

Brain -Computer Interface Technologies for Enhancing Learning in Severe Disabilities

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ABSTRACT:

The Brain-Computer Interface (BCI) technologies have turned out to be a ground breaking solution to the enhancement of the process of communication and learning between severely disabled individuals. Though effective in a variety of situations, the traditional augmentative and alternative communication (AAC) systems usually depend on the motor residual capacities and might not serve the needs of persons with severe physical disabilities completely. The paper will outline the potential of BCI systems as a very advanced motor independent interaction paradigm which makes it possible to interact with the human brain, and digital learning worlds in a face to face

communication. The paper outlines an in-depth discussion of the basics of BCI, such as signal acquisition and pre-processing, feature extraction, and intelligent interpretation and how they are used to facilitate adaptive and personalized learning. An innovative framework of learning is introduced that combines with a neural signal processing system and machine learning with adaptive learning interfaces. The framework is aimed at the real-time feedback, cognitive state-control and dynamic content-adjustment to enhance the degree of engagement and performance among the learners. The comparison of the traditional AAC systems and BCI-based systems will assist in determining the pros and cons of each of the systems and demonstrating that BCI systems are more accessible, flexible, and cognitively-supported as opposed to AAC systems which are easier to use and scale. The paper also presents practical examples and case studies of real life applications of BCI technologies in communication, neurofeedback based learning and rehabilitation as well as inclusive learning classrooms. Although BCI technologies hold great potential, issues like variability of signals, the complexity of the system, cost and ethical issues are major obstacles to mass usage. The article addresses these issues and provides future research directions, which include incorporation of artificial intelligence, creating cheap devices and setting up of standard implementation models. Its results indicate that BCI technologies, especially when used together with the already existing AAC systems, could be of great benefit in improving learning outcomes and ensuring that the inclusion of the severely impaired individuals in education happens.

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I. Introduction

BrainComputer Interface (BCI) technologies are a game changer in the field of neuroscience, engineering and education, which come with opportunities never seen before to assist severely disabled individuals. BrainComputer Interface is a type of communication that allows the human brain to directly communicate with other devices by decoding neural activity into actions. Contrary to the traditional assistive technologies, which use the residual motor skills, the BCIs avoid neuromuscular routes, thus offering an effective means of

communication and learning to those with severe physical and cognitive disabilities. This is of importance especially in special education where in most cases the traditional methods of instruction are not able to address the complex needs of communication and participation of learners with severe disabilities. Severe disabilities such as cerebral palsy, cerebrovascular accidents and other severe neuromuscular disorders greatly limit the capacity of an individual to communicate effectively and also take part in the learning processes. Augmentative and alternative communication

(AAC) research points to the fact that individuals with severe to profound disabilities tend to rely on aided or unaided communication systems to express their needs and be involved in the social life (Simacek et al., 2018; Kuyler et al., 2022). Nonetheless, unassisted communication (including gestures or expressions) is often restricted in its efficiency and reliability, particularly when it comes to people whose speech is not functional at all (Kuyler et al., 2022). This poses significant impediments to access to education, socialization with peers and attainment of meaningful academic results.

The use of AAC technologies, such as speech-generating devices, symbol boards, and eye-tracking systems have greatly increased the chances of communication with individuals with complex communication needs (Beukelman and Light, 2020; Bornman et al., 2024). These tools are important in improving social interaction and involvement as evidenced by research that support systems, such as family members, and siblings can help AAC users develop communication (Hacker et al., 2023). With these developments, a considerable proportion of AAC systems continues to be based on a certain amount of motor control or outside assistance, which might not be possible to provide very physically impaired individuals. Moreover, inconsistency in the intensity of interventions and availability of AAC solutions still influences their general effectiveness in the real-life settings of education (Simacek et al., 2018). In this regard, the Brain–Computer Interface technologies prove to be a valid solution as they allow communicating using the brain directly without participating in physical actions. BCIs enable users to interact with digital systems by controlling the system by tapping into neural signals, usually by a non-invasive method such as electroencephalography (EEG) and choosing what to do or interact with educational material using their cognitive intent. The new paradigm provides a solution to one of the most debilitating limitations of the traditional AAC systems and is more inclusive to accommodate the individuals with little or no motor abilities. Therefore, BCIs can enhance and add to the current AAC models and offer another communication avenue to severely disabled persons.

