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REVIEW PAPER

Bridging the Gap between the Body and the Machine: Embodied Learning with Interventional Brain Computer Interfaces?

Leila Ali[1,2], Clorinda Sorrentino[1], Angelina Vivona[1], Lucia Martiniello[1]

[1]Pegaso University, Faculty for Human Sciences, Napoli, Italy, [2]University of Camerino, School of advanced studies, Camerino, Italy

Abstract

This review aims to understand how the body and the brain interact with different brain computer interfaces (BCI) and to analyze the implications of these tools on embodied learning in the educational field. Through a theoretical approach a review of the literature is developed by studying the relationship between the body, the brain and BCI. To conduct this research, the keywords "embodied learning", "cognition", "digital learning", "body", "brain-computer interface" were used in Pubmed, Frontiers, Google Scholar and Researchgate. There are multiple concepts related to digitization and they can vary from owning digital tools such as computers, phones, virtual reality devices to even using interventional BCI. BCI are being reported safe and are capable of reversing physical and cognitive disabilities. The impact of these tools is variable according to their nature, the environmental factors linked to their use, and the condition of the brain and body while using them. With the massive development of technology nowadays many interrogations are coming into surface about the relationship between the human and the machine, and at what level the digital world will be able to interfere with our lives and integrate our bodies.

Keywords: *brain augmentation, digital learning, neuroscience, education*

Introduction

Brain computer interfaces were established in 1929 with the invention of electroencephalography (EEG) that allowed the detection of brain activity and translating it into electrical signals (Spüler, 2017). But it wasn't until 1973 that Jacques J. Vidal invented in his paper "Toward direct brain-computer communication", the term Brain-Computer-Interface (BCI) (Rebolledo-Mendez et al, 2009). BCIs can be classified according to their external technical implementation to (open-loop: recording) or closed-loop (recording and stimulation), or their internal implementation to non-invasive or invasive (Saha et al., 2021). The 2020 horizon of brain neural computer interaction and the European commission of BCI use in research coordination identified 6 application themes for BCIs as follows: Restore, Improve, Replace, Enhance, Supplement, and use as a Research tool (Saha et al., 2021). BCIs use in cognition lies under the umbrella term of brain augmentation (Jangwan et al., 2022). Some BCIs have been proven to interfere with cognition and thus learning. The term embodied cognition means that the body is crucial for cognition. However, with the invention of BCIs this relationship is questionable regarding the possibility that BCIs can replace or complement the body function in cognitive learning (Serim et al., 2023). The use of BCIs in educational settings is recent and still limited, yet the understanding of how these tools can interfere with physical and cognitive capacities is important. Given the inevitable increase in technologies' implementation in educational settings it is important to describe the underlying theoretical perspectives and recent pedagogical and neuroscientific research findings on the use of BCIs and their impact on embodiment as a physical and cognitive learning phenomenon.

It is in this theme that this research aims to understand

Correspondence:

Leila Ali
Pegaso University, Faculty for Human Sciences, Centro Direzionale Isola F2, Via Giovanni Porzio, 4, Napoli, Italy
E-mail:leila.ali@unicam.it

how the body and the brain interact with different brain computer interfaces (BCI). We will also analyze the implications of these tools on embodied learning (EL) in the educational field.

Discussion

There are multiple concepts related to digitization and they can vary from owning digital tools such as computers, phones, virtual reality devices to even using interventional BCIs. Some BCIs are being reported safe and capable of reversing physical and cognitive disabilities. The impact of these tools is variable according to their nature, the environmental factors, and the condition of the brain and body.

Through a theoretical approach a narrative review of the literature is developed by studying the relationship between the body, the brain and BCIs. To conduct our research, we used the keywords "embodied learning", "cognition", "digital learning", "body", "brain-computer interface" in Pubmed, Frontiers, Google Scholar and Researchgate.

This review will start by discussing embodied cognition and embodied learning (EL) from a neuroscientific point of view. Then describe the different available BCIs used for cognitive brain augmentation and learning. And finally identify the principal theoretical and empirical impacts of using BCIs on EL.

