Limitations, Possibilities and Implications of Brain-Computer Interfaces

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Abstract. **EEG Systems and Brain-Computer Interfaces (BCIs) are terms that are commonly used and discussed in the field of neurological research. From a technological point of view, the components and techniques used to build technical devices for this purpose are also widely discussed. Undifferentiated use of the terms EEG Systems and BCIs in the same context provokes a discussion because they in fact refer to distinct and different concepts and should be treated accordingly. This assertion shall be discussed and established without going into more technical detail of the concrete components. We will discuss the associated problem of the vague definition of BCIs and depict the essential limitations when using skull potential signals to realize such devices. To demonstrate alternative ways of realizing man-machine interfaces, we will describe the most recent research results, based on the example of a complex arm prosthesis. With respect to the requirements for realizing such a complex prosthesis we will show the possibilities and limitations of accessing the human brain structures and finally propose clear conclusions regarding the specifications for Brain-Computer Interfaces and the corresponding long term research and development goals.**

Keywords: **Human-Machine Interaction, Brain-Computer Interface, Brain/ Mind Interfaces.**

I. Cortical Potential Imaging Devices - EEG

Systems named EEG (Electroencephalography) Systems" were originally developed in the first half of the 20th century for different purposes, including the control of prostheses. An overview of the state of the art in current scientific publications can be found in [1], showing the relevance of this area within the scientific community. Advances in micro- and nanotechnology will continue to extend the possibilities in this area in the future. Here, it has to be stated that the technologies used in EEG Systems are partly developed and used in other technical areas as well (for example in radio communication systems). Due to widespread use the components are gradually turning into mass-produced goods and becoming more and more affordable.

However, the question arises whether a correlation can be made between an EEG system and a Brain-Computer Interface (BCI). Neurologists understand the human 'brain' as the combination of the neural part and the mental apparatus, the psyche. For the mental apparatus, no article exists that proposes how one can access the contents of our thoughts. Only in [3], an approach is observable in which such considerations are examined (for more details, see chapter 4). What are the relevant research areas in EEG Systems today? First, we have to mention the field of bio-medical measurement methods. The solutions developed here provide good results, but an ideal solution for measuring skull-potentials which is also easy and comfortable to use does not yet exist. The non-linear variations of resistive and capacitive transitions between the skin and the surfaces of sensors as well as electromagnetic artifacts still pose considerable challenges. Furthermore, even scientifically trivial-looking problems such as the handling of the devices have not yet been solved satisfactorily. Wireless transmission, on the other hand, is a distinct, independent research area, and is therefore not the main challenge in the medical sector. Propelled by technical and economic demands in other fields of application, corresponding digital components and antennas have already been developed (example shown in [2], but a multitude of other applications, e.g. technologies with active antennas, could also be mentioned) which fulfill or even outperform the requirements of the devices that are transferring and preprocessing the signals from the surface electrodes – as shown manifold in [1]. [1]

The next technological area that has to be mentioned is signal processing. Research there provides solutions for how signals can be further processed after sensing and/or wireless transmission. Although remarkable solutions exist, a globally applicable and satisfying implementation has not yet been found. And how would such an all-embracing solution be defined, anyway? Signal processing is and will remain an ever-moving field, since a researcher can never be fully satisfied by the analysis of data, no matter how extensive or precise. However, newly developed algorithms and further knowledge about the interrelationships between the basic brain functions and the resulting EEG-signals will constantly lead to improvements. The authors in [1] are correctly arguing

[1] However, the relationship to real-time requirements cannot be seen by the authors due to the fact that controlling aspects are not considered. N. B. the term real-time refers to signals arriving in time and does not refer to (high) speed.

that “biomedical signal monitoring systems have rapidly advanced in recent years”. Moreover, we postulate further enormous advances triggered by the systematic use of micro- and nanotechnology in future devices.

II. Brain-Computer Interface and the Control of Artificial Arms and Legs

Do Brain-Computer Interfaces as discussed in [1], or general principles being developed on a very high scientific level (for example also in Graz/Austria [4]), have a long term impact on the social or economic sector? What about research results, e.g. those of the company Otto Bock [IL1] as shown in Figure 1? What is their promise for the future?

Figure 1: The first prosthesis developed by the company Otto Bock, global market leader in the area of prostheses which control the five fingers of the artificial hand as well as the hand itself via a complex nervous system.[2]

The EEG measures a mixture of signals originating in neural brain activity. According to Lurija [5, pp. 49] – as well as [6, pp.20] – the two lowest functional layers of the brain are mostly locally oriented. Therefore, the detectable local functional brain areas are responsible for these signals. By observing the brain areas responsible for activating certain muscle strands, it becomes possible to measure a corresponding signal of (conscious or unconscious) muscle stimulus. The higher sublevels of the second level, according to the layer model of Lurija, are assembled on the lower levels and exist only in an abstract way. Direct mapping to the physiological media is therefore no longer possible. To measure processes on these higher layers on a physical level would require additional tools to translate the measured low-level information into the higher-level context appropriately - comparable to trying to understand higher levels of information protocols of computer communications using basic electrical measurements. One needs specific "interpreters" for such operations.

