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Expanding the (kaleido)scope: Exploring current literature trends for translating electroencephalography (EEG) based brain-computer interfaces for motor rehabilitation in children.

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Abstract:
Rehabilitation applications using brain-computer interfaces (BCI) have recently shown encouraging results for motor recovery. Effective BCI neurorehabilitation has been shown to exploit neuroplastic properties of the brain through mental imagery tasks. However, these applications and results are currently restricted to adults. A systematic search reveals there is essentially no literature describing motor rehabilitative BCI applications that use electroencephalograms (EEG) in children, despite advances in such applications with adults. Further inspection highlights limited literature pursuing research in the field, especially outside of neurofeedback paradigms. Then the question naturally arises, do current literature trends indicate that EEG based BCI motor rehabilitation applications could be translated to children?

To provide further evidence beyond the available literature for this particular topic, we present an exploratory survey examining some of the indirect literature related to motor rehabilitation BCI in children. Our goal is to establish if evidence in the related literature supports or discourages research on this topic and if the related studies can help explain the dearth of current research in this area. The investigation found positive literature trends in the indirect studies which support translating these BCI applications to children and provide insight into potential pitfalls perhaps responsible for the limited literature. Careful consideration of these pitfalls in conjunction with support from the literature emphasize that fully realized motor rehabilitation BCI applications for children are feasible and would be beneficial.

- BCI intervention has improved motor recovery in adult patients and offer supplementary rehabilitation options to patients.
- A systematic literature search revealed that essentially no research has been conducted bringing motor rehabilitation BCI applications to children, despite advances in BCI.
- Indirect studies discovered from the systematic literature search, i.e. neurorehabilitation in children via BCI for autism spectrum disorder, provide insight into translating motor rehabilitation BCI applications to children.
- Translating BCI applications to children is a relevant, important area of research which is relatively barren.

Keywords: **Brain-computer interface, neurorehabilitation, motor-imagery, paediatrics, children,**

1.) Introduction

1.1 Background

The past decade has seen a significant increase in researchers pushing the limits of brain-computer interfaces (BCI), devices capable of creating a non-muscular communication channel directly between the brain and an output source such as a computer [1], [2]. BCI has emerged as a malleable technology viable in a myriad of applications (for a general review see [2]). Historically, the non-muscular nature of BCI lent itself to use in communication applications and assistive technologies for patients suffering from conditions such as amyotrophic lateral sclerosis (ALS) or persistent locked in state (LIS) (for reviews on these topics see [3]–[5]).

More recently, BCI research has expanded in scope to include therapeutic applications which harness the underlying properties of brain plasticity for rehabilitation [6], [7]. Some applications using rehabilitation based BCI include neurofeedback therapy for autism spectrum disorder ASD [8], attention deficit hyperactivity disorder (ADHD) [9] and schizophrenia [10]–[12] as well as motor rehabilitation post injury, such as after a stroke [7], [13]–[15]. Current motor rehabilitation techniques can be limiting to some patients, since they require residual movement in afflicted appendages and are potentially too demanding for them [3], [16]. Non-invasive motor rehabilitation BCI offers an alternative therapeutic approach accessible to these individuals [3], [16]. Despite the expanding breadth of current BCI research, the majority of investigations have focused on BCI applications for adults. This is especially evident in motor rehabilitation applications of BCI [17]. Such a restriction undercuts the possible benefits that BCI technology could bring to children who suffer from neurological diseases and disorders. The prevalence of motor impairment from neurological impairments such as cerebral palsy (up to 4 children per 1000 are diagnosed annually with cerebral palsy according to the Centers for Disease Control (CDC) [18]), paediatric stroke (approximately 11 in 100,000 children diagnosed per year [19]), and traumatic brain injury (approximately 3,000 children aged 0-14 will have a TBI per 100,000 in US. [20]), among other conditions present a substantial population which could benefit from the recent advances in BCI technology. Pairing recent breakthroughs in understanding the role of brain plasticity in successful therapeutic BCI applications [6], [7], [14], [21], [22] with considerations on the abundant plasticity in the paediatric brain[23], [24] and the (relatively) limited time since injury, developing early-life BCI applications for motor rehabilitation becomes well-posed as a valuable research topic.

1.2 Motivation

A systematic search of the Pubmed.org database was conducted to encapsulate the state of research concerning such BCI applications. Surprisingly, the systematic search into the literature reflected an almost barren field of research with respect to electroencephalogram (EEG) signals for BCI motor rehabilitation in children. Further, there was limited research on any BCI rehabilitation applications incorporating children. This leads to the following questions:

1) Do trends in the literature support the possibility of developing EEG based BCI motor rehabilitation applications for children?

2) Is there clear evidence in related investigations which indicate there are factors that would hinder the development of such applications?

To answer these questions, this paper proposes to examine some of the literature indirectly related to EEG based motor rehabilitation applications of BCI for children. Evidence provided by the indirect literature will help provide clearer indications on the feasibility of this subject despite the lack of explicit evidence. This paper is therefore not a systematic, exhaustive review of every topic related to EEG BCI, BCI rehabilitation, rehabilitation in children, etc. There is an abundance of such reviews examining those subjects currently (Some examples: For neurofeedback rehabilitation with children see [9]; For BCI in rehabilitation and its current status post stroke see [7]; For assistive technology integration with BCI see [3]; For electrocorticography and implantable BCI used in motor rehabilitation see [25]; For neural plasticity and its role in BCI applications see [13]; For BCI design and interpretation pitfalls to avoid see [26]; For current physiotherapy applications see [27]). Instead, this paper looks to investigate the above questions based on a diverse, exploratory review of literature indirectly related to the proposed EEG based BCI applications for motor rehabilitation in children, in hopes to shed light on its feasibility.

