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A review of fMRI as a tool for enhancing EEG-based brain-machine interfaces

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Abstract. Human-robot interaction has been going stronger and stronger, up to find a notorious level on brain-machines interfaces. This assistive technology offers a great hope for patients suffering severe neuromuscular disorders. Starting from the current limitations hindering its extensive application outside the research laboratories, this paper reviews findings and prospects on functional magnetic resonance imaging showing how fMRI can help to overcome those limitations, while playing a key role on improving the development of brain-machine interfaces based on electroencephalography. The different types of derived benefits for this interfaces, as well as the different kinds of impact on their components, are presented under a field classification that reveals the distinctive roles that fMRI can play on the present context. The review concludes that fMRI provides complementary knowledge of immediate application, and that a greater profit could be obtained from the own EEG signal by integrating both neuroimaging modalities.

Keywords: Brain-machine interface, BMI, BCI, fMRI, EEG, multimodal neuroimaging, human-robot interaction

1. Introduction

Robots were initially conceived for helping on the heavy tasks of the industrial environment. Thus, they have been human companions from their origins. But technology has done a big leap since then, and—whether the *singularity* [7] would be one day reached, and humans and robots were indistinguishable, or not — *human-robot interaction* (HRI) is going stronger and stronger.

Interaction implies communication, i.e. interchange of information. Then, the strongest interaction among humans and robots happens when the machine is capable to recognize automatically the user's intention; just the opposite situation to those cases in which robots are fully programmed, or directly operated by user's commands. *Brain-machine interfaces* (BMI) are the devices that provide to the robots with that recognizing capability and, consequently, that allow such as strong interaction to take place.

Nevertheless, the development of BMIs and their full deployment outside the research laboratories still present obstacles. After introducing them, this paper reviews findings and prospects on *functional magnetic resonance imaging* (fMRI) showing how this technology can help to overcome the current limitations, and to contribute to improve the development of BMIs based on *electroencephalography* (EEG). The derived benefits are presented under a frame according to the different roles that fMRI can play on this context as a tool that complements and boosts the EEG knowledge, and that enhances the EEG-based BMIs.

The paper is organized as follows. Section 2 centres the work on the application domain of the assistive technologies. Also, it introduces the ethics motivating the research on BMIs and the beneficiaries, existing achievements, and promises of this technology. Section 3 defines the concept of brain-machine interface

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and describes their types. Section 4 introduces the main characteristics of the fMRI technology. Having presented the conceptual framework, Section 5 tackles the central issue of the paper, i.e. the open questions around brain-machine interfaces, and how the research on four fields related to fMRI can help to find the right answers to those questions. Section 6 presents the conclusions.

2. HRI in the assistive technologies domain

An important percentage of the population is concerned with some kind of disability. Among them, the most seriously affected are those suffering neuromuscular disorders like amyotrophic lateral sclerosis, brainstem stroke, or cerebral palsy. The symptoms are sometimes so sever that patients even cannot make use of the augmentative communication technology. A promising technical aid relies on the possibility of controlling machines —prostheses, wearable robots, computers, etc.— just by thinking. It is the so called *brain-computer interface* (BCI) technique [41] or, in a more general sense, *brain-machine interface* technique. The development of BMIs offers a great hope for these patients, as it allows them to communicate and to control prostheses and devices. These interfaces have even been proposed as possible communication systems in autism, aphasia and other severe communication disorders [5].

BMIs have so far been studied mainly as a communication means for people who have little or no voluntary control of muscle activity [33]. However, today BMIs, designed for both experimental and clinical studies, are translating raw neuronal signals into motor commands to produce arm reaching and hand grasping movements in artificial actuators. These developments hold promise for the restoration of limb mobility in paralyzed subjects [19]; as for instance those suffering from chronic stroke [6].

3. Brain-machine interfaces

BMIs are communication systems in which the messages and commands that an individual sends to the world do not pass through the peripheral nerves and muscles that the brain normally uses as output channels [43]. Instead, these devices interpret user's intentions, by processing physiological signals of the brain, and send the decoded messages and commands directly to a machine or a robot. Brain plasticity and physiological self-regulation are the key mechanisms that allows to code user's intentions on that signals. The BMI architecture is composed by three modules: signal acquisition system, feature extraction, and translation algorithm [43].