Another intrinsic problem of an EEG is the interpretation of the abovementioned diffuse mixture of measured signals. Hence, for the control of highly complex prostheses as shown in Figure 1, this mixture of signals is not sufficient, and can never be in the future. The signals necessary to control the arm, including the consideration of closed loop controls between the brain and the arm, ideally including the fingers and integrated touch sensors, would be too blurred to be the basis for adequate arm movement execution. Consequently, EEG-driven prosthesis control can certainly mark only a first step to support handicapped people in regaining an independent life.

Electrocorticography (ECoG), on the other hand, measures the brain’s activity invasively and directly at the corresponding neuron groups of the brain – again according to e.g. Lurija and Solms this represents the abstract lowest levels of the brain. Because of its invasive access, ECoG poses a serious disadvantage of its own. Obviously, the neural centers have to be found and connected to the sensors without harming the neurons themselves. We cannot, unfortunately, expect success in this regard within the near future. Placing and permanently integrating proper sensors that guarantee a stable behavior over extended periods of time is a major problem which has yet to be solved from a medical point of view.

The long term solution must therefore consist in a direct coupling to the numerous arm nerves, as under development in the research centers of Otto Bock and shown in Figure 1. These arm nerves are the location within the mental-neural chain to access the final mental output, the control signals for the muscles, without having the problem of interpreting a mixture of signals as is the case with the EEG approach. Figure 1 shows patient K. whose pectoral muscle has been sliced into several, filet-like muscle strands into which the mutilated nerve ends of the missing arm have been inserted. The nerve ends grow into these strands, and over time the patient becomes increasingly able to control his newly acquired pieces of the pectoral muscle and understand these filets as his new arm, including sensitivity to pressure, temperature, and prospectively to pain.

The existing muscle tissue with the newly incorporated nerves acts as a signal amplifier because the produced muscle signals can be much more easily measured with exterior electrodes than (weaker) nerve signals. With this technique it becomes possible to transmit a multitude of neural information from the brain to a complex prosthesis, and back from the sensors integrated in the prosthesis to the brain, using the same interface, placing the abovementioned "interpreter" for the information in both directions (coming from and going to the brain) much closer to the sensors and actuators and thus much easier to develop.

The challenge will be for the signal processing part of the prosthesis to emulate the second layer according to Lurija for the ongoing configuration of the artificial arm, which is not easily comparable to a real arm. This backward signal conversion would make control of the prosthesis more intuitive for the patient because of the adaptation to his particular higher brain structures. The

[2] Global webpage of Otto Bock Health Care GmbH, http://www.ottobock.com/ , accessed on 11th April 2010.

neuro-symbolic approach described in [7] offers a promising basis for this specific problem.

The advantage of the approach by the research team at Otto Bock is obvious: According to [7], the main challenge in finding the appropriate structures and closed loops is that of creating computer models relating to the aforementioned mechanisms and interrelations, thus resulting in optimized adaptation of the prosthesis to the individual patient and reducing the time necessary for training. The amount of time necessary for familiarization decreases the more precisely layer 2 (additionally to layer 1 as shown later in Figure 2), the neuro-symbolization layer, is modeled and implemented. Ideally, patient K. would not only regain his sense of touch and pain but would also be able to perform complex arm movements like rotations while moving his hand and fingers – an impossible scenario for him today.

Especially these last parts are just prospects for the future, however, and many challenges will have to be solved for them to be realized: a complete model of the primary and especially the secondary layer according to Lurija; permanent and stable placement of the electrodes on the pectoral muscle; and efficient energy supply of the prosthesis - to name only a few.

III. Brain-Computer-Interface in Theory

The authors arrived to the impression that the term “Brain-Computer Interface” (BCI) is very vaguely defined and thus used in a misleading fashion. According to [5], [6] or [8] the brain contains everything, from “hardware”, or the network of neurons, up to the abstract higher mental apparatus, the psyche. The term “Brain-Computer Interface” therefore implies an interface between the thoughts of a person and a computer – which is something completely different than what can be detected by mere measuring of skull potentials. Indeed, [1] only refers to measuring the physiological level and does not consider the higher levels of complex abstract functions of the mental apparatus which control direct movement. To call this interface a Brain-Computer Interface is overbearing. In regard to the question which kind of signal needs to be picked up for operating directed complex movements such an assertion is gravely misleading.