The developments in technology in the recent past have greatly enhanced the possibility and functionality of BCI systems. Advancements in signal processing and machine learning facilitate the correct decoding of brain signals connected with focus, purpose, as well as cognitive involvement. An example of this is event related potential based BCIs, like P300 systems and steady-state visually evoked potential (SSVEP) systems have been used to create communication interfaces and virtual keyboards successfully. These systems enable the user to spell words, choose commands and have interaction with digital learning systems thus increasing their capability of engaging in educational activities. Furthermore, BCIs based on neurofeedback have the potential to track cognitive states, and offer real-time feedback to assist with regulation of attention and cognitive training, which are important elements of successful learning in people with severe disabilities. Inclusion of BCI technologies in learning institutions is in tandem with the overall inclusive education objectives that focus on equitable access, involvement and individualised learning. BCIs can be used to provide adaptive learning conditions, through constant evaluation of the cognitive condition of a learner and dynamically modifying instructional data. This feature can be of great use to learners with extreme disabilities, whose learning requirements tend to be very personalized and situation-specific. BCIs have the potential to positively impact learning environments by increasing engagement, enhancing understanding and promoting independence in the learning process through real-time interaction and feedback.

Nevertheless, BCI technologies in education offer a number of challenges although they have great potential in terms of use. The variability and noise of the neural signal acquisition is one of the main issues as it can influence the accuracy and reliability of the system. Also, theoretically BCI systems require a great deal of calibration and training of the user making them perhaps inapplicable in the real-world classroom. Ethical issues, such as data privacy, informed consent, and the psychological impact of the use of BCI on a long-term basis should also be taken into consideration. Moreover, the prohibitive cost, and technical complexity of

BCI systems is an obstacle to its application in the wide range, particularly in schools with small budgets.

Another grave concern is the need to come up with pedagogically effective and user-friendly BCI-based learning systems. Although the AAC research focuses on the significance of user-centered design and contextual adaptability (Beukelman and Light, 2020; Bornman et al., 2024), the same principles are to be implemented to the BCI-based educational tools. It is necessary to have interdisciplinary cooperation between educators, engineers, neuroscientists and therapists to come up with systems that are not only technically sound, but also those that are congruent with the educational goals and needs of the learners. Moreover, an empirical study is necessary to assess the effects of BCI interventions in the long-term on learning outcomes, communication abilities and quality of life. This paper will discuss how Brain-Computer Interface technologies can be used to improve the learning process of severely disabled individuals. It discusses the drawbacks of the current AAC strategies, the promising nature of BCI systems, as a substitute communication and learning tool, and a framework of implementing BCI systems in adaptive learning settings. This study will aim at supporting the creation of new innovative, inclusive, and effective learning solutions by integrating the knowledge of AAC research, with the emerging BCI technologies. To sum up, the potential of Brain-Computer Interface technologies in changing the special education sphere is enormous, since it allows direct interaction and communication between the brain and the computer. Although AAC systems have provided a platform to provide services to people with complex communication requirements, BCIs have provided a new generation solution that can address a lot of their shortcomings. It will be essential to address the technical, ethical and pedagogical issues of BCI implementation to achieve their full potential. As research and interdisciplinary cooperation continues, BCIs can be critical to the establishment of an inclusive learning process, which can enable people with severe disabilities to realize their full academic and social potential.

II. Review of Existing Literature

Augmentative and alternative communication (AAC) has been a widely researched field in terms of its application to meet the needs of people with severe and multiple disabilities (and thus incapacitated people), especially in learning institutions. The literature that is available pinpoints the potential as well as the limitations of AAC systems in the context of enabling communication, participation and learning. It is important to understand these insights in order to recognize the gaps which Brain-Computer Interface (BCI) technologies are intended to fill.