Neuroscientific basis of embodied cognition and EL

Embodiment is a phenomenon that explains how the brain-body interaction with the environment generates intelligent behavior. Cognitive hypotheses of embodied cognition include: 1. Replacement hypotheses that highlight the role of sensory-motor contingencies induced by movement within an environment in controlling behavior. 2. Constitution hypotheses stating that cognitive systems built in the brain extend to the body and environment. And that bodily and environmental cues can be part of the memory system. 3. Influence hypotheses that describe a bidirectional interaction between the body and the brain in cognition. In this context, physical states of the body can alter cognition and cognitive rehearsal training can improve procedural skills. 4. Conceptualization hypotheses postulating that sensorimotor networks stimulation induces concepts' creation that are fundamental building blocks for grounded cognition (Matheson & Barsalou, 2018). Sensorimotor experiences generate information linked to all types of concepts; abstract and concrete (Harpaintner et al., 2020). Conceptualization hypotheses are the most commonly used in embodied cognitive neuroscience. Mirror neurons theory is based on conceptualization and implies that similar neural activation firing occurs when we perform an action, and also when we observe another person performing it (Caramazza et al., 2014). Language as a social communication tool also re-enhances embodied experiences by reactivating sensory-motor networks' clusters and cognitive processes (Macedonia, 2019). These concepts within the brain are represented through neural networks or modality specific systems that respond with high specificity to the different modalities of sensory or motor stimulation and that are organized hierarchically. These hypotheses highlight the importance of sensorimotor stimulation in the generation and quality of embodied cognition and have been confirmed by many neuroimaging studies (Matheson & Barsalou, 2018; Harpaintner et al., 2020). In figure 1 we present a simplified illustration of the basics underlying embodied cognition hypotheses.

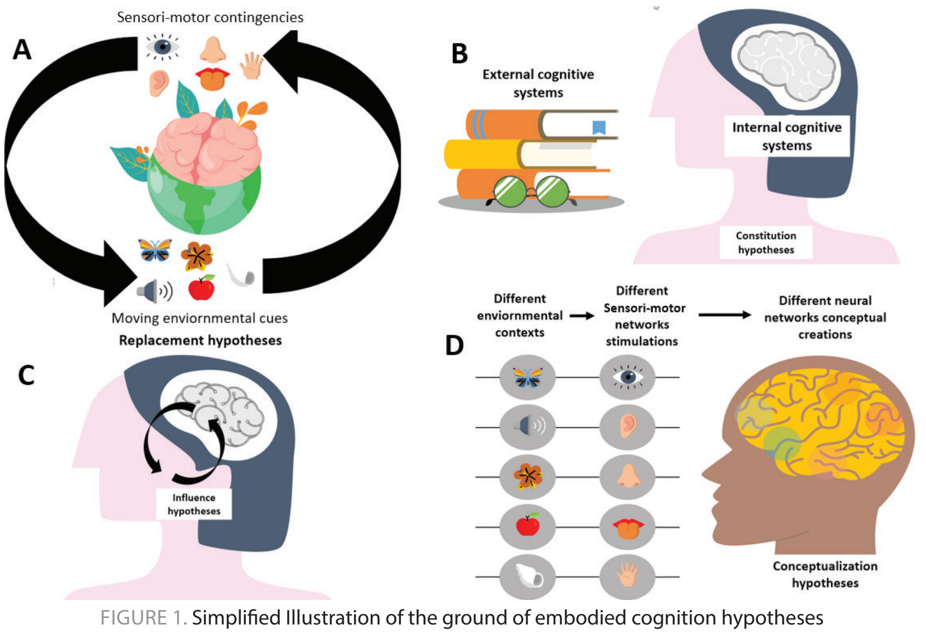

FIGURE 1. Simplified Illustration of the ground of embodied cognition hypotheses
Legend A. Replacement hypotheses: kinetics environmental cues induce sensori-motor contingencies that stimulate embodied cognition and thus control behavior accordingly. B. Constitution hypotheses: there are both external and internal cognitive systems. C. Influence hypotheses: the body and brain are interdependent in generating cognition. D. conceptualization hypotheses: different environmental contexts activate different sensori-motor networks that generate different neural conceptual cognitive networks.

BCIs use in embodied cognition focuses mainly on conceptualization hypotheses. BCIs like transcranial magnetic stimulation (TMS) and magnetic encephalography (MEG) helped understand the role of modality specific stimulation in establishing brain grounded cognition (Matheson & Barsalou, 2018), and how contextualization can modulate motor action and behavior.