To illustrate this claim, the authors would like to introduce several examples from the field of computer engineering: First off, if one were to measure signals from CPU transistors or electrical fields on a computer’s casing, one would still not have internet access or access to programs like Microsoft's "Word" or "Excel" on that computer. Between the transistors and the level of application software are many abstract layers like the BIOS, the operating system, and many application levels. Thus, knowledge about transistor signals is not sufficient to understand the functions of the higher abstract computer levels, because the information processing itself is decoupled from the structure of the semiconductor chip. To gain access to the “knowledge” of the computer, it is not sufficient to understand and map its basic physical workings, it is also necessary to have the required programs integrated that transport and translate the information from the higher abstract layers down to the physical layer (e.g. a USB plug) and vice versa. Similarly, it is only possible to truly speak of a computer interface (and not merely an interface for electrical data transmission) when referring to a connection between a computer and another device or entity if, as with e.g. a USB plug, there are complex device drivers, or software tools, associated with the physical connection which interpret the signals on the physical medium and prepare them for the internal higher layers in the computer software. Thus, there is actually an interface to the computer, not only a cable for data transmission. In our brain, we do not have such complex device drivers and will not have them in the near future. This means that access to higher abstract layers of human thinking will not be achievable anytime soon. As a result, we cannot speak of a true Brain-Computer Interface today, only of an interface to tap neural (physiological) signals. By tapping such signals in this way we can create - in the best case - a “body-interface” or a “skull-interface”. To expect anything more is an unjustified exaggeration of the potential of such devices or wishful thinking, since they have nothing to do with an interface to the psyche (a real complex process with many unknown functional parts).

Another descriptive example would be Van Eck phreaking, first introduced in [9]. For more than two years, Van Eck phreaking (spying out and reconstructing the monitor signal of a cathode ray tube monitor by measuring its electro-magnetic field) has also been possible for flat screens and laptops via distant measuring of the signals emitted from the cable. The signals on the monitor cable, however, are arranged specifically for the visualization and contain only the signals required for viewing the pictures. Thus, it is possible to display the visual output of a computer program by external measurement of signals at some distance from the computer. In a transferred sense, a very basic movement pattern (corresponding to Lurija’s first layer of neurons in the cortex, described in the next chapter) can be reconstructed, since the computer screen corresponds to a human limb, and its cable to the appropriate limb nerves. Unfortunately, an interface between the different layers (like the monitor output on a computer) does not exist in the human brain structure. Additionally, any measurement taken ahead of the cable that transfers already preprocessed, low level information to the monitor would be inconclusive. If one attempted to interpret the electro-magnetic fields of the graphics card or computer CPU, the pictures on the screen could not be reproduced.

As depicted in Figure 2 and derived from Lurija [5] Solms [6] and Damasio [8], the primary, lower layer consists of the “hardware”, the neurons. Above this primary layer lies a functional abstraction layer that is introduced in [7] as the neuro-symbolic layer. This layer is relatively new to science [6], since its functionality cannot easily be interpreted solely from the neuronal layer below. Again, as an example, imagine an electronics engineer, who has knowledge about the functionality of transistors, but no knowledge about computers, to whom a functioning computer is given without circuit diagrams or program documentation. Imagine this pitiable engineer trying to find out how application software like Microsoft's "Word" or "Excel", works or what it is currently doing on the basis of measuring currents on the millions of transistors on all the computer’s different chips. It can be easily seen that it will be exceedingly difficult, if not impossible, for him to succeed in his mission using such a bottom-up approach. The only rational approach is to do this in combination with a top-down approach in order to narrow down the gaps.