Under a broad perspective, BMIs can be classified as *invasive* and *non-invasive*, depending on the method they use for monitoring brain activity. The first ones make use of implanted electrodes to register cortical neural activity, while the last ones use electrodes or sensors situated out of the body. Invasive monitoring has produced notorious results [13, 14]. On the contrary, risk and use easiness favour the non-invasive one [35, 36, 40, 44].

Non-invasive monitoring methods include EEG, magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging, and near infrared spectroscopy. EEG is highly susceptible to noise and requires considerable user's training on the asynchronous operation modes. On their own, MEG, PET, fMRI, and optical imaging are still technically demanding and expensive. Furthermore, PET, fMRI, and optical imaging, which depend on blood flow, have long time constants and thus are less amenable to rapid communication [43]. Therefore, temporal resolution, portability, riskless, cost, and ease of use have made EEG the method of choice when implementing BMIs for humans. This paper is centred on this last type of BMIs.

Depending on the nature of the input signals, two models of EEG-based BMIs can be found [41]: those based on *endogenous electrophysiological activity*, such as the power of the μ and β rhythms in a specific cortical area [28, 42], or the slow cortical potentials (SCP) [6], and those based on *exogenous electrophysiological activity*, such as the amplitude of P300 potential in response to a flash of a letter [10]. Each one of these two types has its own operation mode: the former operates *synchronously* and the later *asynchronously*.

4. Functional magnetic resonance imaging

Several non-invasive techniques, such us electroencephalography, magnetoencephalography, computed tomography and positron emission tomography have been used to investigate the human brain functions [31]. However, the advent of the functional magnetic resonance imaging has largely replaced all of them as the primary tool in neuroscience research.

Functional MRI allows to record temporal sequences of three-dimensional images of physiological changes associated to mental processes. It is based on the sensitivity of magnetic resonance signals to the hemodynamic responses that accompany increased neuronal activity. The fMRI maps have accuracy at the scale of submilimeter neuronal organizations such as the orientation columns of the visual cortex, and are directly proportional in magnitude to electrical signals generated by neurons [34]. This technology has permitted the examination of functional specialization in the human brain with unprecedented spatial resolution, and has revolutionized cognitive neurosciences. Other immanent advantages are: non-invasiveness, reproducibility and interactivity of the procedure. Nevertheless, it is not yet exempt of problems such as: low signal to noise ratio, data distortion, spurious signal intensity fluctuations, sensitivity to patient and respiration motion, sensitivity to cardiac pulsations, limited time for examination, etc.

5. fMRI for improving the development of EEG-based BMIs

The key for the correct operation of BMIs relies on the user's capability to learn codifying commands in brain signals, and on the developer's ability to achieve a continuous mutual adaptation between brain and machine to ensure a stable behaviour. However, the achieved information transfer rate —around 25 bits/minute— is still not enough for neuroprosthesis control [43]. Furthermore, it is still not clear why certain patients and healthy subjects achieve a better control than others. To develop BMIs it is not enough to acquire and observe the electroencephalographic signals. Each user has his or her own abilities and circumstances. Many systems use EEG signals from the motor or somatosensorial cortex. These areas can be severely damaged in patients with apoplexy or degenerative pathologies, and it can be necessary to use other areas of the central nervous system. All these facts raise the question of which areas of the brain take part in the process and what patterns of brain activity characterize the skills required [12].

fMRI is the best suited technique for finding an answer to these questions and for improving the development of current EEG-based BMI systems. Thus, fMRI can play a key role in: patient evaluation, preliminary selection of the preferred areas for monitoring the cortical activity, investigation of the processes that generate the electrophysiological signals, study of the involved adaptive mechanisms of learning and BMI control, research on how user's emotional conditions —such as motivation, intention, frustration, and tiredness— could affect the EEG signals, analysis of the behavioural effects of self-regulated local brain activity, etc. Moreover, MRI offers the unique possibility of integrating anatomical and functional information of the entire brain for the design and adaptation of BMIs to the user.

