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PEDIATRIC BRAIN-COMPUTER INTERFACE COMPETENCY: A PILOT STUDY

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ABSTRACT: Imagine having no functional control over your body—your cognition is unaffected, but you cannot speak or move. Unfortunately, this is the case for many children with severe neurological disabilities, including quadriplegic cerebral palsy. Brain-computer interfaces (BCIs) represent a potential solution for such individuals. BCIs have been widely studied in adults with neurological disabilities, however there is limited research into their use in children. We have therefore established a clinical pilot pediatric BCI program. In order to gauge competency in patients, we aimed here to establish the ability of normal children to use non-invasive BCI systems. Nine healthy children completed tasks on five established EEG-based BCI systems. Performance was assessed by accuracy scores for each paradigm. Our results demonstrate that children can effectively operate a BCI system with accuracies above 60%—comparable to what's been reported in adults. Establishing performance norms for typically developing children across specific BCI systems will inform program development and provide comparisons for children with disabilities.

INTRODUCTION

Cerebral palsy (CP) is the leading cause of lifelong disability, affecting 17 million people worldwide [1]. It is estimated that 1 in 500 babies are born with CP each year, which translates to over 60,000 affected Canadians [2], [3]. A non-progressive neurologic condition characterized by motor impairments, CP is the result of an injury to the brain during early development. [4], [5]. CP may be induced by complications during birth such as hypoxic-ischemic encephalopathy, stroke, prematurity, infections, brain malformations, or an accumulation of bilirubin [4], [5]. Depending on the severity of motor impairment and the limbs affected, CP can be classified into different subtypes: monoplegia describes mild impairments affecting only one limb; diplegia describes impairments of the lower body; hemiplegia describes impairments on one side of the body; and quadriplegia describes the most severe type of CP, which affects all four limbs [6]. Quadriplegic CP often results in devastating loss of all voluntary movement and verbal communication. A substantial proportion of such individuals have preserved cognitive function and may be intellectually normal but trapped in a body that cannot move.

Perinatal stroke is a well understood human model for CP. Perinatal stroke is defined as "a focal disruption" of blood flow to the brain, which occurs between 20 weeks of fetal life up to three weeks after birth [7]. The outcomes for perinatal stroke survivors are usually poor, with neurodevelopmental deficits occurring in 75% of patients and often resulting in a lifetime of disability [8]. It is the leading cause of hemiparetic CP, which is characterized by unilateral motor deficits, as well as higher risks for other developmental disabilities [9], [10]. With no strategies for prevention, recovery mechanisms for children with CP involve supportive care and rehabilitation strategies. When perinatal stroke occurs bilaterally, it can result in quadriplegic CP much like the more global brain injuries described above.

Therapies to improve motor outcomes for children affected by perinatal stroke are limited. Conventional rehabilitation strategies lack supporting evidence and numerous provided interventions are ineffective [11]. In randomized clinical trials, constraint-induced movement therapy (CIMT) has been shown to be effective in improving motor control in children with congenital hemiparesis [11]. However, this intervention excludes individuals with severe CP because they do not meet the minimum criteria for motor function necessary for participation [12]. Recently, neuromodulation therapies, such as transcranial direct current stimulation (tDCS) and repetitive transcranial magnetic stimulation (rTMS) have been combined with CIMT and have shown additive effects on improvement of motor function in children with hemiparetic CP [13], [14]. Recent evidence from adult stroke suggests that BCI can provide new avenues for motor rehabilitation [15], [16]. This concept has not yet been attempted in children with hemiparesis where limited understanding of how children can perform on BCI systems is a barrier to progress.

Children with severe CP are unable to benefit from the combination therapies noted above due to their extensive motor impairments, which prevent them from moving their limbs and, in many cases, speaking. A 2012 review found that 1 in 3 children who have CP cannot walk, and 1 in 4 children with CP cannot talk [17].