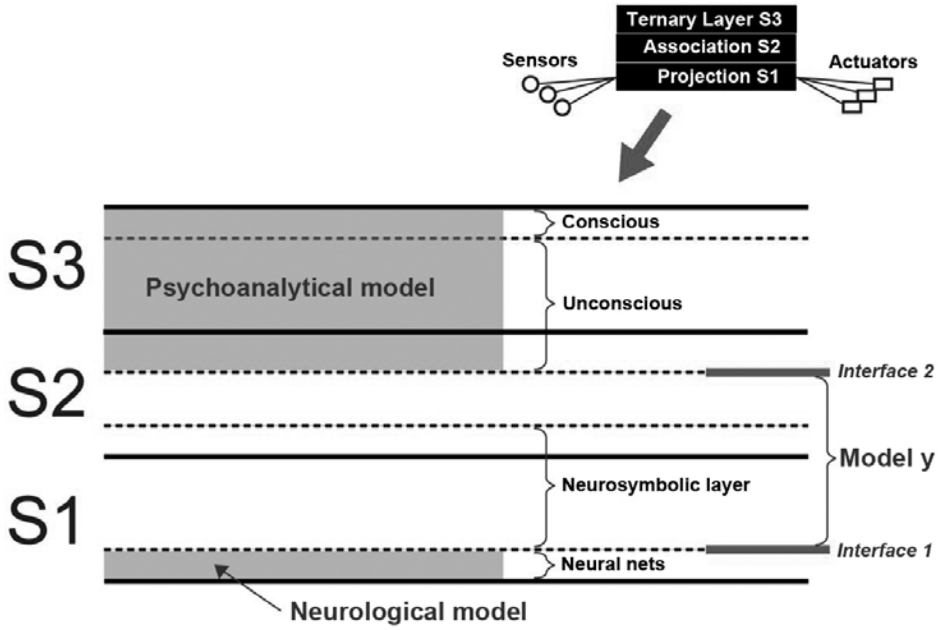

Figure 2: Layered model adopted from [5], [6] and [8].

As described in [6], with the psychoanalytical model at hand, one has a rather good concept of the functionality of conscious and unconscious mental reasoning. Thus, interface 2 in the model in Figure 2 (top right) can be introduced. With neurologists’ knowledge and their models of neural networks at hand, interface 1 can be defined. It is also based on the neuro-symbolic layer presented in [7][3]. In computer engineering, when interface definitions as in Figure 2 are available, it is common work to design the layer in between that needs to fulfill the requirements of the adjoining layers. Following this principle, it will be possible in the long run to develop a comprehensive model of the human mental apparatus.

Coming back to the term “Brain-Computer Interface” we would like to post another thought experiment: To access the “thoughts” – the very “thinking” – of humans, which happens only in the upper abstract “narrow” sub layer of layer 3 (the ternary layer), which discerns humans from other mammals, it would be necessary to implement some “device driver” down to layer 1, similar to the USB interface in a computer, for example. Such a procedure would require somehow “re-programming” or adding millions of neurons. Of course, today we lack any knowledge in this direction4. It has to be additionally noted that in the brain the two lower layers (Figure 2) can be localized, likewise that is possible with the peripheral device driver chips in a computer. By contrast, the upper layers, using a computer engineering term, are a heavily distributed system, which cannot be localized since many functional units interact with and affect each other, so that the functionality cannot be mapped onto the “hardware”, the neurons, anymore. Again, the procedures of the text processor MS Word can also not be broken down to transistor level directly. Data processing happens on many abstract layers which only indirectly communicate with each other via corresponding interfaces. With this in mind, the idea must be abandoned that complex functions can be directly mapped onto neurons. Information theory as part of computer science achieved its breakthrough with the introduction of functional abstraction models as depicted in Figure 2. Today, almost every technical device is designed with the help of these models. Examples of such very widespread and often used models are the Gajski-Walter Y-diagram and the ISO/OSI model in communication technology. Hardware only constitutes the lowest layer and cannot help understand functional higher abstract layers. Even synchronization of brain functions is of no concern in higher layers, because there are dedicated lower layers responsible for all timing issues. Considering this line of thought, the term “synchronization phenomena of information” is a recurring topic in the area of brain research only where differentiated abstract layer model principles are not applied. Researchers like [5, 7, 8] who employ these model principles do not have to focus on such questions.

Finally, an additional remark must be made: Being computer engineers, we feel the need to submit another reason why the term “Brain-Computer Interface” appears somewhat absurd to us. In computer science, the computer is defined as a system that manipulates, stores, and transfers data. This definition includes no imperative requirements on hardware. Therefore, computer engineers often merely distinguish between artificial and biological computers, which is also a reason why a term “Artificial

[3] Project Homepage Artificial Recognition System (ARS), http://ars.ict.tuwien.ac.at, accessed on 11th April 2010.

[4] As engineer one should be careful with posting things that will never come. People who lived 80 years ago presumably had no notion at all about contemporary knowledge. Thus we cannot predict what will be state-of-the-art 40 years in the future.

Intelligence" was coined. Hence, the brain could be described as a biological computer that "controls" the human body. In contrast to this, the term Brain-Computer Interface implies that the brain is in principle something completely different than a computer – which was attempted to disprove with this article.

Admittedly, however, this train of thought is rather monistic, and is not supported by all scientists, not even all engineers.

IV. Conclusion

The authors want to express their conviction with this declaration that careless utilization of popular scientific terms implies wishful thinking that may not be fulfillable even in the distant future. This concern is especially pertinent to natural science. What else besides wishful thinking would make people believe that it will soon be possible to "read thoughts"? When people talk about EEG and use the term Brain-Computer Interface in the same context, it should be cause for skepticism among listeners. It is furthermore unfortunate that truly new and valuable information as presented in [1] pales beside such doubtful phrasing, and unnecessary discussions are provoked as a result.

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