novel sensor technologies that could complement or replace these existing techniques are emerging. These emerging technologies include devices that can measure neurotransmitter release with very high spatial resolution (i.e., 200 μm) and reasonable temporal resolution (i.e., about one second) [110]; fine wires that are placed in the brain's vasculature [111]; stimulation devices that are based on ultrasound or microwaves [112–115]; neuronal axons that have been stretched up to several centimeters, retaining their function [116]; biocompatible polymers with penetrating carbon nanotubes [117]; electro-chemical biosensors using nanotubes [118, 119]; actuated neurotransmitter-based stimulation [120, 121]; optical stimulation of targeted genetically modified cell types with millisecond resolution [122]; or harnessed biologically grown brain cells [123].

It appears entirely plausible that further development and integration of these techniques may result in a device that may receive and generate electrical signals and neurotransmitters, so that in terms of its functional properties it may not be distinguished from structures in the brain.

3.3. Issues and limitations

In addition to the problems of current devices listed above, further development of the physical interface will also face additional issues. That first issue is that, as an increase of the number of sensors will become progressively practical, meaningful and economical, the number of wires that have to be installed to connect the devices to processing units will also increase. At a large number, wires may become too voluminous to be practical. Fortunately, this problem is similar to that in other technical domains, such as in voice or data networks. The usual solution to this problem is that individual signals be multiplexed (e.g., in the time or frequency domain), so that multiple signals can be transmitted using only one wire. Because the bandwidth of brain signals is low, solving this problem should only require appropriate adaptation of existing technology or modest additional development.

The second issue concerns resolution. While an ideal sensor would derive an accurate electrical and chemical sample from every cell in the brain, this will most likely remain impractical. This restriction may ultimately limit the types of interaction, in particular because it is known that different types of cortical representation can be interleaved in neuronal populations within close distances. At the same time, recent studies have shown that relevant information is also spatially widely distributed in the cortex (e.g., see [108, 124] for examples in motor cortex). Other studies have demonstrated that field potentials, i.e., the spatial summation of large numbers of neurons, hold information that in relevant aspects is comparable to that derived by single-unit recordings [108, 125]. These results indicate that it is possible to acquire substantial information from the brain without recording from action potentials.

The third issue relates to the practicality of invasive procedures. As described above and in section 3.1, there is strong evidence that detailed information can be acquired from the brain without its penetration. Furthermore, sensors and implantation procedures can likely be further optimized, such that the implant could be placed in a relatively minor surgery and can provide stable long-term recordings. However, any surgery will always limit potential users to those that can derive a substantial benefit from this technology. Because practically all of the established and novel techniques listed in section 3.2 also require an invasive procedure, this issue may continue to impede wide-spread dissemination.

4. As we may think

The previous sections described the *communication bottleneck* as the fundamental impediment to exploiting the mutual advantages of the brain and the computer, and illustrated the two requirements that have to be met in order to break this bottleneck, i.e. an adequate language and interface. Subsequent sections will discuss the expected development and the profound implications of the expected possibilities of this brain–computer interfacing technology.

4.1. Toward the limit

To further elucidate the limits and the further development of this novel way to communicate, we may first review what is possible today and then ask how we might increase the modest capacities of current brain–computer interfacing technologies. Current devices have been demonstrated in many studies to support simple communication. These capacities can be used by people with or without disabilities to communicate their wishes to their environment. At the same time, the rate of this communication is rather low, i.e., typically not more than 25 bits $\min^{-1}$.

To examine how this current modest performance could be improved, it is illustrative to consult some mathematics: In *Mathematical Theory of Communication* [126], Claude Shannon showed that any noisy communication channel has a channel capacity measured in bits s^{-1}. Consider a communication channel of bandwidth B Hz and a signal-to-noise ratio $\frac{S}{N}$. The channel capacity C in bits per second is then defined as $C = B \log_2 \left(1 + \frac{S}{N}\right)$. Because the properties of any communication channel, including the electrical, chemical, or metabolic ones that are relevant to brain–computer communication, can be expressed in this form, this formula can be used to calculate the capacity of any communication channel between the brain and the computer. In lay terms, the total information rate thus depends on the clarity of the transmitted information (i.e., the sensing/stimulation