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In contrast to most children with perinatal stroke and hemiparetic CP, those with severe bilateral neurological disabilities such as quadriplegic CP, have limited or no motor function and are fully dependent on others for all activities of daily living [18]. Even more unfortunate is that in some children, the cortex is spared and cognitive function is partially or entirely preserved [18]. With virtually no way to communicate or interact with their environments, such cognitively aware children are literally trapped inside a body that does not work. Consequently, they are deprived of their fundamental human rights, including the right to freedom of expression.

Brain-computer interfaces (BCIs) represent a promising solution by which such children might be able to better communicate, interact with their environment, and better realize their own independence [19]. BCIs can allow for real-time mental control of an external device, such as a computer cursor or a communication device. This can be achieved via non-invasive sampling of brain signals with electroencephalography (EEG) [20]. Such mental control signals can be produced in response to external stimuli (evoked potentials and P300 event-related potentials) or they can be generated internally by imagined movements (sensorimotor rhythms) [20], [21]. While there has been an explosion in recent BCI development, the majority of studies have been in adults with a relative neglect of pediatric populations [21], [22]. BCIs represent a potential breakthrough for children with severe neurological disabilities, with the potential to greatly increase their independence and enhance their quality of life [23].

A recent study demonstrated that children can control simple EEG-based BCI systems with minimal training and performance comparable to adults [24]. Clinical research is required to fill a fundamental gap that currently exists between technology development and the pediatric patients and families who could benefit from these new tools [25]. We have therefore initiated a clinical pediatric BCI program to provide severely disabled children with unique opportunities to try a suite of BCI systems to explore possible new avenues for their independence. A major limitation in advancing this program is that we do not yet know how well typically developing children can perform such tasks.

Therefore, the main goal of this study was to establish baseline levels of performance for typically developing children across a suite of non-invasive BCI systems and tasks. This will provide the foundational knowledge necessary for future applications of this technology in children with severe neurological disabilities that have no motor ability. We hypothesized that most typically developing children can achieve basic BCI competency on all modern systems comparable to that seen in adults.

MATERIALS AND METHODS

This was an open-label pilot study of typically developing, school-aged children. Participants were recruited from the community. Nine healthy volunteers aged 11-17 years (2 female) have participated at the time of this report (Tab. 1). Studies took place in the recently established Pediatric BCI Laboratory at the Alberta Children's Hospital. Protocols have been approved by the institutional research ethics board.

Table 1. Details of the participants in this study.

Participant (P)	Sex	Age (years)
1	M	14
2	M	11
3	M	16
4	F	16
5	M	17
6	F	15
7	M	12
8	M	16
9	M	14

Modern, commercially available EEG-based BCI systems were employed (mindBEAGLE and intendiX systems from g.tec medical engineering GmbH, Austria). EEG voltage signals were acquired from the scalp using the g.USBamp EEG system (g.tec medical engineering GmbH, Austria) with either 8 or 16 active gel-based electrodes located according to the international 10-20 system. Electrode locations differed based on which BCI system was being tested. For the mindBEAGLE system, signals were sampled from electrodes at positions FC3, FCz, FC4, C5, C3, C1, Cz, C2, C4, C6, CP3, CP1 CPz, CP2, CP4 and Pz. For the intendiX system, signals were sampled from electrodes positioned at Fz, Cz, P3, Pz, P4, PO7, Oz, and PO8. Additionally, a ground electrode was positioned at AFz and a reference electrode was placed on the ear lobe. Data were sampled at 256 Hz and signal features were extracted using band-pass filtering between 0.1-30 Hz for the mindBEAGLE and 0.5-30 Hz for the intendiX. The digitized data was then transmitted to a laptop via universal serial bus (USB) for processing using a linear discriminant analysis (LDA).

Five BCI paradigms well established in adults were studied: sensorimotor rhythms (SMRs), and auditory, visual, and sensory P300 event-related potentials (ERPs) (two- and three-tactor vibro-tactile stimulation). Each paradigm consisted of tasks with predefined goals. For the mindBEAGLE system, the first run of each paradigm was to train a classifier to recognize the unique brain signals of the individual participant. This was completed using a generic classifier calculated from an online mixed dataset of multiple participants [26]. For the intendiX system, a classifier was trained by spelling the word "LUKAS" at 15 flashes (the number of times each row and column flashed) [27]. The classification was done using LDA, as was developed by Guger et al. (2012) by extracting individual ERPs following each trial [28].