The benefits of fMRI are better understood when they are reviewed according to the distinctive roles that fMRI can play —as a tool for improving the development of EEG-based BMIs— in the following application fields:

1) Mapping of brain functions
2) Combination of neuroimaging modalities
3) BMIs based on real-time fMRI (rtfMRI)
4) Multi-modal BMIs.

As it will be seen, on the first and third of these fields, fMRI provides supplementary knowledge to that already obtained through EEG; being this knowledge of different nature on one field with regard to the other. While the benefits of fMRI on the second and fourth fields would come from the deeper and more general understanding about the brain functioning that the integration of EEG with fMRI can provide. Therefore, in the first situation fMRI acts as a complementary source of knowledge, whereas in the last situation fMRI would act as a tool for boosting the EEG knowledge.

It must be remarked that the above classification does not intend to correspond to any rigorous taxonomy of scientific fields. In fact, not only these fields are not mutually exclusive, but their intersections are promising work areas. By introducing the above classification, our purpose is to provide a frame under which the rich possibilities of the interplaying between EEG and fMRI can be better apprehended. Table 1 shows how these fMRI application fields correspond to different types of neuroimaging modality, and goals that are relevant to the research on BMIs.

Table 1
Fields in which fMRI plays distinctive roles as a tool for enhancing EEG-based BMIs

	Goal	
	Brain function research	BMI development
Involved modality		
fMRI	Mapping of brain functions	rtfMRI-based BMIs
fMRI + EEG	Combination of neuroimaging modalities	Multimodal BMIs

Next, some author's contributions are presented to illustrate the role of fMRI, and the derived benefits for BMIs, on each of these fields.

5.1. Mapping of brain functions

The essential usefulness of fMRI comes from the topographical distributions of brain functions provided by this neuroimaging technique.

Some of the physiological signals that can be voluntarily regulated are the SCPs. Birbaumer [4] began in 1979 an extensive series of experiments demonstrating the operant control of these potentials, and the feasibility of using them to develop BMIs for completely paralyzed and locked-in patients. The SCPs can be observed on different brain areas, like the posterior parietal, the central, and the frontal. However, clinical studies in patients with lesions in the prefrontal lobe, or disorders related to this lobe, showed extreme difficulties for achieving control of SCPs in these patients. Recently, Hinterberger et al. [11] have used fMRI to gain more insight in the involved physiological processes, particularly the effects of self-regulation of SCPs on regional metabolic changes. They found that successful voluntary brain control of SCPs depends on activity in premotor areas and the anterior parts of the basal ganglia.

The capability of fMRI to identify activation in brain regions has proven also its utility for explaining the inter-subject variability of the EEG observations in: studies about the ability of patients with amyotrophic lateral sclerosis to plan a task [30], during passive and attempted foot movements on paraplegic patients [24], and for BCI-controlled spelling by a completely paralyzed patient [25].

Controlling robotic devices through BMIs involves a number of cognitive processes: attention, imagery, planning, decision making, overall control, etc. By this reason, brain signals must be interpreted, not only on an anatomical-base, but also on a physiological-base. fMRI is also very helpful on this. Thus, Pineda [27], investigating the functional significance of mu rhythms, found strong support on previous fMRI studies about the phenomenological independence of mu and other alpha-like rhythms. Mu rhythms are other kind of physiological signal that can be voluntarily regulated and is broadly used in BMIs.