The rest of this paper is structured as follows:

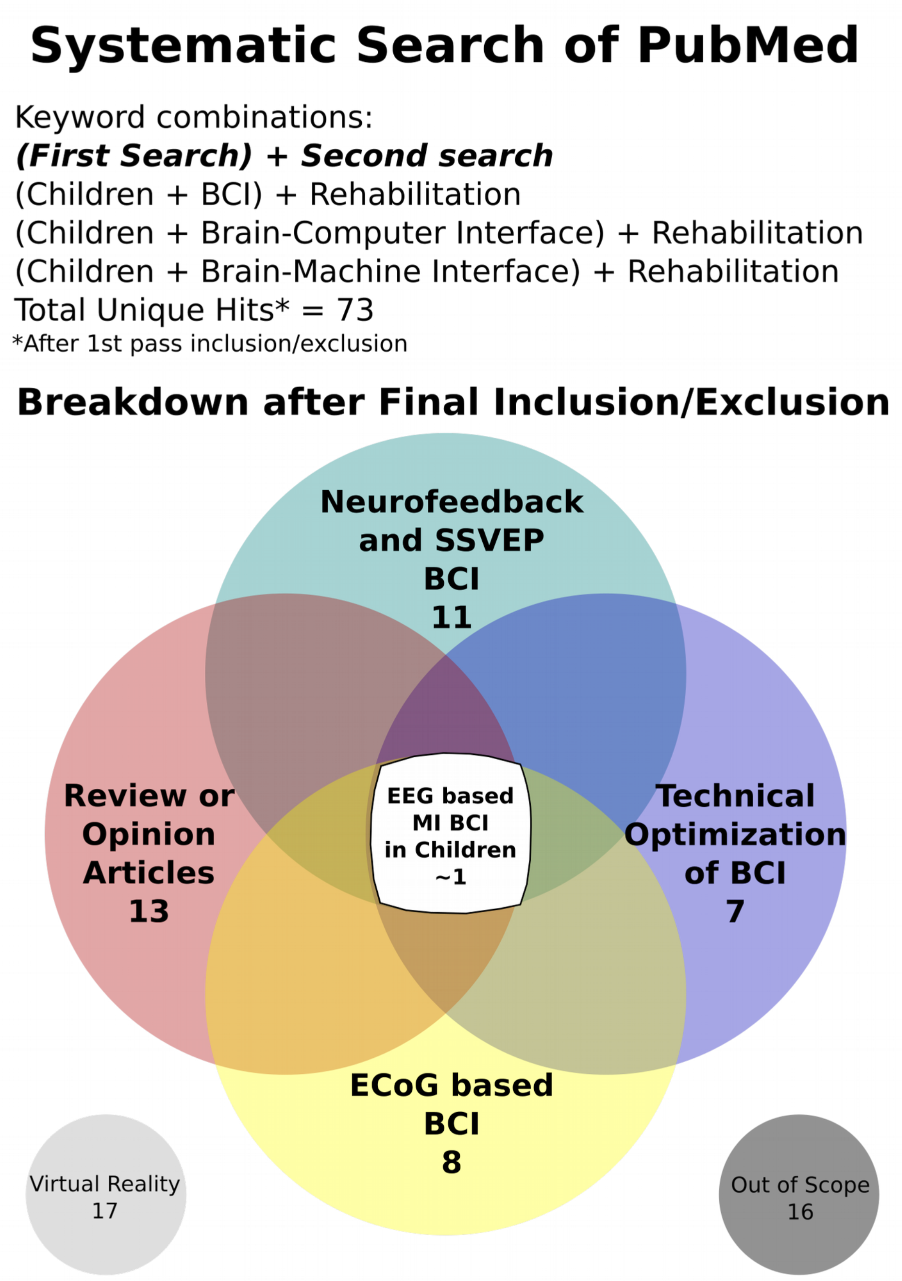
- The immediate section, '*The systematic search*', describes the systematic search conducted on the Pubmed.org database, whose results helped define indirect categories to explore for evidence in addressing the questions of interest.
- The following section, *'BCI therapy: Motor imagery BCI in rehabilitation applications'* provides a look at current investigations which have successfully implemented a BCI motor rehabilitation paradigm for adult patients and considers how this literature may support or dissuade motivation for similar applications for children.
- Then, *'Barriers to entry: Neurofeedback applications and designing BCI for children'* examines the EEG based BCI paradigms which have used child populations, highlighting particular examples and roadblocks associated with developing BCI applications for children.
- Afterwards, '*Alternative inputs for BCI control- A glance at ECoG'* delves into data reported for recording modalities other than EEG, specifically electrocorticography (ECoG), and what achievements using those inputs with children may indicate for EEG-BCI.
- In the subsequent section, *'A new hope: Justification for BCI and prospective solutions'* we provide more in depth justification for examining BCI in children and speculate on potential solutions to some of the translational barriers examined in previous sections. Additionally, we synthesize the

trends inspected in the previous sections to attempt to answer the initial questions of the manuscript.
- In the final section, *'Limitations and conclusions'* limitations on the literature survey will be covered and a conclusion is presented.

2.) The systematic search

A systematic search of the Pubmed.org database was conducted on May 04, 2016. The search included a combination of multiple key words and related synonyms including 'children', 'kids', 'paediatrics', 'BCI', 'Brain-computer interface', 'Brain-machine interface', 'BMI' and 'rehabilitation'. Results from all combinations of key terms were saved, and examined for relevance with respect to BCI rehabilitation in children. Inclusion or exclusion of literature was done in two phases. First, manuscripts were excluded based on titles definitively not related to rehabilitation in children through BCI and/or neurofeedback means (i.e. 'Spatial knowledge of children with spina bifida in a virtual large-scale space'). First pass inclusion criteria was lenient to avoid possible exclusion of related manuscripts. Abstracts of the remaining publications were then examined, with those directly related to BCI then included. All remaining articles were then examined in depth, with relevant references investigated for additional insight and information. Results were categorized based on major themes present, and separated accordingly. In our inclusion criteria, and therefore throughout this review, individuals between the ages of 2 and 16 years old were considered as 'children'. Figure 1 illustrates a visual breakdown of the search, along with the categorized results.