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Task 1: Communication board spelling using visual P300 event-related potentials: In the visual P300 paradigm, participants performed a spelling task using the intendiX row-column speller at various difficulty levels (flash rates). Faces of adult celebrities were presented in colour as the stimuli for the flashing characters of the spelling board [29], [30]. Participants were seated in front of a laptop and were instructed to remain still and relaxed. Once a classifier was trained, the participant started by spelling the 3-letter word "cat" at a range of 8 (min.) to 10 (max.) flashes. The participant was instructed to pay attention to and to silently count the number of times the target letter flashed while disregarding other flashes, until a letter was selected and displayed on the screen. If a letter other than the target letter was chosen, the participant was instructed to move on to the next letter in the word. This trial was counted as a failed attempt at the specified flash rate and the participant was instructed to try again. If the participant was successful in spelling the word at this difficulty level, they advanced to the next level, which involved spelling the same word with less time (decreased number of flashes). Participants had three chances to spell the word before it was established that they were unable to perform the task at the difficulty level. If the participant was unsuccessful in spelling the word at the starting maximum of 10 flashes after three chances, the flash number was increased by two after each unsuccessful trial, up to a maximum of fourteen flashes. If the participant remained unsuccessful at fourteen flashes, a new classifier was generated and the participant retried. Accuracy was averaged over each trial per specified number of flashes. For example, if the participant correctly selected 1 out of 3 letters in the word 'cat', they received an accuracy score of 33% for that trial and were instructed to try again at the same flash rate. Subsequently, if they correctly selected 2 out of 3 letters, they received an accuracy score of 67% and were instructed to try again at the same flash rate. If, on their third try, the participant correctly selected all of the letters of the word, they received an accuracy score of 100% for that trial and advanced to the next level with a lower flash rate. The accuracy scores for the three trials at the same specified flash rate were then averaged into one score for that flash rate. Performance was determined by the lowest number flashes in which the participant was successfully able to spell the word within three trials.

Task 2: Identification of a target stimulus in the oddball paradigm using 3-tactor vibro-tactile P300 event-related potentials (VTP3): Vibro-tactile stimulators were fixed on each wrist, with an additional distractor stimulator fixed to the lower right leg. Using the mindBEAGLE system (g.tec medical engineering GmbH, Austria), participants were asked to identify target stimuli during the oddball paradigm. Non-target, distractor stimuli on the leg were presented frequently (75%), while target stimuli on the left and right wrists occurred infrequently (12.5% for each wrist). Participants were asked to close their eyes to minimize distractions, and to silently count the number of times they felt the infrequent, target stimulus in order to evoke a P300 response. The primary outcome was classification accuracy, as generated by the mindBEAGLE software by comparing target and non-target signals generated by the system with those generated by the participant.

Task 3: Identification of a target stimulus in the oddball paradigm using 2-tactor vibro-tactile P300 event-related potentials (VTP2): Vibro-tactile stimulators were fixed on each wrist. Using the mindBEAGLE system, participants were asked to identify target stimuli during the oddball paradigm. Non-target stimuli were presented frequently (87.5%) while target stimuli were presented infrequently (12.5%). Participants were asked to close their eyes to minimize distractions, and to silently count the number of times they felt the infrequent, target stimulus in order to evoke a P300 response. The primary outcome was classification accuracy, which was calculated by the mindBEAGLE software.

Task 4: Identification of a target stimulus in the oddball paradigm using auditory event-related potentials (AEP): In the auditory P300 paradigm, performance was assessed on the mindBEAGLE system and involved the identification of a target stimulus by selectively paying attention to deviant, target stimuli among frequent, non-target stimuli (oddball paradigm). The auditory paradigm consisted of frequent low tones (87.5%) and infrequent high tones (12.5%) and lasted approximately 7.3 minutes. Participants were asked to close their eyes to minimize distractions, and to silently count the number of times they heard the infrequent, target stimulus. The primary outcome was classification accuracy, which was calculated by the mindBEAGLE software.