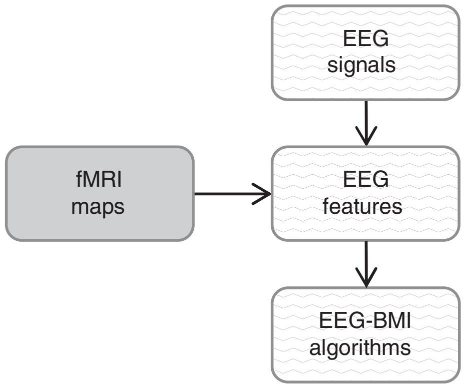

Fig. 1. Schematic showing EEG-based BMI data-processing complemented with functional maps supplied by fMRI.

fMRI, along with other neuroimaging techniques, has been used to study Neuroplasticity in amputees aiming to develop a new generation of prosthesis. So, Di Pino et al. [9] reviewed the literature concerning this phenomenon, assuming that in-depth analysis of the nervous system reorganization following limb amputation would allow deriving functional and technical specifications for bidirectional neural interfaces of cybernetic hand prosthesis. They concluded that new generations of 'natural' BMIs can be developed by fully exploiting neuroplastic phenomena to restore neural connections originally governing the lost limb and linking them to the prosthetic system.

In summary, the topographical distributions of brain functions provided by fMRI are helpful in many ways; namely: to localize, more accurately, the brain regions involved in the BMI operation, to determine their respective functional significance, and to adapt the interface to each specific user, not only at the initial stage, but also along its whole life-cycle. All of this complementary knowledge can have a positive impact on the feature extraction module of the BMI (see Fig. 1).

5.2. Combination of neuroimaging modalities

The previous section has presented fMRI as an independent, complementary source of knowledge to be added to the one derived from EEG. But, on the neuroimaging community there is a clear consensus that the most promising applications will come from the integration of different modalities of brain imaging.

Several works have already shown the kind of knowledge that multimodal acquisition and fusion can provide about the neural basis of hemodynamic and electrophysiological responses. Most of them follow one of these two approaches: to consider the combination of modalities as a simple verification of evidence convergence [8, 21, 29], or to localize the dipoles that generate the EEG signal, by assuming that there are a few equivalent dipoles and approaching the solution with the local maxima of the fMRI image used as constraints [1, 18, 23].

A weakness of the first approach is the lack of robustness of the obtained results. The trouble with source localization procedures is that they are ill-posed inverse problems and, without constrains, they have no unique solution; a fact that affects any data fusion scheme [15]. A second problem in this line of research is that it eludes the question of under what conditions co-registration makes sense [26], and how should EEG and fMRI signals really be combined, since they have not only very different spatial and temporal resolutions, but also correspond to different biophysical processes, even when both are products of a common brain activity.

Therefore, other efforts are oriented to develop true multimodal fusion methods; as for instance: extension of statistical parametric maps to evoked potentials (EP) [17], and decomposition of the EEG signal and correlating the results with the fMRI image [22].

The research on information integration methods is been enriched by investigations on the relationships among the physiological processes originating the different brain signals. Thus, Sotero and Trujillo-Barreto [32] have proposed an integrative biophysical model after studying the coupling between neural activity, electrophysiological, hemodynamic and metabolic processes. Other experimental studies have also reported couplings, and similar task-related activation patterns, between EEG slow waves and blood oxygenation level-dependent (BOLD) signals. Furthermore, both signals parametrically increased with increasing processing demands. Khader et al. [16] reviewed these studies founding support on them to claim that hemodynamic and electrical brain signals are systematically related in humans performing demanding cognitive tasks. They also extended the findings to the EEG waves slower than 1 Hz.

There is a growing interest in combining EEG and fMRI data, as they provide paired information. EEG is characterized by high temporal, poor spatial resolutions, while fMRI is characterized by just the opposite. However, experiments combining both neuroimaging techniques pose their own technical challenges. Hinterberger et al. [12] conducted the experiments with an EEG-driven BCI inside a MR scanner while recording simultaneously both functional signals. In their paper they discussed the technical aspects and pitfalls of combined fMRI data acquisition and EEG neurofeedback. Also, efforts have even been devoted to develop data formats for simultaneous EEG and fMRI recordings [2].

Multimodal imaging allows also trying out with new experimental paradigms. Bianciardi et al. [3], after reviewing previous studies, concluded that simultaneous recording of EPs and fMRI is necessary when stimulus-related activity has certain degree of unpredictability. So, they recorded BOLD-fMRI interleaved with EPs for single-epochs of visual stimulation. Their goal was to investigate the possible relationship between these two measures, similarly to other abovementioned works. Their results showed that the concurrent recordings of EPs and fMRI, on a single-trial approach, permits the assessment of between-trials variations of EEG responses and their relationship with other parameters, i.e.: stimulus intensity, psychophysical performance, and fMRI responses.