Figure 1. A visual representation of the results from the systematic search of Pubmed.org. Acronyms: SSVEP = Steady-state visual evoked potential, MI = Motor Imagery.



It is important to note that the systematic search revealed no study explicitly examining EEG for motor rehabilitation through motor imagery (MI) for children. There was a single manuscript, [28], which mentions one of its participants was aged 12 while another three were age 16. However, the manuscript focuses on BCI used with assistive robots rather than neurorehabilitation. Therefore, it is reflected as an '~1' instead of a hard '=1' in the breakdown of the systematic search seen above.

The category of virtual reality (VR) literature was considered to be a grey area with respect to what could be considered as 'true' BCI applications. Although VR studies had some aspects of BCI, such as haptic feedback coupled with a virtual environment stimulus, interaction with the VR was not necessarily accompanied or driven by direct recordings of the brain (i.e. [22], [23]). Therefore, we have elected to keep the VR literature separate from our consideration of BCI. However, considering its related nature we have not excluded it completely to the 'Out of Scope' category. We refer interested parties to the reviews [31], [32].

Finally, it is important to mention commercially available BCI toys and games (i.e. [33]–[36]). These technologies were excluded from our systematic review for several reasons. First, they are not documented as related to neurorehabilitation or motor rehabilitation and were not found during our systematic search. Additionally, their intended purpose is out of scope for the present paper as it is not rehabilitation focused. Further, the structure of these toys often relies on a minimalistic EEG set-up, basing their BCI signal acquisition on only a few electrodes. These minimal electrodes do not often include covering the whole of the motor cortices, but are rather placed on the frontal or temporal lobes [33]–[36]. The driving signal from these tend not to be from motor imagery, which is the paradigm currently used in BCI motor rehabilitation. To the best of our knowledge, excluding these commercially available products does not affect our analysis of the current state of BCI for children. However, the relative success of these toys suggests that children are likely to find BCI technology attractive. Perhaps, then, children would find BCI more engaging for rehabilitation than other alternatives, such as constraint movement rehabilitation, thus supporting the need to fully explore the potential of EEG based motor rehabilitation BCI applications for children.

3.) BCI therapy: Motor imagery BCI in rehabilitation applications

3.1 MI-BCI and neurorehabilitation: Initiating plasticity through thoughts in post-stroke patients:

A recent BCI application generating interest is the use of motor imagery BCI (MI-BCI) in therapeutic paradigms to improve impaired motor control due to trauma or disease, such as stroke (for a general review see [7]). MI-BCI functions through modulating sensorimotor rhythms over the primary somatosensory and motor cortical areas through imagined self-movement, which causes a measurable event related desynchronization (ERD) to occur [7], [21]. Imagined movement generates other measurable potentials that can be integrated with BCI technology, like the movement-related cortical potential (MRCP) associated with pre-motor planning of volitional movement [14]. Literature evidence shows that MI and MRCP based BCI alike can induce pathways which influence the underlying mechanisms responsible for brain plasticity [7], [14], [21]. One concrete example showing this relationship is from the work of Pichiorri et al. [21]. The authors demonstrated that successful MI-BCI lead to increased motor cortical excitability, visible within 24-48 hours post intervention in ten healthy subjects [21]. The authors suggested that goal-oriented MI-BCI training could re-instantiate more efficient connections within motor cortical areas, leading to potentially better motor recovery [21]. The suggestion for more goal-oriented MI-BCI training has been adapted, to a degree, by pairing BCI with stimuli to enhance possible Hebbian-associated learning. In a proof-of-concept study by Mrachacz-Kersting et al. [14], a transcranial magnetic stimulus (TMS) was used to measure how Hebbian-associated feedback with MRCP-BCI potentially improved lower-limb function. A subset of 22 chronic-stroke patients received Hebbian-associated feedback with MRCP-BCI while no Hebbian-associated feedback was given to the another subset. The authors report a significant increase in the power of the associated tibialis anterior (TA) muscle evoked potential in the associated group that was absent in the non-associated group [14]. The authors highlight that the associated learning method employed in their work may be crucial to unlocking the full potential of BCI induced neuroplasticity for motor rehabilitation [14]. Other researchers have also reported positive changes in stroke patients from MI-BCI for motor rehabilitation [16], [22]. In a pilot study, Young et al. [22] successfully exploited the reorganization function of brain plasticity to promote functional improvement in upper-extremity movement for eleven post-stroke victims suffering from motor loss. Using a closed loop, multi-modal neurofeedback (NFB) BCI which included visual, functional electric stimulation (FES) and tongue stimulation, the group discovered positively correlated gains in both objective (neural responses to BCI treatments) and subjective (self-reports on improvement after treatment) measures after MI-BCI intervention [22]. The investigators used the laterality index (LI) of functional magnetic resonance imaging (fMRI) to measure the functional brain organization of patients before and after MI-BCI therapy [22]. They found a reorganization and re-lateralization of the lesioned cortex in response to MI-BCI therapy which corresponded to improved motor recovery by patients [22]. This finding echoed results described in a case study by Caria et al. [16]. Caria and company explored the motor recovery of a chronic stroke patient who had undergone combined BCI training and physiotherapy [16]. The authors report functional changes in the brain organization, with a significant re-lateralization towards the perilesional cortex post combined BCI training measured by several neuroimaging modalities [16]. Interestingly, physiotherapy alone was not enough to induce such neuroplastic alterations to the laterality index and the re-organization of structural white matter [16]. Changes were only found after the combined BCI-physiotherapy training [16].