Three major themes are the basis of future research in grounded cognitive neuroscience (Matheson & Barsalou, 2018): The first is associative processes that help generate predictions based on bidirectional feedback of Hebbian learning rule. Hebbian learning postulates that synaptic plasticity is at its maximal function when both the presynaptic and post-synaptic neurons are activated (Munakata & Pfaffly, 2004). Sensory-motor features are thus modulated by networks of neurons called "maps" among which some are "controllers". These latter are formed and activated based on variable experiences that generate different associative weights guiding intelligent behavior (Matheson & Barsalou, 2018). The second is network dynamics. In fact, this phenomenon implies that brain cognitive function is based on connectomes and clusters of concepts that are characterized by their dynamic distribution, degree of activation, and the modality of physical and environmental stimulation (situatedness). Network dynamics are thus context dependent (Matheson & Barsalou, 2018). The third theme is representation. Representation is a foundation of classical construct cognitivism that depends on semantic content and implies a structural aspect that requires 4 elements: homomorphism between the target and the internal state, causal connection between them, the possibility of decoupling, and their role in action control (Piccinini, 2018).

To summarize, there 4 four main hypotheses that tried to explain embodiment and these are replacement, constitution, Influence and conceptualization hypotheses. They all affirm the important role of the body and external environment in cognitive embodiment processes. This interaction is dynamic and complementary at different levels. This dynamicity and interaction occur hypothetically through associative processes, network dynamics or representation.

Definition and use of BCIs in cognition and education
BCIs and brain augmentation

BCIs used to improve cognition and motricity fall under the umbrella term of brain augmentation (Jangwan et al., 2022). BCI tools are classified according to their external technical implementation to (open-loop: recording) or closed-loop (recording and stimulation), or their internal implantation to non-invasive or invasive (Saha et al., 2021). In the group of invasive BCIs (IBCI) a new term minimally-invasive has emerged describing interventional tools that do not require a craniectomy or do not enter in a direct contact with the brain parenchyma and that can be of temporary use with a possibility of safe removal, some of these tools include functional ultrasonography (fUS), the layer 7 cortical interface (Ho et al., 2022), and endovascular Stentrode (Mitchell et al., 2023).

Non-invasive BCIs can be subdivided into recording and stimulation tools (Saha et al., 2021). Brain augmentation interventions can require one or multiple BCIs (Jangwan et al., 2022). Brain augmentation in the classroom experiments used EEG (Rebolledo-Mendez et al, 2009; Spüler, 2017; Caitlin et al, 2017), EEG combined to virtual reality (VR) and intelligent tutoring systems (ITS) (Tremmel, 2019) or functional near infrared spectroscopy (fNIRS) (Watanabe et al., 2016; Oku et al, 2021) (Table 2). Other tools have potential cognitive benefits and are still limited to laboratory research or clinical settings like transcranial magnetic stimulation (TMS) using magnetic stimulation (Grau et al., 2014; Rao et al., 2014), and transcranial electrical stimulation (tES) and transcranial direct current stimulation (tCDS) using electric stimulation (Dockery et al., 2009; Coffman et al., 2014; Heth & Lavidor, 2015; Younger et al., 2016). Other tools like neuro-prosthetics are often used for restoring deficient senses (Wegemer, 2019). Table 1 summarizes the different BCIs according to their external and internal technical implementation.

Many BCIs are used in medicine for neurorehabilitation in patients with cognitive and motor disabilities (Jangwan et al., 2022). Their use has extended recently to robotics and healthy humans to serve in physical brain augmentation (Jangwan et al., 2022). Brain augmentation can occur through the use of physical, biochemical or behavioral strategies (Jangwan et al., 2022). Invasive BCIs' use is still limited to laboratory research and clinical settings for patients with neurological and psychiatric disorders (Zhao et al., 2023). Motion-based video games using computers and VR have been proved useful in EL efficacy by increasing academic performance and student engagement (Howison et al., 2011; Abrahamson & Lindgren, 2014; Verkijika & De Wet, 2015; Cook et al, 2016; Sullivan, 2018; Kosmas et al., 2019). Recording, stimulation and hybrid BCIs have been used in the classroom, computational neuroscience research, and clinical settings in patients with neuro-

Table 1. BCI tools according to their external and internal technical implementation.