There is a considerable amount of literature highlighting the issues related to implementation of the AAC in the classroom environment. As an example, the research has revealed that teachers usually have challenges with the implementation of AAC tools because of the low level of training, absence of resources, and institutional support (Aldabas, 2021; Terblanche et al., 2022). The attitudes and perceptions of the teachers towards AAC are also very important factors in the effectiveness of AAC because without sufficient knowledge of these technologies, proper use of these technologies may not be possible. On the same note, speech-language therapists have indicated inconsistency in AAC practices, noting discrepancy in intervention patterns, and service delivery (Dada et al., 2017). These results indicate that although the AAC technologies are possible, the implementation of the technologies is highly reliant on the context and human factors. The other important theme in the literature is the problem of AAC implementation and continuous use in the educational establishment. Studies show that adoption of AAC devices is affected by several factors, such as the need among the users, and the ease of use of the devices as well as the presence of continuous support (Norrie et al., 2021). A mismatch between the specifics of the technology and communication needs of users is the reason AAC systems are under-used in most instances (Da Fonte et al., 2019). This brings out the issues of the need to have personalized and user-based design to create efficient communication systems. Moreover,

research on early childhood education underlines that it is critical to implement AAC in a structured way to enhance its adoption and integration into classroom activities (Quinn et al., 2023).

The literature also highlights the differences in the AAC access and implementation in various educational and socio-economic settings. As an illustration, studies carried out in low- and middle-income countries (LMICs) have found that key obstacles, such as insufficient funds, among other trained experts, and resources, include inadequate infrastructure (Meenakshi et al., 2026). Likewise, research in segregated schools has found that the AAC interventions are frequently limited by both environmental and system factors to a lesser degree of effectiveness (Iacono et al., 2022). The above difficulties highlight the need to have scalable and flexible communication solutions, which are capable of operating effectively in varying settings.

Cooperation and alliances were determined as the vital elements towards enhancing AAC outcomes. Multi-stakeholder engagement, such as educators, families, healthcare professionals, and policymakers are also highlighted as crucial in ensuring that people with a communication disability can participate equally (Dada et al., 2023). These collaborative methods are in line with the development objectives of the world and emphasize the necessity to have comprehensive frameworks that incorporate communication technologies in the general educational and social systems. Methodologically, the studies in the field of AAC and associated areas tend to be based on descriptive and qualitative and mixed-method research to comprehend user experiences and effects of interventions. The issue of population, exposure, and outcome variables are essential ideas to consider when assessing the impact of communication interventions and comprehend their role in learning and participating (Kestenbaum, 2019). The frameworks are structured to offer a guideline on the evaluation of the traditional AAC systems and the new technologies like BCIs.

Although there has been advancement in the study of AAC, there are still a number of limitations that could be seen. Among the main issues is the lack of

accessibility to people with severe motor impairments due to the need to use physical interaction as a communication method. Moreover, the quality of interventions varies, intervention is not standardized and little long-term outcome research impedes the generalization of the results. Another gap in literature is the lack of integration of the advanced technologies, including artificial intelligence and neurotechnology, into the communication and learning systems. In this regard, Brain-Computer Interface technologies could be a fruitful addition to the current AAC models. The BCIs enhance direct brain-based interaction and thereby face a lot of the physical and operational constraints of the traditional AAC systems. Although AAC studies are useful in understanding the needs of the users, the difficulties of implementation and the contextual factors, there is a new paradigm introduced by the BCIs which can improve the communication and learning with the help of neural signal processing and adaptive interfaces. The AAC literature brings out important issues of implementation, adoption, access and personalization challenges. Such issues highlight the importance of new solutions capable of offering a more inclusive and effective communication channel. With the contributions of AAC studies and the mitigation of its limitations, BCI technologies can be used to provide invaluable benefits in the learning processes of severely disabled people.

III. Proposed BCI-Based Learning Framework

The Brain-Computer Interface (BCI)-based learning paradigm proposed is aimed at improving communication, interaction, and cognitive abilities of severely disabled people through a combination of neural signal processing with adaptive learning tools. Expanding on the shortcomings found in existing augmentative and alternative communication (AAC) systems, including the need to rely on motor processes, lessening the level of personalization, and imposing difficulties in implementation, this framework proposes a more straightforward brain-driven interaction model allowing students to take an active role in the learning process without the need to apply physical input systems.