Throughout these studies, the theme of improved motor function due to MI or MRCP BCI enhanced therapy which causes activation of neuroplastic pathways illustrate a trend of positive improvements of BCI applications for motor rehabilitation (some additional examples include [15], [37], [38]). The studies mentioned are in no way an exhaustive list of studies looking at BCI applications for stroke, nor are they intended to cover all approaches within this broad research field. They were selected to help highlight the use of MI-BCI as a platform for inducing neuroplasticity. These studies fulfill a call for more empirical evidence demonstrating MI-BCI as a neurorehabilitation tool [13], and provide insight into addressing the initial proposed questions with respect to motor rehabilitation BCI applications in children.

3.2 BCI control and motor rehabilitation: Pathologies outside of stroke

Displaying a functional control over MI based BCI implicitly provides a basis for BCI motor rehabilitation applications due to MI-BCI inducing activity-dependent neuroplasticity [22], [39]. Exploring control of MI-BCI in populations beyond stroke can help support development of BCI motor rehabilitation applications for patients across the spectrum of motor disability. For example, Faller et al. [40], demonstrated users with severe motor impairment including multiple sclerosis (MS), traumatic brain injury (TBI) and spinal cord injury (SCI) could use MI-BCI. Through the use of a novel co-adaptive training paradigm, which provided immediate feedback of the user's brain-activity with continuously updated the underlying classifier model, 22 users were able to effectively control a MI-BCI [40]. The authors suggest the co-adaptive BCI training paradigm could be a potentially useful tool in neurorehabilitation for future work [40]. In a similar vein, Daly et al. [41] explored the practicality of BCI control in 14 cerebral palsy (CP) patients naive to BCI using several different control schemes, including sensorimotor rhythm modulation, like MI. The study reports at least six of the subjects could control MI-BCI to a significant degree, despite only interacting with the BCI system for a relatively limited period of time over the course of a few days [41]. The intent of the paper was to demonstrate the feasibility of control, and thus extended training and interaction with the BCI system, which may improve subject control over the system (as seen in [42]), was not examined [41]. Why only some users possess innate abilities to use BCI without prior exposure or training is an ongoing topic of research and an open question (for a review see [43], for other examples see [44], [45]). Further, a pilot study by Cincotti et al. investigated control of assistive technologies in 14 able-bodied subjects, and 14 patients suffering from Spinal Muscular Atrophy type II (SMA II) or Duchenne Muscular Dystrophy (DMD) through both standard muscle input and MI-BCI [28]. Their goal was to evaluate the effectiveness of BCI and standard inputs for using commonplace technology (i.e., accessing a computer cursor) and aide technology (i.e., as a controller for intelligent motion devices) [28]. The researchers found when using a BCI application, able-bodied subjects were able to control a standard application of the BCI (i.e. moving a cursor on a screen) with an overall accuracy above 70% [28]. Retention of control was substantially maintained when using BCI to drive other environmental output devices as well [28]. The authors report similar levels of performance were achieved by the four motor impaired patients who underwent BCI training [28]. (Although the authors do not explicitly mention which patients participated in the standard BCI training, it is important to keep in mind that the study included three patients aged 16 or younger who were possibly included.) These results illustrate BCI applications can be controlled with reasonable accuracy for both DMD and SMA motor disorders [28].

These investigations highlight that MI-BCI can be controlled by a diverse user population across the motor impaired spectrum. They also illustrate these groups as potential candidates for MI-BCI motor rehabilitation applications. It is important to note that although rehabilitation applications have been highlighted, more overtly assistive technology (e.g., a BCI spelling machine) may be more beneficial for some patients with motor impairment, especially in extreme cases such as LIS. Decisions to more heavily stress assistive, rehabilitative or a combination BCI should be assessed at an individual patient level, taking into consideration factors like residual movement and tolerance to available technologies [28]. Additionally, rehabilitation applications may be considered as implicitly assistive, blurring the decision on which BCI paradigm to emphasize [46]. The studies mentioned here have been selected to highlight the interaction between control of a MI-BCI and its related rehabilitation or assistive benefits in several different adult motor impairment pathologies. These examples illustrate a key concept needed in translating such applications to the developing brain and its varied pathologies.

3.3 Neuroplasticity and age: Motivation for translating MI-BCI motor rehabilitation to the developing brain.

The positive literature trends in neuroplastic initiation via BCI supports motivation for developing motor rehabilitation BCI for children. Core to general BCI rehabilitation applications is the interaction between patient controlled BCI, the corresponding activation of neural plasticity and the correlated functional improvement in the patient. In their publication, van Dokkum et al. stresses the importance of properly selecting time windows for optimal BCI neurorehabilitation, asking the question of when BCI could be applied to gain the most from plasticity [7]. Looking at this question broadly, children may be ideal candidates for therapeutic motor rehabilitation using MI-BCI intervention. For example, they are ideal due to the enhanced natural plasticity of the developing brain, evidenced by its remarkable ability to recover from early injuries and enhanced capability in learning [23], [24]. Earlier therapeutic intervention via BCI applications could also have additional benefits when considering temporal factors like regional recruitment (the brain's capability to recruit new pathways to compensate for deficits) and learned non-use of afflicted regions post injury [24]. This sentiment is echoed by Daly et al. [47]. In discussing their results, the investigators report a lower event-related desynchronization (ERD) strength in patients with lesions occurring in early childhood, as compared to patients who had lesions occur in adulthood (e.g. stroke) when using MI-BCI [47]. They hypothesize that recruitment of the cortical areas for other functions or slower learning of motor processes, and by extension possibly motor imagery, may explain the relative difference in impaired ERD strength for the 14 cerebral palsy patients in the study [47]–[50]. The authors suggest that introduction to BCI rehabilitation early in childhood is a promising route which could encourage greater ERD strengths for patients and potentially lead to improved usability of BCI applications [47]. This could impact sustained BCI rehabilitation over time, as familiarity with the technology reduces frustration, leading to increased use and potentially better long-term improvements [42], [51]. Additionally, earlier exposure to BCI induced therapy could potentially improve the re-lateralization of the brain, which then elicits greater improvements for traditional therapeutic approaches [52]. In a study by Manning et al. [52], researchers found a positive neuroplasticity activation in seven children with cerebral palsy using the relatively common therapy of constraint-induced movement for motor recovery. Crucially, Manning et al. mention that the greatest improvement in motor recovery was found in children with the greatest asymmetrical laterality indices at the start of the intervention [52]. They also report the inverse situation to be true; namely, the least improvement corresponded to children with a brain baseline which was highly bilaterally organized [52]. These findings are possibly the result of recruitment of those regions for other functions [52]. Therefore, early-life therapeutic intervention could lead to a more effective rehabilitation for BCI. Changes in the child's brain plasticity resulting from therapeutic interventions could be monitored through cutting-edge tools and neuroimaging modalities, like functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI), to assess efficacy [16], [53].