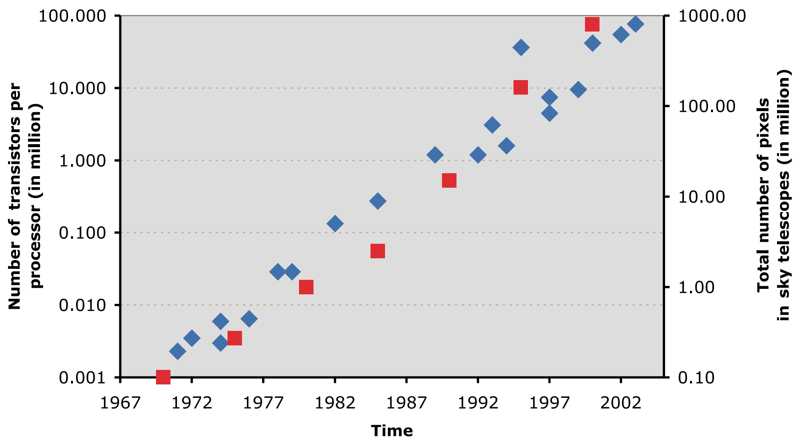

Figure 4. Example performance increases that represents advances of many technical developments. These examples illustrate the exponential growth in the number of transistors in Intel microprocessors (source: http://www.intel.com, blue diamonds) and the total number of CCD elements in the world's best telescopes (source: Jim Gray and Alexander S. Szalay [134], red squares).

resolution in a particular domain (e.g., spatial, temporal, frequency, chemical, etc) and on the amount of noise incurred at the sensor/stimulator or during transmission) and on the number of such communication channels.

Hence, I postulate that the communication rate between the brain and the computer will increase with the number of mental faculties that can be interacted with and with the clarity of that interaction. This concept strongly suggests that, as technologies improve to interact with more areas of the brain with higher fidelity, the communication rate between the brain and the computer will also increase. At the same time, it is not clear which factors will eventually limit this improvement. The brain contains about 100 billion neurons (e.g., [127–129]) and the theoretical upper bound for the information rate was estimated at 300 bits s^{-1} per neuron [130, 131]. It was actually measured, in a number of different brain systems, at about 80 bits s^{-1} per neuron [132]. These considerations and measurements suggest a high upper bound for the information rate. Whatever the true limit, there is no reason to believe that we should not be able to substantially increase the communication rate from the current maximum of 25 bits min^{-1}.

4.2. Expected performance and price development

The radical promise of these novel communication capacities will remain elusive if they remain a theoretical possibility rather than a practical reality, and practical reality is determined by at least two important factors: performance and price.

Many historic examples in technical history, including those in sensor and communication technologies, have exhibited radical and sustained improvements (i.e. 40–60% performance increase per year, which is often called *Moore's Law*) resulting from adequate research activities. Two of these examples are illustrated in figure 4, and others in [133]. In addition, many examples show that typically, the unit cost of a product declines by typically 20–30% each time the cumulative output of that product doubles (this is often called the *Law of Experience*).

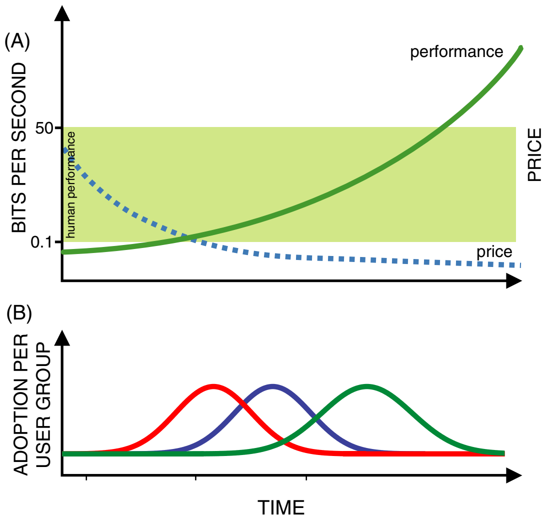

Figure 5. Expected performance/price development and associated technology diffusion. Based on historical examples, performance and price of brain–computer interfacing technologies can be expected to improve (A). These devices will begin to be adopted by different user groups as their price and performance make them attractive to each group (B).

