Journal of Psychiatry and Neurology

Nogueira GN, et al., 2023-J Psy Neurol
Research

Advances in Brain-Machine Interface Research: 2023 update

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Received Date: 11-03-2023

Accepted Date: 11-13-2023

Published Date: 11-24-2023

Abstract

Introduction: There have been many studies proposing new functionalities that would increase the capacity of the brain-machine interface and significantly improve the quality of life of people with reduced mobility, such as the combination with virtual reality, which would provide a safe navigation experience. There are still many topics that have not yet been fully explored in the brain-machine interface.

Objectives: List the most recent and main discoveries on the subject and showing the importance of these discoveries.

Methodology: This study is a literature review, which used the DeCS/MeSH descriptors "Brain-Computer Interfaces","neural pathways" and "brain mapping" intertwined with the Boolean operators "AND" or "OR", to search the PubMed, ScienceDirect and VHL databases.

Results: Brain-machine interfaces have shown great success in decoding intended movements from neural activity recorded in the primary motor cortex and then restoring motor control of their own hand in people with tetraplegia. The big problem lies in the lack of tactile feedback, which undermines this significant progress in neurorehabilitation. Some brain-machine interfaces provide a direct and intuitive means of communication between external devices and people, eliminating the need for external controls. They record brain activity and translate control commands to an output device.

Conclusion: The data is still limited, and the information obtained on the Brain-Machine interface is not close to an outcome. There is still a need for more work to have a broader understanding of the subject.

Keywords: Neural pathway; Stroke; Neurorehabilitation; Brain machine; Chronic lesions.

Abbreviations: BMI: Brain Machine Interface; FES: Functional Electrical Stimulation.

Introduction

Brain-machine interfaces are systems that decode the intended movements of neural activity and use it to control external devices such as wheelchairs, mechanical prostheses, exoskeletons, and voice synthesizers [1].

The brain-machine interface is an interface that has the potential to reach high expectations, establishing a two-way interaction between the brain and the machine. In recent years, the creation of a closed circuit between the brain and the external device for movement control has received enormous attention.

Researchers have focused on developing brain-machine interface algorithms and in most of these algorithms the recorded activity of the motor section has been used to restore movement capacity or eliminate neurological deficiencies in people who have lost it [2].

Other advances in the field of brain-machine interfacing show that it is possible to artificially bypass severe neurological injuries and reanimate paralyzed limbs through the learned control of external devices [3].

Recently, there have been many studies proposing new functionalities that would increase the capacity of the brain-machine interface and significantly improve the quality of life of people with reduced mobility, such as the combination with virtual reality, which would provide a safe navigation experience.

There are still many topics that have not yet been fully explored in the brain-machine interface [4].

The aim of this study is to carry out a literature review on the importance of and advances in brain-machine interface research, listing the most recent and main discoveries on the subject and showing the importance of these discoveries, in order to stimulate further studies on the brain-machine interface.

Methodology

This study is a literature review, which used the DeCS/MeSH descriptors "Brain-Computer Interfaces”, "neural pathways" and "brain mapping" intertwined with the Boolean operators "AND" or "OR", to search the PubMed, ScienceDirect and VHL databases. The period was from 2019 to 2023.

Thus, 88 articles were found, according to the inclusion criteria, language in English, Portuguese and Spanish, free text in full and relevant aspects on the guiding question, such as direct approach on the importance of Brain-Machine interfaces and the main achievements discovered and applied in everyday life. In the end, 88 articles were analyzed, of which 16 were selected to make up this review.

Results

Brain-machine interfaces have shown great success in decoding intended movements from neural activity recorded in the primary motor cortex and then restoring motor control of their own hand in people with tetraplegia.

The big problem lies in the lack of tactile feedback, which undermines this significant progress in neurorehabilitation. Some brain-machine interfaces provide a direct and intuitive means of communication between external devices and people, eliminating the need for external controls. They record brain activity and translate control commands to an output device.