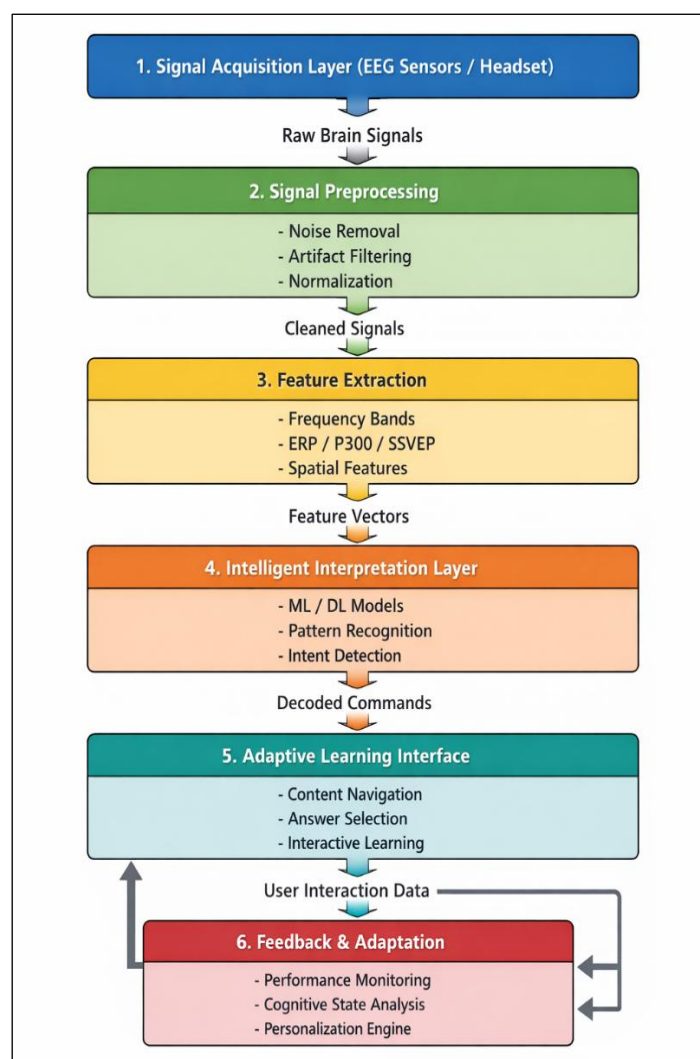


Figure 1. Architecture of the proposed BCI-based learning framework showing signal acquisition, processing, intelligent interpretation, adaptive learning interface, and feedback-driven personalization.

Figure 1 shows a stratified BCI-based learning model that is targeted at people with severe disabilities. Signal Acquisition is where the workflow starts by EEG sensors recording neural activity. The information is then transferred to the Signal Processing Layer that does noise cleaning and feature extraction. Then the Intelligent Interpretation Layer is applied that perceives user intent based on machine learning algorithms on brain signals. This command line is read and forwarded to the Adaptive Learning Interface that students interact with educational content (e.g. selecting answers, going through modules). The performance, engagement and cognitive state is continuously monitored by a Feedback Mechanism that facilitates a closed-loop solution which

dynamically modifies learning content. This will ensure that it is personalized, more accurate and enhanced learning.

The primary pillars of the proposed framework are flexibility, scalability and adaptability in different learning contexts as it is a modular and a layered architecture. The architecture consists of five key components; the signal acquisition, signal processing, intelligent interpretation, adaptive learning interface and feedback mechanism. Signal acquisition module: the neural activity is captured using non-invasive devices such as electroencephalography (EEG) thereby being safe, and simple to use by the learners. Since the neural signals are not predictable, with a lot of noise, the signal processing module uses the advanced method

of signal preprocessing, such as filtering and artifact removal, to improve the quality and reliability of signals. This is a critical step towards attempting to get the correct reading of user intent.