These observations strongly indicate that the performance (i.e. number and sensitivity) and price of sensors/stimulators should increase and decrease, respectively (figure 5), assuming that research activities in this area will continue. Fortunately, brain–computer interface research has recently experienced large and accelerating research activities (see figure 6).[3]

To further examine the possibilities of even today's technologies, we may visit an example of a hypothetical device that can detect one thousand signals with high fidelity. Such a device could use sensors and electronics patterned on thin films (which allows economical high channel counts)

[3] One practical caveat is that the developments in these other areas were accompanied by or even required large up-front investments that drove the price per item (e.g., per transistor, copy of a software program, etc) down to almost zero, and these large investments are typically only made if the primary target market is large and accessible within a few years.

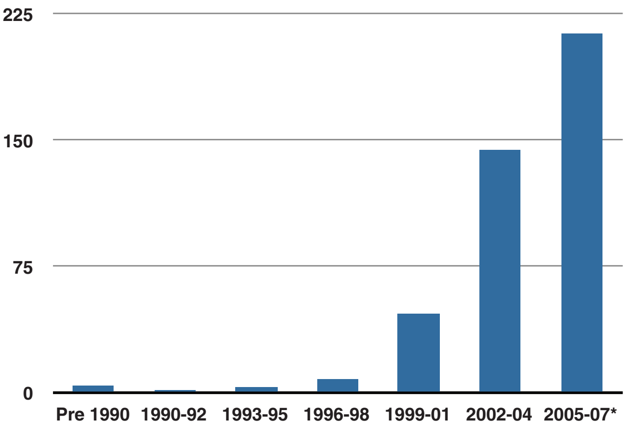

Figure 6. Increasing research activity in brain–computer interface (BCI) research. This figure illustrates the exploding increase in research activity (in number of peer-reviewed papers) over the past 15 years. Results are collected from relevant databases and represent the subset of research activity that studies communication using a new language (2.2). (*Values for 2007 are extrapolated.)

and could be placed on the surface of the brain (where they can detect high-fidelity signals at modest clinical risks [79]). Such patterned CMOS electronics have recently been described and used in a number of studies (e.g. [135–139]). A small thin film could contain electronics to realize amplification, analog-to-digital conversion, and extraction and wireless transmission of signal features. These signal features could be received by an external computer and converted into device commands (such as the many examples of current brain–computer interfacing technology illustrates). Because even a full-fledged microprocessor with dramatically more transistors can be designed to use only about 1 W of power (e.g. [140]), we may use this figure as an upper bound for the necessary power consumption. Rechargeable and implantable lithium–ion batteries already exist that could support almost one full day of operation for such a device away from a charging station (e.g., [141]). The features that are extracted by the electronics may be transmitted to an external computer over a Bluetooth-based wireless link. Class 2 Bluetooth devices consume about 2.5 mW, have a range of about 10 m, and can transmit up to 125 KB s^{-1} (see [142, 143]). (The recently announced Bluetooth 2.0 standard already provides 3–10 times that bandwidth.) At 1000 channels and 2 bytes per sample, this device could transmit 60 signal samples or signal features per channel per second (without any data compression), which is sufficient to support rapid communication.

In summary, a device that can detect large numbers of brain signals with high fidelity could be created using current technology given adequate funds; and clearly, the performance and price of this hypothetical device can be expected to dramatically improve over time. In consequence, there is every reason to believe that rapid communication between the brain and the computer is not only a theoretical possibility, but will also become technically possible and practical. Given this expectation, we may begin to elucidate the expected impact of this new technology.