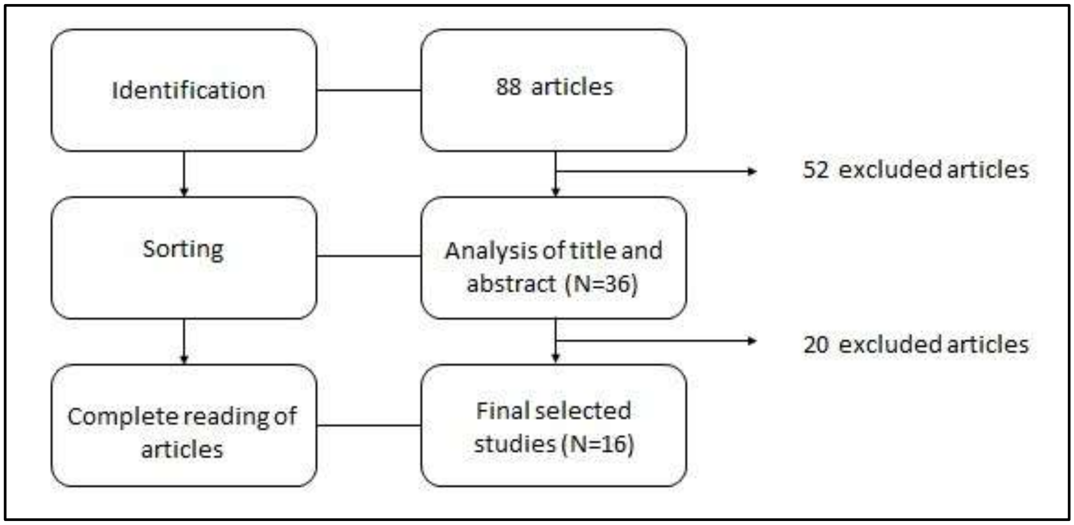

Figure 1: Flowchart of the articles selected in the narrative literature review.

Discussion

The brain is a dynamic and complex network, and an advanced understanding of its working mechanisms requires observation and study. The study of brain disturbance can provide insights into cause and effect, as well as how it can represent and process spatial information in complex multi-level and multi-room environments [5,6].

With the creation of a closed circuit between the brain and the external device to control its movement, these circuits have received more attention in recent years. The possibility of using decoding signals from the motor cortex to directly stimulate the spinal cord to create movements in paralyzed limbs is a topic that has been well explored in recent years [2]. Brain-machine interfaces have shown great success in decoding intended movements from neural activity recorded in the primary motor cortex and then restoring motor control of their own hand in people with tetraplegia. The big problem lies in the lack of tactile feedback, which undermines this significant progress in neurorehabilitation [1]. Some brain-machine interfaces provide a direct and intuitive means of communication between external devices and people, eliminating the need for external controls. They record brain activity and translate control commands to an output device [7].

One of the recent advances in the stereotactic placement of depth electrodes, also known as stereo electroencephalography, is that they provide more reliable access to cortical and subcortical targets deeper in the brain.

These electrodes are widely used to localize the onset of drug-refractory epileptic seizures and also to better understand the functioning of neural connections in movement studies.

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In addition to all the advantages, the electrode implantation procedures are minimally invasive and have low infection rates [1,8].

Another advance in the field of brain-machine interface is the reanimation of paralyzed limbs through the learned control of external devices. Patients with severe neurological insults, such as quadriplegics, can bypass the lesion by means of multiple implanted electrodes, where spikes and field potentials are recorded in the motor representation areas of the hand, and have been able to learn to control a computer cursor in different directions, as well as a robotic arm, performing three-dimensional reaching and grasping movements [3].

In addition, several stroke-related studies have recently been published, such as functional connectivity and the reconfiguration of neuronal networks. Stroke patients show more extensive interruptions in brain pathways during movement activities compared to healthy individuals.

In addition, a reconfiguration between the contralateral ipsilesional and subcortical somatomotor networks showed a better outcome of motor activity, so the use of the contralateral hemisphere may represent a compensatory mechanism for recovery in chronic stroke patients [3,9].