The intelligent interpretation layer makes use of neural signals by making use of machine learning and deep learning algorithms to decode the neural signals to meaningful commands. This aspect is developed to detect the patterns that are related to attention, intention and mental states in order that the system can be developed to understand the user response in real time. This layer allows an ease and free interaction as opposed to the traditional AAC whereby one may need to key in data manually or have some other facilitation. In addition, the system has adaptive algorithms, which are acquired in the process of using the system, making it more accurate and customized. This is in line with the individualism in communication solutions as expressed in AAC research.

The learning part of the framework is adaptive learning interface, interpretation of the signals is transformed to meaningful learning actions. This interface is characterized with various features such as the ability to select answers, navigate through the content, interact and access multimedia learning contents. The system is set up to dynamically adjust the content difficulty, presentation mode and speed to the state of cognitive and performance of the learner. Such a flexibility will be able to satisfy the needs of learners with severe disabilities as these are diverse and constantly evolving and they become engaged and learn better. Further, the interface can be integrated into the existing AAC tools and a hybrid one will be created that will be a combination of the two approaches.

One of the main characteristics of the suggested structure is the use of a real-time feedback system. This element constantly tracks the response of the learners, their engagement and cognitive load and gives feedback to the learner and the teacher. To learners, feedback can be in the form of visual or auditory signals to encourage learners to provide the correct answer or to focus attention. To teachers, the system will produce analytics and data on performance that can be used in making decisions. This feedback will ensure that it is continuously

improved and is in line with the best practices of inclusive education where one has to constantly assess and make changes.

The framework also establishes the importance of the contextual and environmental factors towards successful implementation. Based on the AAC literature, which has identified lack of training, limited resources and lack of consistent support to be the main barriers, user-friendly design principles, and minimum requirements to set up the model are introduced in the proposed model. Portable and affordable BCI devices are used to enhance the accessibility, particularly in the resource-constrained setting. Besides this, the framework will aid in collaborative involvement of the teachers, therapists and parents in that the system becomes well integrated in the learning ecosystem of the learner. The other significant aspect of the framework is that this is a framework that is concerned with personalization and inclusivity. The system will be designed in such a way that it supports the various levels of cognitive and physical abilities, with customizable interfaces and training tools. In one example, the less attention spans would be able to practice on the simplified interfaces that have fewer stimulus as compared to high end users who are able to practice on more challenging tasks. The flexibility will address the issue of mismatch of features as introduced by AAC systems and will ensure that the technology aligns with needs of individual users.

Although there are benefits, the framework proposed also recognizes the possible obstacles such as signal variability, fatigue by the user and the calibration. To address these, there are adaptive calibration techniques, and user training systems to the system that are continuously improved to enhance the system performance. Moreover, the ethical considerations, such as data privacy, informed consent and user control are also taken into consideration by the design to ensure that BCI technologies are used responsibly in education. To summarize, the suggested learning framework that is based on BCI is an innovative and holistic way of improving the learning of people with severe disabilities. The framework integrates neural signal processing, intelligent interpretation and adaptive learning systems that assist the framework to

overcome some of the drawbacks of the traditional AAC technologies. It provides an inclusive, flexible and more personalized solution that assists in the active engagement and increased learning outcome. Such a framework can create a remarkable shift in the sphere of special education and introduce equitable access to education to all people via the interdisciplinary cooperation and continuous research.

IV. Comparative Analysis and Discussion

Application of Brain-Computer Interface (BCI) technology in learning institutions of severely disabled individuals is an enormous leap as compared to the traditional and ancient technique augmentative and alternative communication (AAC). Here, a comparative analysis of the conventional assistive technologies and the BCI-based system will be provided considering some of the crucial parameters such as accessibility, usability, adaptability, learning outcomes, and implementation issues. Traditional AAC systems like speech-generating, communication boards and eye tracking technologies have played a paramount role in supporting communication of persons with complex needs. But still these systems are usually limited to the use of residual motor skills and external facilitation. The research has proved that the implementation of AAC in schools can be undermined by such factors as the lack of teacher training, the fact that the infrastructure is not sufficient, and the context does not adapt well (Aldabas, 2021; Terblanche et al., 2022). Moreover, inconsistency in AAC practices and support services also lead to the variability in learning outcomes (Dada et al., 2017). These constraints suggest that there is a need to have additional independent and responsive communication solutions.