Motivation for developing BCI based motor rehabilitation applications for children is clearly supported by the evidence in current adult literature. Also, almost no evidence of an explicit barrier impeding development of such applications was discovered in reviewing this set of literature. Improvement concerns for BCI in general were present, but nothing explicitly illustrating why there has been no attempt at such a BCI paradigm. Although barriers may well exist, we aim to investigate this concern in the next section using the literature evidence from groups who have implemented other BCI paradigms in children. The literature examined is the indirect results obtained from our systematic search in Pubmed.org.

4.) Barriers to entry: Neurofeedback applications and designing BCI for children

4.1 Growing into BCI: Current literature results from the systematic search

The systematic search revealed a sparse set of studies actually using BCI applications to treat children, a trend observed previously [17], [54], [55]. Manuscripts which explicitly report using EEG based BCI paradigms are highlighted ([56]–[58]) here in hopes to elucidate current approaches to BCI in children and potential pitfalls which may inhibit translating motor rehabilitation BCI applications to children.

Research concerning child-focused BCI applications is limited in terms of both empirical examples and success. While the majority of the literature describing BCI applications with children have focused on neurofeedback applications aimed towards developmental disorders such as attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder (ASD), few groups have successfully implemented these paradigms (for a general review see [59]). One group, Lim et al., describe successfully developing an attention-based BCI training program geared towards improving ADHD symptoms on 20 unmedicated children aged 6-12 years old [56]. Their attention-based BCI-training program included an engaging, 3D graphic game as the user interface for the therapeutic BCI intervention, with 8 weeks of intervention [56]. The authors remark that with BCI intervention, parent-reported symptoms of ADHD were significantly improved with sustained results evident as far out as 3 months post treatment [56]. Another study by Rohani et al. describe a prototype BCI system which uses the P300 potential as the driving feedback in two separate VR games [57]. The investigators developed the set of VR games to reward simultaneous stimulus of the P300 with correct information gathering as a means to measure subject attention for five healthy young subjects [57]. The authors conclude that the preliminary data demonstrates that a system using the P300 potential can be used to measure attentiveness of subjects [57]. They also suggest an approach to game design with respect to addressing distractions for ADHD individuals [57]. Outside of these two neurofeedback manuscripts, only one other group explicitly mention using an EEG based BCI with children. In their paper, Ehlers et al. investigated the extent development-specific changes in background EEG would influence the ability of children age 6-10 years to control a stimulus-driven steady-state visual evoked potential (SSVEP) BCI [58]. The researchers investigated a total of 14 adults and 37 children between age six and 33 years [58]. The children were separated into approximately 3 equal groups, resulting in a mean age for each group of 6.73, 8.08 and 9.86 [58]. Their results report a significant difference in ability to control a SSVEP-BCI spelling application between the children and adults, with greatest disparity between the youngest group (approximately age 7) and the adults [58]. Ultimately, they highlight that an appropriate SSVEP-based BCI system for children currently remains purely academic [58].

Although not directly empirical, Friedrich et al. [8] proposed a combined neurofeedback and biofeedback treatment for children on the autism spectrum through a BCI game application. The authors underscore the importance of entrenching the positive benefits of BCI therapeutic intervention, in this case via neurofeedback, in a medium of play for children [8]. Friedrich and company speculate that play is an ideal medium to encourage and engage children in sustained interactions, especially in BCI design for children on the autism spectrum [8]. This perspective on play may be a critical philosophy needed when considering developing any BCI applications for children.

4.2 Potential barriers to BCI in children: Limitations in the literature

With respect to the literature examined above, there were several limitations and concerns which should be kept in mind when interpreting and expanding upon the results. In the study by Lim et al. the authors highlight that the intervention was well tolerated, but a side effect of a mild headache was reported for two of the participants [56]. This side effect, however, did not stop them from continuing with the treatment [56]. Additionally the uncontrolled, unblinded nature of the study may have a biased treatment effect [56]. In the work by Rohani et al., the system may need to be redesigned to be useful in a rehabilitation setting through improving the error rate and reliability of feedback to the user [57]. Additionally, concerns with the reliability of a P300 as a measure of attention should be addressed as the user improves their attention [57]. Potential design limitations are present in the work from Ehlers et al. as well. The authors mention that the observed age-group differences might be due to development-specific deficits in dealing with visual search tasks for children under ten years [58]. Considering the SSVEP-BCI spelling system relies on the ability to spell, the 79% failure rate for completing tasks by the youngest age group (~7yrs) may be partially explained as a developmental limitation in the design paradigm [58]. This concept is further supported by the decreased failure rate corresponding to increasing age [58]. These limitations do not encompass all possible concerns with translating BCI to children, but help serve as guides when drawing conclusions from the current state of BCI applications which include children. A summary of these studies is provided below in Section 6.2, Table 1.