In short, the combination of neuroimaging modalities is a powerful tool to get insight about the interrelationship of the biophysical processes underlying mental activities. It is particularly useful when the combined images are concurrently recorded and, overall, when images are really fused on integrated models. The provided benefits may improve significantly the development of BMIs by allowing better feature extraction and more robust translation algorithms (see Fig. 2). Moreover, it allows the development of multimodal BMIs, from which additional benefits will be obtained —see section 5.4—.

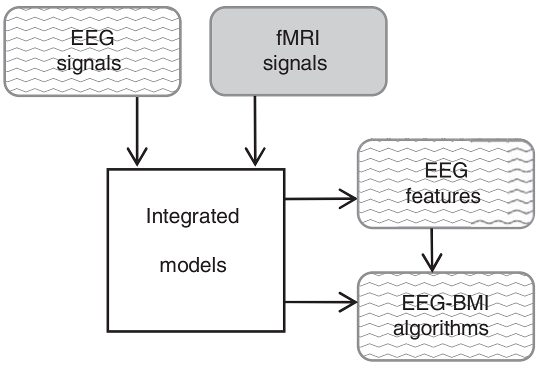

Fig. 2. Schematic showing EEG-based BMI data-processing boosted by the combination of EEG and fMRI imaging modalities.

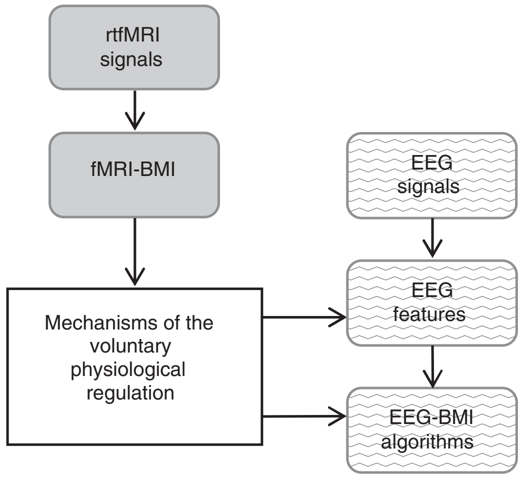

Fig. 3. Schematic showing EEG-based BMI data-processing complemented with knowledge supplied by rtfMRI.

Nevertheless, many challenges still exist in this application field as regard to key issues like: integration methods, biophysical modelling, experimental techniques, etc. Consequently, the prospects for enhancing BMIs on this field exceed thus far the practical achievements.

5.3. *rtfMRI-based BMIs*

Further potentials of fMRI arise when it is used to drive the brain-machine interface by itself. Weiskopf et al. [37] demonstrated for the first time that healthy patients are capable to regulate BOLD responses from circumscribed cortical and subcortical brain regions using on-line functional magnetic resonance imaging [6].

Lee et al. [20] have extended this research line to the fields of HRI and BMI. Thus, they have presented recently a rtfMRI-based BMI whereby 2-dimensional movement of a robotic arm was controlled by the regulation —and concurrent detection— of regional cortical activations in the primary motor areas.

Other immanent benefits of real-time fMRI were pointed out by Weiskopf et al. [38], after reviewing the studies that made fMRI feedback be a feasible methodology to facilitate the voluntary control of brain activity. They conclude that physiological self-regulation of the local BOLD response is a new paradigm for cognitive neuroscience to study neurobiology of learning, brain plasticity, and the functional relevance of regulated brain areas by modification of behaviour.

Concerning the benefits of this novel technique for complementing the knowledge provided by EEG, and then for overcoming limitations on the development of EEG-based BMIs, Weiskopf et al. [39] have pointed out the utility of rtfMRI on neurofeedback experiments. Neurofeedback allows studying the effect of self-regulated brain activity on behaviour. While some behavioural effects have been reported for EEG, its limited spatial resolution complicates the assessment of how they depend on the location and function of the self-regulated brain structure. On the contrary, rtfMRI-based BMIs allow studying of self-regulatory activity across the whole brain with high spatial resolution. Also, Lee et al. [20] have reported that the information obtained from rtfMRI for BMI may also be adopted to calibrate and optimize the EEG-based BMIs.