Conversely, the systems based on BCI provide an essentially new form of interaction through brain-to-computer communication. This does away with the need to rely on physical movement and enables individuals who are severely motor impaired to be more self-reliant in their learning activity. The fact that BCIs can decode neural signals associated with attention and intent offers a further benefit in the educational setting since it allows one to monitor

and can adjust the learning processes in real time. In contrast to the AAC systems which are mainly oriented on communication, BCIs are also functional in cognitive assessment and personalized learning. Accessibility wise, BCIs prove to have a greater inclusivity potential especially to those with minimal or no functional speech or movement. Nonetheless, such a benefit is associated with technical issues like signal variability, calibration needs, as well as sensitivity to environmental noise. Although AAC systems tend to be more stable and simpler to deploy, they might not be effective due to user-specific limitations and environmental factors (Norrie et al., 2021). Conversely, BCIs have high-level infrastructure and technical skills demanding constraints on their scalability into practical educational contexts.

The usability and user experience is a crucial consideration when considering both AAC and BCI systems. The years of development and user-friendly design have resulted in a relatively user-friendly nature of AAC technologies that can be used by a broad group of users (Beukelman and Light, 2020; Bornman et al., 2024). Nonetheless, their effectiveness can be decreased by problems like a mismatch of features and their insufficient personalization (Da Fonte et al., 2019). Although BCI systems are more personalized, based on adaptive algorithms, some initial training and calibration are necessary, which can be challenging to some users. These problems are slowly being solved due to advancements in machine learning and interface design to make BCI systems easier to use.

BCI-based systems demonstrate a promising outcome in terms of improving engagement, attention, and cognitive performance in terms of learning outcomes. The provision of real-time feedback and adaptive content makes it possible to have more dynamic and responsive learning. AAC interventions also demonstrate in studies the significance of systematic application and continual feedback towards enhancing communication and learning outcomes (Quinn et al., 2023). Combined with the latest neural signal processing techniques these principles can make BCI systems potentially

better than the old methods. Issues of implementation and contextual issues are also discussed. According to AAC research, collaboration between educators, therapists and families is important in making sure that adoption is successful (Dada et al., 2023). Likewise collaborative structures are necessary in the implementation of BCI, including other factors like ethical issues, data

privacy and cost. The utilization of both AAC and BCI technologies is a major problem in low- and middle-income settings where access to resources is low (Muttiah et al., 2022). As such, the need to come up with solutions that are cost effective and scaled is necessary to ensure the full effectiveness of these technologies.

Table 1. Comparative Analysis Table

Parameter	Traditional AAC Systems	BCI-Based Systems
Input Method	Physical (touch, eye gaze, switches)	Neural signals (EEG-based)
Accessibility	Limited for severe motor impairments	High (motor-independent interaction)
Usability	Mature, user-friendly	Requires training and calibration
Adaptability	Moderate (manual customization)	High (AI-driven personalization)
Learning Support	Communication-focused	Communication + cognitive enhancement
Implementation Complexity	Low to moderate	High
Cost	نسبياً moderate	High (but decreasing with technology advancement)
Scalability	High	Limited (currently)

As mentioned in Table 1, as much as AAC systems are still critical in assisting communication, they cannot be used to meet the needs of all people with severe disabilities. Table 1 indicates that while AAC systems remain essential for supporting

communication, they are not sufficient to address the needs of all individuals with severe disabilities. BCI technologies augment and expand the capabilities of AAC with a direct and adaptive interaction mechanism.