4.3. Expected adoption and impact of brain–computer interfacing technology

As any other innovation, brain–computer interfacing technology will begin to be adopted once its value to an individual exceeds the cost to that individual. As the improvements in performance and price described above, this adoption or *technology diffusion* process has been observed and described for many different innovations [144]. Typically, it only takes a modest amount of time until 50% of the market has adopted the new technology, and complete market penetration is achieved after twice that time [144]. For example, using data from radio, television, VHS recorders, cable and satellite TV, DVD players, the Internet and wireless phones, a recent article [145] calculated that it only took an average of 13 years to achieve 50% market penetration. These examples suggest that brain–computer interfacing technology might also be adopted, at least by particular user groups, over a relatively short period of time. I anticipate that this process will eventually proceed in mainly three groups of users (figure 5). Each of these three different user groups will begin to benefit from this new communication capacity as its price and performance improve to a certain point.

With relatively modest improvements, brain–computer interfacing technology will become a practical and safe, albeit simple and slow, communication aid. It will thus soon become of interest to the first group of adopters: handicapped individuals who are currently limited for essentially all tasks by their limited communication capacity. For these people, even the modest rates of communication that will initially be achieved should dramatically improve quality of life.

With further improvements, technology will improve such that it rivals or exceeds some of the conventional human capacities. The second group that I expect to benefit from improved communication abilities are thus healthy individuals for whom communication is currently a pressing and limiting issue in many of their tasks. For example, limited communication input and output capacity is a serious issue for soldiers in combat. (In absence of the ability to increase these capacities of the brain, the military is currently trying to optimize this communication given our body's constraints.) In consequence, as soon as communication rates between the brain and the computer start to rival those that can currently be achieved with our sensory and motor systems, I expect that this group of users will begin to adopt this new technology.

If it becomes possible to design an (ideally non-invasive) interface (see section 3.3) that can support high performance at an affordable price, brain–computer interfacing technologies will become of interest to the third group of users—most other members of society—that could use these technologies for a wide variety of purposes. At the same time, this new communication capacity will constitute a radical and disruptive innovation that will not be immediately compatible with existing practice and that will evoke change in many complementary processes. It will thus take some time, perhaps a few decades, until this technology has been fully integrated in human societies [144, 146, 147].

In summary, I expect that, as performance increases and price decreases, brain–computer interfacing technology will become beneficial to an increasing number of individuals, that the direct and indirect effects of its use will become increasingly pervasive, and that the implications on individuals and society will grow in parallel. I thus anticipate that this development of brain–computer interfacing technology will in many ways mirror the development of computers (that addressed the previous bottleneck in human productivity) and of other general-purpose technologies (GPTs) [148]. GPTs have been found to have a wide variety of major effects on private and social performance [149]. For example, information technology and the Internet have wide applications and productivity-enhancing effects in numerous downstream sectors with high social rates of return that often exceed private rates of return [150, 151], and their dissemination is having a sustained, long-lasting impact on productivity and economic growth. Brain–computer interfacing technology can thus be expected to have a similar profound impact not only on individual, but also on societal performance.

5. Brain-computer symbiosis

To illustrate the anticipated impact of brain–computer interfacing technology, let us visit examples of their applications to the three user groups listed above.

The physically handicapped will primarily benefit from restoration of function. I anticipate that this restoration will initially mainly concern simple communication and control functions and eventually extend into full restoration of movement capacities using existing or artificial limbs. Because there are about 225 000–290 000 individuals with spinal cord injury in the US alone who would benefit tremendously from restored capacities, I anticipate that the commercial application of brain–computer interfacing technology will become a significant driver of progress once system performance improves to the point at which it becomes interesting to this large group of individuals.

As system performance increases further, individuals who are often limited by their communication capacity could benefit from this technology in a number of ways. First, direct communication from the brain could entirely eliminate the roughly 100 ms delay that is currently introduced by our nerves and muscles. Second, direct communication from the brain could practically eliminate the constraints imposed by the movement capacities supported by our limbs. Specifically, rather than optimizing interfaces to the static capacities of our body, we could optimize the whole system, human and computer. For example, imagine a jet pilot who currently has to deal with many controls for the many degrees of freedom the airplane supports. Because the number of degrees of freedom of the airplane exceeds the degrees of freedom of our motor system (or at least is very inadequately matched to it), the jet pilot might have to operate specific functions in sequence rather than in parallel. Using direct communication from the brain, the degrees of freedom that the pilot can support could be matched to the degrees of freedom of the airplane, which would transform the airplane from an external tool to a direct extension of the pilot's nervous system, in which different areas of the pilot's motor system would be responsible for controlling movements of the airplane rather than movements of the pilot's limbs. In addition, sensors in the plane could be connected to the brain's sensory areas such that these measurements can provide the pilot with information about the current state of the plane, much in the same way that our bodily sensors provide us with comprehensive information about the state of our body.