To sum up, rtfMRI-based BMI is a novel technique which can supply complementary knowledge for EEG-based BMI, in a very similar way that fMRI is complementary to EEG (see Fig. 3).

5.4. *Multimodal BMIs*

Multimodal BMI can be considered as an extension of the combination of neuroimaging modalities —see section 5.2— with the particularity that the concurrent recording is oriented to drive the BMI by means of integrated features and algorithms, instead of applying it for enhancing one modality by the other (see Fig. 4).

Bianciardi et al. [3] have recently suggested that this kind of BMIs might be developed for patients with severe motor deficits. According to their findings, the combination of EEG and fMRI, concurrently recorded

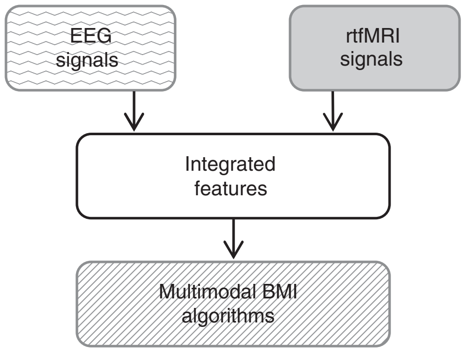

Fig. 4. Schematic showing the data-processing of a multimodal BMI based on EEG and fMRI.

within a single subject, provides additional benefits to those obtained from single-modality BMIs; as for instance: paradigm improvement, enhancing the sensitivity and selectivity of BMI algorithms by on-line dipole modelling and/or weighting the EEG signals measured at different electrodes, direct comparison of the performances of BMIs based on different single modalities, etc.

For the moment, multimodal BMIs are more a matter of concept than lab prototypes. Certainly, they will have their own interest as a new category of BMIs, but it is also expected that its use would provide useful knowledge for the design of EEG-based BMIs, in a similar manner that the rtfMRI BMIs are useful for this purpose.

6. Conclusions

Brain-machine interfaces are promising technical aids for people affected by severe neuromuscular disorders. Among them, those based on electroencephalography are today the better trade-off choice and the most commonly used. However, there are still important bottle-necks preventing these interfaces being broadly used by patients in their every-day life. Important topics to be addressed are:

1) Understanding the neurophysiologic processes in which BMIs are based.
2) Monitoring activity across the whole brain with enough time and spatial resolutions.
3) Developing efficient and reliable brain signal decoding algorithms.
4) Faster and easier adaptation of the BMI to the user.

Reviewing a representative sample of author's contribution, this paper has shown how fMRI can play a major role on the investigation of the abovementioned topics. The review has distinguished four fMRI application fields in which this technology plays distinctive roles as a tool for improving the development of EEG-based BMIs. These fields cover the use of single and multiple neuroimaging modalities, and the two basic goals that are relevant to the research on that interfaces.

Concerning to the use of fMRI alone, functional brain mapping is the field from which more obvious and immediate benefits are obtained for the development of EEG-based BMIs. Further benefits of fMRI are obtained when it is used on real time to drive brain-machines interfaces by itself. In both cases, fMRI acts as a complementary source of knowledge about the brain functions and the underlying mechanisms involved in BMI.

Concerning to the combined use of the complementary, non-invasive EEG and fMRI modalities, the expected benefits from this field are enormous for EEG-based BMIs, but they heavily depend on the previous development of effective data fusion methods, and accurate models relating the EEG and fMRI observations to the neural activity. Therefore, though the combination of neuroimaging modalities is a fertile research field, getting practical results for EEG-based BMIs is not so immediate. The last field, multimodal BMIs, is also subordinated to these developments and its results are even more distant on time. In both fields fMRI would act as a tool that boosts the EEG knowledge.

Acknowledgments

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