Task 5: Sensorimotor rhythm modulation using hand motor imagery: In the SMR paradigm, participants were assessed on the mindBEAGLE system. They were instructed to imagine left- and right-hand movements (opening and closing of each hand) for 8 seconds, with 2 seconds between trials. One run consisted of 60 imagined movements in randomized order, lasting approximately 9 minutes. The primary outcome was a classification accuracy score ranging from 0 to 100%. This score was generated by the mindBEAGLE software via cross validation of the classifier data with the testing data.

RESULTS

All nine participants completed one or more sessions successfully. There were no serious adverse events. Procedures were generally well tolerated. One participant expressed that auditory stimuli in the AEP paradigm induced feelings of sleepiness. Sessions averaged 40-60 minutes with the longest being 90 minutes. No participant ended the session early and all were agreeable

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to participating again.

Visual P300 paradigm: Figure 1 demonstrates the performance of each of 5 participants, as indicated by average accuracy score at various number of flashes. The average accuracy scores ranged from 33% to 100%. The general trend of the results show that performance decreased as the number of flashes decreased and, consequently, the difficulty level increased. Three out of the five participants achieved accuracy scores of 100% on the first two difficulty levels (8-10 and 6-8 flashes) (P1, P3, P9), however their accuracy scores decreased by as much as 45% at a flash rate between 4-6 flashes. The lowest number of flashes achieved by any participant was 2-4 flashes, with the highest accuracy score at this flash rate being 50%. Participant 2 (P2) was unable to spell the word after three tries at 8-10 flashes, therefore the flash rate was increased by two up to 12-14 flashes. Correspondingly, a linear increase in average accuracy of 33% was observed each time flash rate was increased, up to 100% at 12-14 flashes.

VTP3 paradigm: Five participants were assessed in the VTP3 paradigm (Fig. 2). Accuracy scores ranged from 25% to 100%, with a median accuracy of 70% and an average accuracy of 66%. Three out of the five participants demonstrated improvements in accuracy scores between their first and last run (P2, P7, P8). The accuracy score of participant 5 did not change between the first and last run (remained at 90%) however, once a new classifier was generated for the participant (following run 1) an improvement of 30% was observed between the second and third run and the last run. A decrease in performance was observed in participant 4, however this participant performed only two runs.

VTP2 paradigm: Four participants were assessed in the VTP2 paradigm over two runs (Fig. 2). Accuracy scores ranged from 65% to 100%, with a median accuracy of 100% and an average accuracy of 94%. All four participants achieved 100% in the first run using the generic classifier. In the second run, one participant achieved 100% using their own classifier (P1), while participants 2 and 8 also achieved high accuracy scores of 90% and 95%, respectively. The lowest accuracy score observed in this paradigm was 65% (P4).

AEP paradigm: Two participants were assessed in the AEP paradigm (Fig. 2). Participant 5 completed three runs and was able to achieve an accuracy score of 100% in all runs. Participant 8 completed one run using the generic classifier and achieved an accuracy score of 100%.

SMR paradigm: One participant was assessed in the SMR paradigm in one run using the generic classifier (Fig. 2). Participant 8 was able to achieve an accuracy score of 61%.

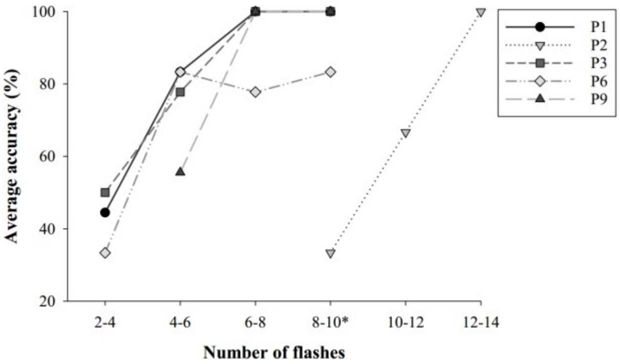

Figure 1. Average accuracy of five participants performing a spelling task using visual P300 event-related potentials on the intendiX row-column speller system. *indicates the starting number of flashes.