Another alternative treatment for patients suffering from chronic lesions caused by strokes is the use of Functional Electrical Stimulation, combined with the use of the Brain-Machine Interface. The study concluded that this therapy helps to strengthen the corticospinal tract, although more patients need to be tested in order to have a more conclusive answer. In addition, the novel-PAS intervention was investigated, and it was concluded that the use of the technique increases corticomotor excitability, which can enhance motor learning. However, this technique has only been tested on healthy people and therefore needs to be tested on people who have suffered a stroke in order to better understand the capabilities and limitations of this technology [10,11].

Another study on freezing gait, characteristic of Parkinson's Disease, revealed that this sign is due to a loss of synchrony between the cortex and the striatum. Such deficiencies in connectivity are related to behavioral factors (cognitive, motor, and limbic) that can contribute to the appearance of this sign. Once again, there is a need for further studies to better investigate this sign and its subtypes, as well as proposing an improvement in therapy and prognosis [12].

The anatomical correlation of neural pathways is also of paramount importance for the development of new technologies related to this new part of medicine. One study correlated the use of virtual tools and real tools and how they are interpreted in the brain and the visual pathways used by them. Virtual tools are treated by the brain in a similar way to physical tools, but cortical currents respond more intensely to visible tools.

Three main pathways have therefore been defined: the dorsal pathway, related to motor planning; the ventro-dorsal pathway, related to how a tool works in each environment; and the ventral pathway, which identifies the

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ways in which a tool should be interacted with. Understanding the motor pathway can also be greatly explored by the Brain-Machine Interface, which suggests how many therapies are being created using this technology [13,14].

Author/Year of Publication	Journal	Object of Study
CHANDRASEKARAN et al, 2021	Journals Elsevier	Two participants with intractable epilepsy.
AMIRI et al, 2022	Heliyon	Anesthetized rats.
FERRERO et al, 2023	iScience	Ten healthy individuals and two patients with spinal cord injuries.
CARIA et al, 2019	Neurotherapeutics	Thirty participants.
QIAN et al, 2018	Translational Psychiatry	Sixty-six boys with ADHD, combined or inattentive subtypes.
CASPAR et al, 2021	PLOS ONE	Thirty right-handed participants were recruited.
YANG; VAN HULLE 2023	Sensors	Twenty-one healthy adults with no neurological complaints, aged between 18 and 31 years old.
KLINK et al, 2021	NeuroImage	Literature review.
VANGILDER 2021	Acta Psychologica	Forty-five non-demented elderly people.
WU et al, 2022	Journal of Neural Engineering	5 people with epilepsy - 2 children.
CHENG et al, 2021	Scientific Reports	19 people with subcortical stroke and 11 healthy people.
STAIGER et al, 2021	Physiological Reviews	Literature review.
CARIA et al, 2020	Neurotherapeutics	16 people with stroke and loss of unilateral hand movements and 14 people under control.
HENNIG et al, 2018	eLife	Three male Rhesus monkeys.
BIASIUCCI et al, 2018	Nature Communications	27 people with a stroke, which caused chronic disability.
KIM; MAGUIRE, 2018	Cerebral Cortex	30 healthy people, 15 men and 15 women, all right-handed.
EHGOETZ et al, 2018	BRAIN	41 people with Parkinson's disease
RALLIS et al, 2018	Neuropsychologia	12 participants, 7 women and 5 men, all right-handed.
OLSEN et al, 2018	Neuromodulation	10 healthy adults.

Table 1: Characterization of studies according to authorship, year of publication, journal, language, and object of study.

Author/Year of Publication	Objective	Results
CHANDRASEKARAN et al, 2021	The use of stereoelectroencephalography with depth electrodes aimed at stimulating the sulci of the primary somatosensory cortex can evoke focal sensory perceptions in the fingertips.	Stimulation of the sulci in humans in the region of the somatosensory cortex evokes sensory perceptions located in the fingertips more often than gyral stimulation.
AMIRI et al, 2022	Use the brain-machine interface algorithm based on local field potentials to create the closed-loop interaction between the external device and the S1-M1 network model.	The proposed algorithm based on local field potentials was better than the "spike train" algorithm at controlling an external device. The quantitative and qualitative results confirm the adequate performance