In summary, I anticipate that for these first two groups of users there will be many applications that will prove beneficial and thus will be commercially attractive. At the same time, the full potential of direct brain-to-computer communication will only be realized when this technology can benefit most members of society. As soon as interfaces can be built that can interface safely, economically and concurrently with most of the major systems in the brain, many applications will emerge that will augment our senses and our communication capacities with others and with computers. It will be then that enhanced communication capacities will pervade the fabric of society with a multitude of side effects on many other technologies and processes.

6. Ethical issues

The previous sections outlined the potential benefits of brain–computer interfacing technology. Similar to any other type of technology, these potential benefits also come with inherent ethical concerns (see [152, 153]), which mainly include issues of privacy and liability. These two concerns are described in the following paragraphs.

The first concern relates to privacy. The state of our brain normally expresses itself almost exclusively only through our actions, and it avails itself for modification only through our senses. As described in section 2.1.1, direct assessment of the state of different systems in our brain could be used to add context to existing communication, and thus be beneficial. At the same time, this assessment necessarily has to be processed by a computer. This raises privacy concerns, because this information may not be securely stored and thus accessible to third parties. Furthermore, as described in section 2.1.2, the capacity to induce information into the brain may provide us with the ability to base our actions on a better assessment of the environment. Because this information is provided by a computer, it could be accessed and modified by third parties, which may allow them to influence our actions. As alarming as this may sound, several existing techniques (e.g., subliminal advertising, brainwashing strategies, etc) are specifically designed to effectively modify behavior. Just as society has responded to these techniques (e.g., by banning subliminal advertising) or to other issues of privacy (e.g., by creating privacy regulations (such as HIPAA in the United States)), society will have to establish necessary guidelines for responsible use of this new technology.

The second concern is liability. Most people would agree that, under normal circumstances, we are fully responsible for our actions. However, if our intent was effected by a brain–computer interface, incorrect actions may be produced simply by incorrect detection of correct intent. In this case, who would be liable for potential damages: the provider of the detection algorithm or the individual? How would one even determine that our intent was incorrectly detected? Alternatively, a brain–computer interface could be configured to utilize commands from executive functions before they are being screened by the brain's validation processes. Thus, an intent that under normal circumstances would not have been acted on may be effected when using a brain–computer interface. In this case, detection of the temporary intent could be correct, but the action would still be undesirable. In both of these scenarios, this problem progressively increases with increasing communication speed. For example, when a user utilizes a word processor by controlling a cursor toward the desired letter, incorrect movements could be detected using visual feedback, and thus may be corrected. This ability for correction decreases with increasing selection speed.

7. Conclusions and recommendations

This paper discussed the promise that interactions with the brain could improve or augment conventional forms of human communication. To many, the vision presented here will be as utopian as JCR Licklider's and Doug Engelbart's predictions about the significant utility of computers almost 50 years ago. However, the foundations of technical innovation and economics that drove this development have not changed. Because the present vision depends largely on technological improvements rather than on hopeful speculation, and because its realization is subject to the same forces that have governed the course of many previous technical developments, it is, in the end, a logical step in our own evolution. The hope is that the resulting partnership of the brain and the computer will be able to think, act and feel in ways that humans have never thought, acted and felt before.

While this paper (in sections 2.3 and 3.3) discusses several issues that need to be overcome, the currently biggest limitations are the fidelity, practicality and/or safety issues of available sensors. Thus, many of the promises described in this paper could be realized with better sensors. The design of such an improved sensor will require full appreciation of the problem at hand, which is to design a system that can accurately, practically and safely interact with the brain over extended periods, and that can use this capacity to communicate beneficial information between the brain and the computer. This demands an integrated approach dedicated to providing people with improved brain-based communication and control options as opposed to isolated efforts in neuroscience, engineering, or signal processing.

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