		BCIs	References
Recording	Non- invasive	EEG, MEG, fMRI, fNIRS, PET	(Jangwan et al., 2022)
	Invasive	Electrodes: ECog, ICRT, Neuralink, iMEA	(Jangwan et al., 2022) (Saha et al., 2021)
	Minimally invasive	FUS Layer 7 cortical interface Endovascular: Stentrode	(Soloukey et al., 2023) (Ho et al., 2022) (Mitchell et al., 2023)
Stimulation	Non- invasive	tES, TMS, tDCS	(Jangwan et al., 2022)
	Invasive	Electrodes: ICST, ICMS, DBS, Neuralink,, iMEA close-loop-DBS	(Jangwan et al., 2022) (Saha et al., 2021)
	Minimally invasive	FUS Layer 7 cortical interface Endovascular: Stentrode	(Soloukey et al., 2023) (Ho et al., 2022) (Mitchell et al., 2023)

Legend: EEG: electro-encepahlography, MEG: Magnetic encepaholgraphy, fMRI: functional magnetic resonance imaging, fNIRS: functional near infrared spectroscopy, PET: positron-emission tomography, ECog: Electrocorticography, ICRT: intracortical recording, iMEA: intracortical microelectrode array, tES transcranial electrical stimulation, TMS: Transcranial magnetic stimulation, FUS: transcranial focused ultrasound stimulation, tDCS: transcranial direct current stimulation, ICST: intracranial stimulation, ICMS: intracortical micro-stimulation, DBS: deep brain stimulation.

logical and psychiatric disorders (Table 2). These tools showed promising results in neurorehabilitation, brain augmentation, and also personalized learning through the measurement of cognitive load (Table 2). The integration of BCIs in educational laboratory research is still scarce, and this may be due to their high cost (Vourvopoulos & Badia, 2016), the absence of a clear policy regarding their use in research education and the ethical consideration related to brain augmentation in the school environment (Zeng et al., 2021). With the new rising of minimally invasive BCIs, many questions are rising regarding the future of this human machine relationship and the evolution of homosapiens to homosapiens technologicus (Zehr, 2015). Table 2 summarizes classroom Kinetic virtual games to study the relationship between EL and BCIs reported useful in cognitive research in the classroom, laboratory research and clinical settings.

This section summarizes the classification of BCIs according to their technical external and internal implementation and the results of actual research on their use in brain cognitive augmentation and education. The rapid evolution of technology is bringing about breakthroughs in cognitive science evolution and opening up perspectives about the use of BCI in education to achieve a maximal and personalized learning efficacy. Nevertheless, the implementation of BCIs in schools should be planned ahead according the possible personal and social benefits and drawbacks. Their impact on brain health on the short and long term should be considered. In the next section we will discuss the dual relationship between BCIs and embodied learning and the controversies related to their impact on the body and embodied learning.

Theoretical and empirical concepts of embodied learning related to BCIs' use

Many BCIs have been used in research of embodied learning. To understand how BCIs interfere with EL we need to understand how the body participates in learning and the impact of these mechanistic aspects of BCIs on the body.

How the body participates in learning?

The body and language learning

Macedonia et al, showed that using fMRI brain network mapping in 31 right handed German natives helped identify enhanced linguistic performance by combining audio and visual stimulation by using metaphorical gestures with words in second language learning (Macedonia, 2019). Significant activation correlations ($p<0.05$) during sensorimotor and audiovisual tasks observations were found in the left fusiform gyrus, right superior temporal gyrus, right cerebellar vermis, right and left precentral gyri, and right and left inferior parietal lobules (Macedonia, 2019). In fact, during speech processing the brain uses a multi-sensory Hub for audiovisual information pairing. This hub includes areas in the posterior superior temporal sulcus/gyrus, or the superior parietal lobule (Gonzales et al., 2021). PET and fMRI studies have shown that abstract concepts of the amodal symbolic verbal system are mediated by the middle and superior temporal gyri, and left inferior frontal gyrus (Harpaintner et al., 2020). Which again highlights the role of sensorimotor modalities in abstract language processing.

The body and sciences learning

School experiments enhanced mathematic concepts learning by combining speech and gestures, and a link between counting and fingers (Macedonia, 2019). This association has been proven by functional MRI studies and seem to be linked to Hebbian learning mechanisms (Macedonia, 2019). The theory of grounded and embodied mathematical cognition (GEMC) implies that gestures are fundamental in learning sciences (Nathan & Walkington, 2017). Nathan et al showed in a study of 120 participants that mathematical intuition depended on body actions (Church et al., 2017). Smith et al on the other hand could prove that metaphorical arm gestures helped understand better geometric angle concepts (Smith et al., 2014). Studies in brain lesioned patients have shown that the motor cortex participates in processing numerical concepts, social interactions and mental processes (Harpaintner et al., 2020).