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		of the proposed algorithm compared to the "spike train" algorithm, which is known as a validated algorithm on real data.
FERRERO et al, 2023	Explore the use of the brain-computer interface based on motor imagery for the control of a lower limb exoskeleton to aid motor recovery after a neural injury.	It was found that the use of virtual reality for shorter training did not reduce the effectiveness of the brain-machine interface, in some cases even improving it. It was observed that the patients were able to cope with the experimental sessions while reaching high levels of physical and mental effort.
CARIA et al, 2019	To investigate neural plasticity in the motor network of severely impaired stroke patients after treatment based on electroencephalogram-ICM (brain-machine interface) reinforcing the sensory-motor contingency of ipsilesional motor commands.	Structural connectivity analysis revealed a decrease in fractional anisotropy in the splenium and corpus callosum, and in the counter-lesional hemisphere in the posterior branch of the internal capsule, the posterior thalamic radiation and the superior corona radiata. Functional connectivity analysis showed decreased negative interhemispheric coupling between contralesional and ipsilesional sensorimotor regions and decreased positive intrahemispheric coupling between contralesional sensorimotor regions.
QIAN et al, 2018	To examine the large-scale topological changes of brain functional networks induced by the 8-week BCI-based attention intervention in boys with ADHD using resting-state functional magnetic resonance imaging.	The results suggest that attention training based on the brain-machine interface facilitates behavioral improvement in children with ADHD by reorganizing the brain's functional network from more regular to more random configurations, particularly by renormalizing the processing of the salience network.
CASPAR et al, 2021	To examine whether the lack of sensory-motor information when using a brain-machine interface would diminish the primary experience of agency and to investigate how the degree of control over the brain-machine interface would lead to greater incorporation of the robotic hand.	The lack of sensory-motor information when using the brain-machine interface did not seem to influence the sense of agency. It was also observed that experiencing less control over the brain-machine interface reduced the sense of agency. It was also observed that the better the participants controlled the brain-machine interface, the greater the appropriation of the robotic hand, as measured by scores. of the robotic hand, as measured by body ownership and agency scores.
YANG; VAN HULLE 2023	A new MI-BCI (motor imagery-brain-machine interface) application was proposed, based on an 8-electrode dry electroencephalogram configuration,	The results showed acceptable performance, even given the limitations of the electroencephalogram configuration, which we attribute to the design of the

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	with which users can explore and navigate in Google Street View®.	BCI app. The study suggests the use of MI-BCI in future games and virtual reality applications for consumers and patients temporarily or permanently deprived of muscle control.
KLINK et al, 2021	Research established and new non-reversible (lesion) and reversible brain disruption approaches using electrical, pharmacological, optical, optogenetic, chemogenetic, pathway-selective or ultrasound with the aim of providing a resource on the most commonly used techniques and some new ones with substantial promise.	Brain disruption methods are vital for advancing our understanding of the causal mechanisms of distributed brain functions. Employing brain disruption techniques in non-human primates has been and will continue to be instrumental in scientific advances. Combined with neuroimaging, this technique can become even more powerful, allowing visualization throughout the brain of the impact the perturbation has had on brain systems and interconnectivity.
VANGILDER 2021	To identify which visuospatial test is most predictive of motor learning in the elderly.	The long-term motor learning capacity of the elderly can be assessed using the Rey-Osterrieth test, which is the most feasible to administer before motor rehabilitation to indicate the risk of non-responsiveness to therapy.
WU et al, 2022	Investigate the possibility of continuous force decoding using stereoelectroencephalography (SEEG) signals.	Initially, temporal-spectral representation analyses were carried out, which revealed very distinct spectral modulation in sustained grasping tasks compared to previous studies using ECoG or EEG. It was then shown that sustained grip force can be decoded with high accuracy, with a deep learning method achieving the best decoding accuracy. The decoded force reflected the true "rest or task" state, as well as the continuously changing amplitude under different increasing rates and force targets.
CHENG et al, 2021	To understand the functionality of the brain-machine interface in restoring movement in patients with lesions, especially in subcortical areas.	Chronic subcortical stroke patients showed more extensive changes in functional brain networks during tasks compared to the resting state, especially in cognitive, somatomotor and subcortical networks. In addition, they showed less efficient reorganization of task-related brain networks compared to healthy individuals, at different levels of task demands. It is worth noting that the functional connectivity of the brain and the specific reconfiguration of networks at baseline were able to predict motor recovery.