5.) Alternative inputs for BCI control- A glance at ECoG

5.1 ECoG and EEG

Beyond the scope of EEG-BCI lies a handful of studies using alternate inputs which directly investigate motor imagery based BCIs in children. Again, these indirect studies were discovered through the systematic search and examined for evidence that sheds light on the feasibility of EEG based motor rehabilitation BCI for children.

A variety of input recording technologies have been used to drive BCIs, including magnetoencephalography (MEG), electrocorticography (ECoG) and electroencephalography (EEG). The non-invasive, cheap and portable advantages of EEG based BCI (EEG-BCI) provide certain benefits for developing BCI applications, leading to it becoming the most widespread recording modality [2], [60]. The relatively cheap components and portable nature of EEG-BCI means a larger number of potential patients and more convenient use [60]. The trade-off for these benefits is the relatively poor spatial resolution of EEG [2], [60]. Since EEG-BCI exploits changes in electric currents on the scalp, there is higher noise in recorded EEG signals due to the signals crossing through the skull and scalp before reaching the EEG electrodes [60]. Further, the high noise and lower power in EEG may inhibit higher frequency signals (>40 Hz) from being reliably deciphered and interpreted [60], [61]. These disadvantages are not present in other input modalities, like ECoG. ECoG offers a greater spatial resolution, higher sensitivity to neural activity and larger discernible electro-physiological spectrum than EEG [60]. The main trade-off for the benefits in ECoG is the highly invasive craniotomy procedure required to place electrodes on the cortical surface [60]. Due to how invasive this procedure is, ECoG based BCI have often been implemented only with patients already scheduled for surgery (i.e. [62]). Therefore, current ECoG based BCI is an option for only a small subset of the population.

5.2 Paediatric BCI studies using ECoG

The systematic search revealed several groups successfully used ECoG based MI-BCI with children. In a pioneer study by Breshears et al. [62], researchers revealed that signals from the paediatric cortex could successfully be decoded to control a MI-BCI to an accuracy similar to those found in adults. Six paediatric patients aged 9-15 were able to rapidly achieve control over the BCI using both overt and imagined cognitive modalities, including using MI to control a game or an external robotic hand [62]. Importantly, the results exhibited no significant differences between the time or accuracy needed for the paediatric patients to gain control of the BCI compared to adults [62].

The authors promote these results as a successful proof of concept that decoding signals from the paediatric cortex is possible for use with motor imagery based BCI [62]. The capability to decode, identify and classify signals from the paediatric brain for use in a BCI, in spite of significant electro-physiological differences, is a promising finding for translating BCI technology to the paediatric brain. It is important to note that the majority of features used to control the BCI here were attained from high-gamma bands (60-130 Hz), a frequency range not readily accessible by EEG [60], [62]. However, recent improvements in signal processing and artefact detection could potentially unlock these high-gamma bands for use in EEG [63]. At a minimum, four of the six participants were able to control the BCI with signals from the primary motor and pre-motor areas using the classic beta band (15-40 Hz) as well [62]. Additionally, the researchers Roland et al. [64] investigated the effect of age on ECoG signals and evaluated their implications for BCI applications for 23 patients aged 11 to 59 years. The researchers found that the magnitude of percent change in power for all low-frequency bands was not largely correlated with age, while high-frequency bands showed significant correlation [64]. However, a correlation between age and area of activation for the alpha/beta bands and a correlation between age and cortical networks for just beta bands was found [64]. Roland and company conclude that the more stable the signal platform is, and by extension the underlying physiology, the more likely control of the BCI will remain reliable with time [64]. Thus they argue for the use of high gamma rhythms as the best choice for long-term ECoG-BCI use [64].

The results from these ECoG-BCI studies demonstrate strong BCI control through modulating motor imagery in children is possible. This supports the conclusion that motor rehabilitation BCI could be functional for children, at least with respect to using ECoG. When generalizing to our main question of using EEG-based BCI for motor rehabilitation, some barriers present in these ECoG studies provide additional considerations for development. With respect to long term motor rehabilitation, the issues arising due to differences in changing cortical maturation of children is an important concept. Additionally, advancing signal processing techniques to mimic the improved signal sensitivity in ECoG compared to EEG could help further realize an EEG-based motor rehabilitation BCI for children.

6.) A new hope: Justification for BCI and prospective solutions

6.1 Justification for BCI in children

BCI technology has innate advantages for use in neurorehabilitation which can be further capitalized upon during early-life intervention. The main advantage of BCI is its accessibility to all levels of physical deficits. Current physical therapy (PT) treatments, like constraint-induced movement (CIM), may not be possible for patients when residual movement and control is below certain thresholds, as mentioned in [3], [16]. BCI, on the other hand, is accessible to all individuals with physical deficits despite their level of residual control. Since early-life motor rehabilitation helps ebb regional recruitment and learned non-use for patients [52], the inclusiveness of BCI extends these benefits to children who could not use traditional PT. Early-life BCI intervention does not necessarily need to be used in isolation for therapeutic gains. In fact, supplemental use of BCI with physical therapy or other associated learning provides a strong option which may help reduce the physical demands on the patient while still promoting healthy rehabilitation [3], [14]–[16], [55]. Incorporating in the more approachable therapeutic option may help develop a more consistent and enjoyable rehabilitation scheme for the patient. While BCI technologies have their own trade-offs, the freedom from physical limitations allows the benefits of rehabilitation to be accessible to a wider scope of patients.

Beyond advantages in accessibility, BCIs provide an opportunity for more customizable motor rehabilitation schemes. The programmable nature of BCI allows a freedom to create and refine engaging applications to enhance neurorehabilitation approaches at functional and user-interface levels [51]. Functionally, customizing BCI for individual end users could include concepts like targeted rehabilitation and improved neuroplastic activation specificity, leading to more personal rehabilitation. At a user-interface level, presenting therapeutic activities under the guise of an engaging application or game is extremely promising for development of BCI, especially for younger users [9], [65]. Increased user-interface accessibility to the rehabilitation paradigm can reduce user frustration and promote engagement leading to improved patient rehabilitation [42], [51]. These advantages help justify translating BCI technology for early-life neurorehabilitation applications.