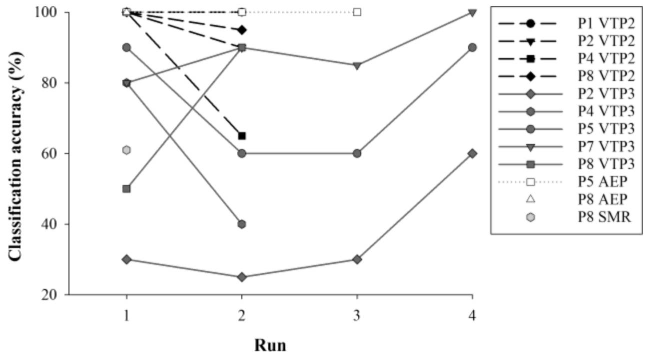

Figure 2. Classification accuracies for six participants who completed various runs in VTP2, VTP3, AEP, and SMR paradigms using the mindBEAGLE system.

DISCUSSION

This pilot study investigated performance on multiple noninvasive modern BCI systems in a pediatric population. Our results suggest that many children can operate such systems with minimal training and favorable tolerability. Performance appears within the ranges established for adults though additional testing on larger samples is obviously required. Establishing pediatric-specific performance standards will facilitate the development of BCI training programs for children with severe neurological impairments.

Our findings included children successfully completing a spelling task using the intendiX system with an average accuracy of at least 80% within a maximum number of 14 flashes. This is comparable to performance in adults using the same system [31]**.** Most participants were able to achieve an average accuracy of at least 80% within a maximum of 10 flashes, except for one participant. Interestingly, this individual was also the youngest to be assessed in this paradigm and was at least three years younger than the other participants performing the same task. Such communication systems may be particularly valuable for clinical populations such as severe quadriplegic cerebral palsy where affected children are

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often non-verbal but possess the visual fields and eye movements required to use such systems.

Across the four paradigms assessed using the mindBEAGLE system, performance was more wide ranging across our modest sample. Abilities to operate were suggested in most subjects though accuracies ranged from 25% to 100%. The average accuracy was 66% for the VTP3 paradigm, 94% for VTP2, and 100% for AEP. The sample size of this pilot study is too small to reach any conclusions regarding relative performance across the different tasks. However, our observed performance on the VTP2 and AEP paradigms does appear to be on par with that seen in adults [32]. Average performance in the VTP3 paradigm in adults has been reported to be 88% [32], [33]. Although we did not clearly observe comparable performance in this pediatric population, it is important to recognize that our performance results were all above the recommended threshold of 60% suggested by g.tec medical engineering [33]. The recommended threshold for the SMR paradigm is 61%, which was achieved by the sole participant in their first and only run. This accuracy score is comparable to and better than some scores achieved by healthy adults in multiple runs [32], [33]. All participants also achieved at least 60% accuracy in at least one run using the mindBEAGLE system.

CONCLUSION

We report pilot data suggesting that many children can competently operate modern BCI systems with accuracy scores comparable to established thresholds necessary for determining conscious awareness, device control, and augmented communication. Additionally, we have demonstrated that at least some children can rapidly achieve BCI competency comparable to that observed in adults. The comparability in performance between children and adults has important implications for future BCI research in both populations where results from progressing adult research may be applicable to children while lessons learned in the more plastic brains of children may also advance the field of BCI. If nothing else, this work provides a useful starting point for screening programs and the development of BCI training programs for children with severe neurological disabilities.

In future work, we intend to investigate performance on additional BCI systems across multiple runs and we will evaluate factors affecting performance, including age and gender. Additionally, once we have established a complete baseline level of performance across these systems in typically developing children, we can begin to modify the systems and tailor tasks specifically for use by disabled pediatric populations with no motor ability. This will provide such children with increased independence and will enhance their quality of life.

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