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CARIA et al, 2020	The structural reorganization of motor networks in chronic strokes was investigated with a brain-machine interface treatment based on electroencephalography.	The changes in the fractional anisotropy of the white matter were predominantly related to the connections between the cerebral hemispheres and to the hemisphere unaffected by the stroke. This finding suggests that recovery in chronic patients with severe stroke can be achieved by reorganizing brain connections in the unaffected hemisphere and taking advantage of preserved motor circuits in the affected hemisphere. The chronic phase of stroke is widely known as a period in which the adaptive processes of regeneration are considered to be practically non-existent. This has led to a significant limitation in treatment options, with the clinical community generally focusing on palliative and assistive interventions. However, our results highlight the essential importance of the non-invasive BMI approach, as it makes it possible to stimulate preserved brain systems that would normally not be accessible in patients with severe motor network dysfunction. This stimulation can trigger functionally adaptive mechanisms that favor motor recovery.
HENNIG et al, 2018	Neuronal redundancy in the primary motor cortex using a Brain-Machine Interface.	Assumptions based on the principles of minimum firing and minimum intervention, derived from theories of muscular coordination, did not accurately predict the activity observed without output. On the contrary, the distribution of dead-end activity was well predicted by the activity in the two dimensions with output potential. This connection between activity with output potential and activity without output suggests that when activity with output potential is used to meet the demands of the task.
BIASIUCCI et al, 2018	To study motor improvement in stroke patients through the use of a brain-machine interface for rehabilitation together with the use of FES in therapy.	The study concludes that functional electrical stimulation (FES) alone is not sufficient for the long-term rehabilitation of stroke patients; however, the brain-machine interface combined with FES aids recovery and therefore improves the patient's prognosis.
KIM; MAGUIRE, 2018	How a three-dimensional multi-compartment space (a multi-level gallery building) was represented in the human brain using behavioral	Behaviorally, we observed faster egocentric spatial judgments within the same room and a priming effect when visiting the same room in an object

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	tests and functional magnetic resonance imaging repetition suppression analyses.	location memory test, suggesting a segmented mental representation of space. At the neural level, we found evidence of hierarchical coding of this three-dimensional spatial information, with the left anterior lateral hippocampus containing local information about the corners within a room, while the retrosplenial space cortex (RSC), parahippocampal cortex and posterior hippocampus contained information about the rooms within the building. In addition, both behavioral and fMRI data were consistent with an unbiased coding of vertical and horizontal information.
EHGOETZ et al, 2018	To deepen our knowledge of the freezing of gait in Parkinson's disease. Understand how the three visual streams work (dorsal-dorsal, ventro-dorsal and ventral) when using a virtual tool to reach a target.	The deficits are related to cognitive, motor and limbic factors. Thus, the study concludes that there are different types of gaits, however, the best way to treat it is by treating the main causes, such as anxiety.
RALLIS et al, 2018	To deepen our knowledge of the freezing of gait in Parkinson's disease. Understand how the three visual streams work (dorsal-dorsal, ventro-dorsal and ventral) when using a virtual tool to reach a target.	Virtual tools activate the same cortical areas as physical ones. Thus, the most used pathway was the ventral, however, in more complex moments, the dorsal-dorsal and ventro-dorsal pathways were more requested, although there was still a predominance of the ventral pathway.
OLSEN et al, 2018	Changes in the excitability of the motor cortex of healthy people in a single 60-minute session of paired associative stimulations (novel-PAS).	Paired associative stimulations (novel-PAS) can increase the excitability of the motor cortex in healthy people, however, more studies are needed to find out whether people who have suffered a stroke will have the same effect.

Table 3: Description of the objective and results of the studies in the sample according to authorship.

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