The body and sports education

Recent literature have demonstrated that physical activity and sports use embodied learning to improve motor and creative skills acquisition (Ravn, 2022). Embodied learning research in sports science helped identify that the intensity of physical exercise and situational variability induce motivation and improve attention, executive functions, and empathy (Ceciliani, 2018). Engström identified that movement enhanced expressing creativity during dance performance (Engström et al., 2018). Other studies have shown that mountain biking skills required embodiment experience shaped through environmental interaction (Ravn, 2022). The use of body-machine interfaces allowed a sophisticated and detailed analysis of the relationship between movement and emotional stimulation and the mirror neuron system (Grodal, 2009; Lim & Ku, 2018). A BCI-based action observation game in 15 healthy sujbects showed a significant stronger activation of the mirror neuron system (Lim & Ku, 2018). Other studies identified a relationship between specific situational race performance simulations and enhanced learning through perception-action and imagery skills (Bedir & Erhan, 2021).

BCIs and embodied classroom learning

Embodied cognition based on conceptualization and mirror neurons theory has been used in the classroom and has shown positive outcomes in terms of efficacy of learning based on motor actions, imitation, increased recall and comprehension (Sullivan, 2018; Macedonia, 2019). The challenges observed in learning in online-classroom could be explained by the low solicitation of embodied grounded cognition that requires motor and gesture-based cognitive stimulation (Sullivan, 2018). Within the context of education neuroscience, learning outcomes depend on instruction embodiment and its degree of sensitivity. Digital kinetic based learning tools using BCIs were used in the classroom and have proven efficacy in learning outcome and cognitive functions (Kosmas et al., 2019; Macrine & Fugate, 2021). BCIs that served in grounding embodied classroom learning include motion-based or kinetic games (Kosmas et al., 2019; Sullivan, 2018), functional brain imaging tools (fMRI/PET) (Harpaintner et al., 2020), and EEG coupled to VR or ITS or fNIRS (Rebolledo-Mendez et al., 2009; Spüler et al., 2017; Oku & Stato, 2021).

New brain to brain interfaces are short-cutting the necessity of body-to-body interactions for communication and individuals can communicate with computers and other indi-

Table 2. Kinetic virtual games studying the relationship between EL and BCIs reported useful in cognitive research in the classroom, laboratory research and clinical settings

BCI	Invasive (I) /Non-invasive (NI)	Healthy (H)/ Unhealthy (UH) participants	Use in the classroom (CL)/ laboratory (LAB)/ Clinical setting (CS)	Recording/Stimulation	References
			Motion based virtual games to assess embodied learning in the classroom		
Kinect Sensor	NI	H	CL	Embodied learning in physics education Engaging Statistics and research methods in psychology	(Sullivan, 2018)
Kinemathics project	NI	H	CL	Mathematical imagery trainings	(Howison et al., 2011)
Other video games	NI	H	CL	Reduce math anxiety	(Verkijika & De Wet, 2015)
MEteor	NI	H	CL	Astronomy education	
Uniboxit/ Lexis	NI	H	CL	Attention, working memory and language	(Kosmas et al., 2019)
Instructional avatar	NI	H	CL	Role of using gestures in mathematics learning	(Cook et al., 2016)
			Brain imaging, recording and stimulation tools in ground cognition		
fMRI	NI	H	LAB	Visual and motor abstract concepts' grounding Social cognition	(Harpaintner et al., 2020) (Parvizi & Kastner, 2018)
fMRI/PET	NI	H	LAB	Role of perceptual system in concrete concepts and verbal system in abstract concepts	(Wang, Conder, Blitzer, & Shinkareva, 2010)
EEG	NI	N/A I H H	LAB LAB CL CL	Humanoid robotic control Attention Attention cognitive work load	(Choi & Jo, 2013) (Cinel et al., 2019) (Abrahamson & Lindgren, 2014) (Rebolledo-Mendez et al, 2009) (Spüler et al., 2017, Caitlin et al., 2017)
EEG+ VR/ ITS	NI	H H H I	LAB CL CL CS	Emotion detection, and decision making Brain painting in virtual reality settings (art) Neuro-ergonomics, measuring work load Motor and cognitive rehabilitation	(Winslow et al., 2016) (Botrel et al., 2015) (Tremmel et al., 2019) (Vourvopoulos et al., 2016) (Arpaia et al., 2020)
MEG	NI	H	LAB	Social cognition	(Acar et al., 2013)
fNIRS+EEG	NI	N/A H H	LAB CL CL	Robotic control Attention Language learning	(Sereshkeh et al., 2019) (Oku et al., 2021) (Watanabe et al., 2016)
TMS+ EEG	NI	H (Animal) I	LAB CS	Brain to brain interaction Learning, attention, perception, memory, and decision making Treat pain, depression and psychotic disorders	(Rao et al., 2014) (Grau et al., 2014) (Coffman et al., 2014) (Lefaucheur et al., 2014), (Brunoni et al., 2016)
tES	NI	H	LAB	Learning, attention, perception, memory, and decision making Treat pain, depression and psychotic disorders	(Coffman et al., 2014) (Lefaucheur et al., 2014), (Brunoni et al., 2016)
tDCS	NI	I/H	LAB	Reading difficulties Sight word efficiency Memory enhancement Complex problem solving	(Heth & Lavidor, 2015) (Younger et al., 2016) (Cinel et al., 2019) (Dockery et al., 2009)
CLDA	NI	H (Animal)	LAB	Visuomotor learning	(Orsborn et al., 2014)
ECog	I	H	LAB	Social cognition, theory of the mind default mode network Working memory	(Tan et al., 2022) (Zhang & Jacobs, 2015)