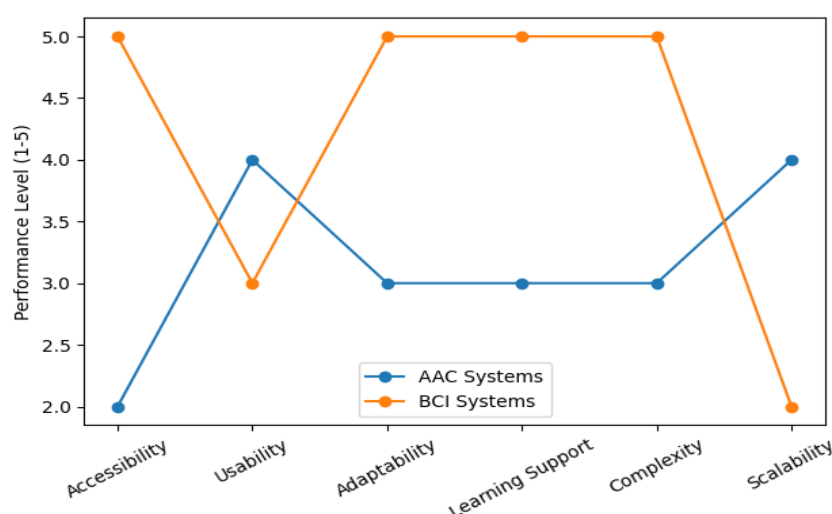


Figure 2. Comparison between traditional AAC systems and BCI-based systems based on the major parameters such as accessibility, usability, adaptability, learning support, complexity and scalability

As shown in figure 2, BCI systems can outdo AAC systems in areas such as accessibility, adaptability, learning support and system intelligence which are areas that AAC systems can be improved to support the advanced personalized learning. Nevertheless, AAC systems are more usable and scalable, i.e. can be used in the modern educational environment. This contrast is brought out to emphasize the need to come up with hybrid AAC-BCI solutions to balance the innovative and the usable.

During the integration of BCI with the existing AAC systems that have the potential to offer a more comprehensive approach at the inclusion education, hybrid solutions that incorporate reliability and innovation can be created. However, the transfer of traditional AAC to new systems, founded on BCI, needs to be carefully thought out regarding the technical, pedagogical, and ethical factors. In order to have successful implementation, there is a need to ensure user acceptance, minimize cognitive load and system reliability. In addition, such technologies are supposed to be streamlined by constant research and cross-disciplinary collaboration and be both more accessible and cheaper. To sum up, BCI-based learning systems have a potential to become an important step in the sphere of assistive education. They may be a good addition to existing education technologies although they still have some challenges to address since they can make education more accessible, personalized and more successful. The future research should be in how to maximize the performance of the system, reduce costs and how to devise standardized structures to apply them in mainstream education environments.

V. Case Studies and Applications of BCI in Enhancing Learning for Severe Disabilities

The applied use of the Brain-Computer Interface (BCI) technologies in the real-life educational and assistive settings has shown potential results in enhancing the communication, learning activities and autonomy of the severely disabled. This part will showcase important case studies and application case scenarios to point out the effectiveness and the possibilities of BCI-based systems when combined with other already existing augmentative and alternative communication

(AAC) systems. Among the most popular applications of BCI is the communication systems with people who have no or little functional speech. P300-driven BCI speller has been effectively employed in facilitating people with severe motor disabilities to build words and sentences by choosing the characters displayed on a virtual screen. These systems are based on the principle of sensing the event-related potentials in response to visual stimuli, that gives its users the opportunity to communicate without having to touch each other. Such systems in education have been tailored to assist in activities like giving multiple choice questions, taking part in quizzes and basic writing activities. BCI spellers provide an inclusive alternative to the very restricted motor control of users with no motor control at all compared to the traditional AAC devices which can use eye-gaze or switch-based inputs.

The other major usage is in neurofeedback-based learning systems whereby the BCIs are employed to monitor and improve mental processes of attention, focus and mental workload. EEG-based neurofeedback systems have been used in the classroom setting to monitor changes in student engagement and give real-time feedback. In the case of learners with attention deficits or severe disabilities, the strategy allows individual learning experiences by dynamically modifying the level of difficulty, pace and presentation of learning content. The sustained attention and rates of task completion have been enhanced by such systems and they have proved to be useful in cognitive training and development of skills. Adaptive learning platforms that are based on inclusive education have also been incorporated with BCI technologies. Such systems take the input in the form of neural signals that are utilized in controlling the digital interfaces that allow learners to navigate through the materials, make selections and interact with multimedia resources. As an example, a learner can use a BCI system to control a cursor, select options in one of the assessment modules or to use audio-visual aids in learning. These platforms are dynamic and ensure that content is always modified depending on the thinking of the learner, thereby enhancing the interaction and comprehension.