6.2 Prospective solutions to barriers affecting BCI in children

Synthesizing the literature evidence above, it becomes clear there is support for translating motor rehabilitation applications to children. Further, literature evidence presented throughout this paper help outline potential barriers to translating motor rehabilitative BCI to children. Below, potential solutions to some of these barriers are explored alongside suggestions for research topics which could help develop BCI in children.

There are unique technical challenges facing EEG based BCI development for children. One technical challenge facing BCI in children is constructing a dynamic BCI system which can adapt to and handle the developing brain. In creating these rehabilitation BCI applications, understanding the underlying EEG characteristics of children is critical. EEG properties alter significantly throughout development, resulting in key EEG frequency bands, topography and power distribution shifting dramatically with age [66]–[68]. These alterations are more prominent for some types of BCI, e.g. MI-BCI, since they rely on EEG parts of the spectral landscape which change dramatically throughout childhood [59], [60]. Designing an EEG-BCI which can accurately interpret this flexible spectral landscape is a critical open question. The challenge is unique to child BCI research, but its solution may be applicable to improving other general BCI issues, i.e. variance across sessions. This challenge could be approached through several different methods. For example, recent research developing adaptive boosting-algorithms [71] could be utilized to help appropriately identify MI signals from children. Considering the adaptive algorithm does not require a priori definitions for frequency bands [71], it is a potential option to partially circumvent issues like evolving frequency band ranges in the developing brain. Another option may be to incorporate higher dimensional information, like age, into the signal processing and analysis aspects of BCI through tensor techniques [72]–[74]. Tensor methods may prove to be additionally useful to translating BCI to children as a means to remove artefacts [75], potentially mitigating some of the increased noise in children's EEG. Exploring topics like convolutional neural networks [76] and deep learning structures [77] within the framework of the developing brain provide additional paths which could produce key developments useful in translating BCI to children. Building upon concepts like these for use in the developing brain, be it the flexibility in autonomously defining spatial-spectral configurations [71] or utilizing higher dimensional information in tensor methods [78], will likely be key. Research which focuses incorporating the dynamic EEG characteristics of children into machine learning and signal processing methods can help in resolving some of the technical aspects barring the translation of BCI applications to children.

Suitable development of engaging and accessible BCI applications is another challenge to focus on for BCI research for children. The benefits of this research could applicable to older BCI users, but is *critical* for success for younger BCI users. Younger BCI users may have reduced attention spans and a potentially higher sensitivity to the fatigue associated with BCI. Long training sessions and mental strain in BCI are thus two areas of research which need to be addressed. A greater push for development of engaging age appropriate applications may partially resolve these concerns. Having an age appropriate paradigm embedded in the medium of play could influence sustained use by the user (like in [8], [56]) while less appropriate designs can lead to high task-completion failure rates (like in [58]). Engaging paradigms for the training component of a BCI may be especially important for neurorehabilitation applications, as improved training can greatly improve the accuracy of the BCI [42], [51]. Improvements in dry electrode hardware helps address the concern of attention in paediatric populations through reducing the initial set up and preparation time of EEG [79]–[81]. Research providing methods to reduce the required number of electrodes needed for effective

EEG based BCI [82] provides another opportunity which could be further explored to optimize BCI for children. These considerations are some examples of research areas which could be focused on to improve BCI applications for children.

Ethical considerations are also of particular concern when translating and designing BCI technology for children (for a general review of BCI ethics see [83], and human ergonomic considerations see [46], [84]). This area is crucial to effective understanding of how to translate the BCI rehabilitation technology to children in a realistic manner. Concerns about long-term effects and any possible complications of sustained BCI use is currently unknown, and must be weighed heavily before implementation in a clinical setting. Also, it is imperative to clearly describe to both the children and parents alike each part of the BCI, such as the sensor array, its role and how the system will be run to alleviate as many worries as possible prior to use. These prospective solutions are not comprehensive, but present several significant challenges in technical execution, analytical development and realistic implementation when designing and developing BCI applications for the paediatric brain. A summary of these solutions and their prospective role in translation is provided below in Table 1. Fully realizing BCI applications for children is dependent on being careful and mindful of these challenges.

Table 1. Summary table of key aspects. Includes literature explicitly using BCI with children, potential technical developments to facilitate translation of BCI applications to children and examples of considerations beyond technical improvements critical to application development. Acronyms: Attention-deficit hyperactivity disorder (ADHD); Autism Spectrum Disorder (ASD); Electroencephalography (EEG); Electrocorticography (ECoG); High gamma (HG); Independent Component Analysis (ICA); Motor Imagery (MI); Minimum norm least squares (MNLS); Neurofeedback (NFB); Region of Interest (ROI); Steady-state visual evoked potential (SSVEP); Support Vector Machine (SVM); Tensor-based nearest feature line distance (TNFLD).