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Table 2. Kinetic virtual games studying the relationship between EL and BCIs reported useful in cognitive research in the classroom, laboratory research and clinical settings

BCI	Invasive (I) /Non-invasive (NI)	Healthy (H)/ Unhealthy (UH) participants	Use in the classroom (CL)/ laboratory (LAB)/ Clinical setting (CS)	Recording/Stimulation	References
ICMS	I	H (Animal) I	LAB CS	Brain to brain interaction Perceptions (tactile and visual) restitution	(Rao et al., 2014)
DBS Closed loop DBS	I	I I I I	CS	Obsessive compulsive disorder, movement disorders, Post-traumatic stress disorder Insomnia Severe depression	(Dougherty, 2018) (Meeres et al., 2022) (Castillo et al., 2020) (Guidetti et al., 2021)
Neuralink	I	I/H	LAB	Potential in motor and cognitive rehabilitation, and brain augmentation	(Musk, 2019)
FUS	Minimally I	H (Animal)	LAB	Movement planning	(Norman et al., 2021)
L7CI	Minimally I	I	LAB	Potential cognitive and motor rehabilitation	(Ho et al., 2022)
Stentrode	Minimally I	I	LAB	Cognitive computer control in motor disabled patients	(Mitchell et al., 2023)

viduals through brain signals (Hildt, 2019). This phenomenon can have big implications on the necessity to learn from body movement and gestures, besides other ethical issues like individual brain autonomy, the possibility of brain-hacking and cognitive bias (Hildt, 2019). Decreasing or suppressing physical solicitation can harm the learning process, since silencing body movements and environmental interactions can hinder human skills and activities.

This review discusses the neuroscientific theories of EL and embodied cognition. Conceptualization hypotheses are mainly used to explain EL phenomena and the dynamics linking the brain-body-environment interaction through sensorimotor networks. Then provided an updated summary of the available invasive and non-invasive BCIs used for cognitive brain augmentation and learning. Given the limited literature on the use of BCIs in classrooms, the use of non-invasive tools, primarily EEGs linked to VR, artificial intelligence ITS, or fNIRS, has been identified. These tools have proven promising outcomes in terms of attention, language learning, and cognitive work load control. Finally, an attempt was made to decipher the primary theoretical and empirical impacts of using BCIs on EL based on an understanding of the role of the body in the learning processes. The role of the body in language learning, science, and physical education is highlighted. And how technology-based tools helped understand the complex relationship between movement, perception, emotion and cognition. It could also be identified through recent literature that the use of BCIs has expanded from being cognitive, motor and brain augmentation tools to brain-to-brain and brain-to-machine interaction platforms, which can either exclude or limit the role of the body in interpersonal interactions. This contribution outlines the principal theoretical frameworks in scientific literature about BCIs and EL and highlights the enormous potential of BCIs in learning and cognitive augmentation. Although empirical studies about BCIs' use in education are scarce, a bigger interest should be given and translational studies need to be implemented from laboratory to classroom settings to analyze their potential educational implications. With the massive and fast development of technology nowadays many interrogations are coming into surface about the relationship between the human and the machine, and at what level the digital world will be able to interfere with our lives and integrate our bodies.

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Conflict of Interest
The authors declare that there is no conflict of interest.

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