Rehabilitation and skill development programmes along with the sphere of education are the other areas of the investigation of BCI. To illustrate, the use of motor imagery based BCIs has been used to aid cognitive and motor rehabilitation by encouraging the users to visualize some actions and this is translated directly into actions within a virtual environment. This method not only contributes to the rehabilitation, but also improves the learning process via the use of interactive and immersive experiences. Applications like these can be applied to special education to impart cause and effect relationships, problem solving skills and simple motor coordination concepts in a regulated and interactive way.

The BCI applications have also been applied to the low-resource and inclusive educational environment though challenges are still present. The cost and infrastructure limitation of advanced assistive technologies in most areas limit access to such technologies. Nevertheless, the recent trends in low-cost and portable EEG devices are approaching BCI technologies by making them more affordable. Simplified BCI systems have been shown to be viable in such environments with pilot implementations showing that it is possible to use this system in basic communication and learning tasks, which indicates its wider use in the future. In the collaborative point of view, the successful case studies put emphasis on multi-stakeholder intervention which includes educators, therapists, caregivers and technology developers. The successful implementation should be based on technological innovation but also on the training, support, and evaluation. This kind of collaboration is crucial in BCI-based learning environments to adjust the functionality of the system to educational objectives and user requirements. With its ability to interact directly with the brain, promote adaptive learning, and be compatible with existing AAC systems, BCIs offer a potent solution to improve communication and engagement in education. Although there are still some challenges, it is hoped with the continuous research and technology that these systems will continue to be improved thus making it possible to introduce them in large numbers in inclusive education.

VI. Conclusion and Future Directions

The technologies of Brain-Computer Interface (BCI) mark a new era in the assistive education, especially in assisting people with severe disabilities who are severely hindered by their inability to communicate and learn. This paper has discussed the principles of the BCI systems, limitations of the traditional forms of augmentative and alternative communication (AAC) systems, and provided a detailed model of the BCI based learning system that would facilitate the accessibility, interaction, and cognitive involvement. The results show that although AAC systems have resulted in significant contributions to inclusive education, they are dependent on physical contact and contextual restrictions, which restrict their performance with people with severe motor disabilities.

The comparative analysis of AAC and BCI technologies conducted in this paper, shows the complementary aspect of these technologies. Since AAC systems are stable, user-friendly and practices of implementation are already in place, BCI systems introduce new possibilities, such as monitoring cognition, making real-time adjustments and communicating without the use of limbs. This hybridization of these technologies can harness the full potential of any of the technologies and provide a more comprehensive and effective communication and learning environment. This kind of integration is especially needed in dealing with the varied needs of learners with severe disabilities as they need flexible and context-based solutions. Even though BCI technologies have a huge potential, they are yet to be implemented in the educational context and are already associated with numerous challenges. System reliability and usability can be impacted by technical problems like signal variability, interference with noise and required calibration. Also, BCI devices are expensive, and they require expert knowledge which is also a limiting factor to their widespread use. The issue of ethics such as privacy of the data, informed consent and psychological effects of continuous neural monitoring should also be handled with a lot of care to make sure that these technologies are used responsibly.

The other issue is critical BCI systems which are to be pedagogically integrated. Even though technological advancements have allowed developing highly-developed applications of the BCI, it is important to consider its usability in the educational process in terms of its compatibility with the instructional strategies, curriculum design and interaction with the learners. Teachers should have sufficient training on the application of these systems and interdisciplinary cooperation between the engineers, teachers, therapists and policymakers is needed to achieve success in the implementation. Additionally, the need to introduce standardized assessment mechanisms to measure the impact of BCI-interventions on the quality of life and learning

outcomes is possible. To steer the research and development in this direction in the future, it can be resorted to a few promising directions. Firstly, the accuracy and efficiency of the BCI systems can be enhanced through the assistance of the innovations in the artificial intelligence and deep learning systems, which will enable interpreting neural signals stronger. Even better would be multi-modal data i.e. EEG and eye-tracking or body physiological sensors would enhance the system performance and reliability. Second, the cheapness, ease of use and portability of the BCI devices will be crucial in increasing accessibility particularly within the low resource environments.

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