BCI Literature feat. Children				
Study	**Number of Patients (Age Range)**	**Pathology of Interest / Aim of BCI**	**BCI Methodology**	**Limitations**
Lim et al. (2012); [56]	N = 20; (Age 6-12)	ADHD	EEG (NFB)	Non-blinded study, potentially biased results
Rohani et al. (2014);[57]	N = 5; (Age Not Disclosed)	ADHD	EEG (P300)	Ages not disclosed, paradigm needs redesign
Ehlers et al. (2012); [58]	N = 51; (Age 6-33), N = 37; (Age < 11)	Communication via BCI Speller	EEG (SSVEP)	Application design may have led to high failure rate for youngest subjects
Breshears et al. (2011); [62]	N = 6; (Age 9-15)	Neuroprosthetic control	ECoG (MI)	Invasive, control derived from high gamma band
Roland et al. (2011); [64]	N = 23; (Age 11-53), N = 10; (Age < 25)	Neuroprosthetic control	ECoG (MI)	Invasive, control derived from high gamma band
Potentially Applicable Technical Developments				
Study	**Research Goal**	**Relevance to EEG based Motor Rehabilitation BCI**	**Relevance in Translating Motor Rehabilitation BCI to Children**	
Darvas et al. (2010); [63]	To demonstrate EEG can be used to acquire high gamma (HG) signatures through functional mapping of HG activity to a cortex model using MNLS and voxel-wise computed time-frequency maps for ROIs.	Provides access to task induced HG frequency signatures in EEG. Spatially localized HG power changes and interhemispheric phase synchronization signals derived from EEG using this method were akin to ECoG values.	HG control in MI-BCI in paediatric populations using ECoG provides a stable signal robust to age [62]–[64]. Being able to access and analyze these signals using non-invasive EEG could provide a partial solution to dealing with the changing electro-physiological profile [70], [85] of the developing brain.	

Liu et al. (2015); [71]	To autonomously select key channels and frequencies for stroke rehabilitation through an adaptive boosting algorithm applied to the usually pre-determined spatial-spectral configurations modelled as variable preconditions.	Provides details on a technique for training weak classifiers through a new heuristic supervisor of stochastic gradient boost strategy applied to preconditions leading to optimal spatial-spectral selection for BCI rehabilitation.	Autonomous spatial-spectral configuration can help address differences in the spectral landscape present throughout development [66]–[68], [70]. EEG processing techniques which do not require a relatively broad or pre-determined frequency range and channel selection can also help indicate which spatial-spectral configurations are actively changing throughout recovery [71].
Liu et al. (2014); [73]	To detect MI-EEG patterns in spatial-spectral-temporal domains by a tensor-based scheme constructed by a wavelet transform method.	Tensor methods retain the multidimensional nature of EEG. Extraction by a TNFLD algorithm and SVM classification allow greater separation of MI patterns from EEG in stroke patients.	Maintaining higher dimensionality in the signal analysis provides options to incorporate developmental information, like age, to tackle differences in signal patterns and selection for BCI. Tensor factorization methods also provide a method to address the changing MI EEG patterns during rehabilitation therapy [73].
Zhang et al. (2016); [75]	To remove EEG artefacts for BCI through Bayesian Tensor Completion via specifying a sparsity-inducing hierarchical prior and automatically inferring model parameters of the underlying low-rank tensor through Bayesian inference.	Recovers the disturbed data in EEG data with artefacts and uses possible outliers as missing values for EEG tensor completion. The artefact completion method provides additional information for BCI which is lost in artefact rejection.	Children are naturally prone to EEG artefacts and noise [70]. Retaining as much information as possible from EEG in children is important due to their shorter attention spans (and hence high artefact probability) and reduced signal power [66]. Converting EEG data with artefacts into usable information through signal recovery methods helps address these problems, leading to more information for BCI applications.
Lau et al. (2012); [82]	To determine how reducing the number of EEG channels affects electrocortical source signals that can be parsed from recorded EEG.	Provides a basis to examine how many EEG sensors are required for BCI applications through applying an adaptive mixture ICA algorithm on EEG channel subsets.	Reducing the required number of EEG channels can help reduce set-up time of BCI. This reduction may be critical for young BCI users due to their shorter attention spans and consequently shorter set-up times could improve BCI interaction for children.

Considerations on BCI User Interaction and Ethics

Study	Research Goal	Relation to Translating BCI to Children
Friedrich et al. (2014); [8]	To design a combined BCI and biofeedback treatment for children with ASD based in play	Provides an example for designing BCI applications specifically for extended rehabilitation in children based around play. Obstacles in the development process help highlight the importance of clever paradigm design for applications for children.
Nijboer et al. (2011); [83]	To discuss ethical issues related BCI and its research.	Provides a starting place for ethical considerations which need to be identified for BCI for this vulnerable group. Ethical questions are important to evaluate when designing rehabilitation applications, especially for children.

7.) Limitations and conclusions

7.1 Limitations

The manuscript presented has several limitations. First, the review is limited when drawing some conclusions based on post-stroke studies for evidence while other motor impaired conditions, like cerebral palsy, are more common in children [18], [19]. As motor rehabilitation BCI becomes more accessible and is applied across different pathologies, a re-evaluation of this restriction can be more appropriately examined. This review is also limited when drawing conclusions about appropriate age ranges of subjects for BCI due to the limited literature and resources available. Additional studies are needed in order to more definitively designate specific age ranges that could use different types of BCI technology.

7.2 Conclusion

Therapeutic BCI applications have shown great strides in neurorehabilitation and the recovery of motor deficits for patients. These advances in rehabilitative technology have yet to manifest in therapeutic BCI applications for children. Examining current literature evidence clearly illustrates a positive trend which suggests that developing motor rehabilitation applications akin to those seen in adults could be beneficial for children [8], [17], [22], [41], [52], [62]. Exploring results in the adjacent literature recovered from a systematic search provides insight into concerns and barriers to bringing motor rehabilitative BCI to children. Current literature from ECoG applications with children highlights that functional control of a BCI is possible for young users. Prospective solutions to some of the main methodological barriers are suggested, with recommendations for potential future work. These barriers include developing technical advancements in BCI signal processing which accurately evolve with the dynamic structure of the developing brain and creating engaging age appropriate BCI paradigms which minimize user fatigue. These advancements should be carefully analysed in context with potential ethical questions on BCI use by children, like potential long-term effects of sustained use or user discomfort. In conclusion, the set of literature evidence presented here emphasizes the benefits of translating motor rehabilitation applications to children and supports that such a system could be fully realized through careful consideration of BCI design and limitations.

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