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A novel EEG-based brain mapping to determine cortical activation patterns in normal children and children with cerebral palsy during motor imagery tasks

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Abstract. *Purpose:* The purpose of this study was to compare EEG topographical maps in normal children and children with cerebral palsy (CP) during motor execution and motor imagery tasks.
Method: Four normal children and four children with CP (mean age 11.6 years) were recruited from a community medical center. An EEG-based brain mapping system with 30 scalp sites (extended 10–20 system) was used to determine cortical reorganization in the regions of interest (ROIs) during four motor tasks: movement execution (ME), kinesthetic-motor imagery (KMI), observation of movement (OOM), and visual motor imagery (VMI). ROIs included the primary sensorimotor cortex (SMC), premotor cortex (PMC), and supplementary motor area (SMA).
Design: Descriptive analysis.
Results: Normal children showed increased SMC activation during the ME and KMI as well as SMC and visual cortex (VC) activation during KMI. Children with CP showed similar activation in the SMC and other motor network areas (PMC, SMA, and VC). During the OOM and VMI tasks, the VC or occipital area were primarily activated in normal children, whereas the VC, SMC, and bilateral auditory areas were activated in children with CP.
Discussion: This is the first study demonstrating different neural substrates for motor imagery tasks in normal and children with CP.

Keywords: Motor imagery, EEG, cortical activation, topographical map

1. Introduction

Motor imagery is a promising neurorehabilitation technique that plays a crucial role in motor relearning and associated skill reacquisition in children with hemiparetic cerebral palsy (CP) [1]. Recent empirical evidence suggests that motor impairments in children with CP are associated not only with movement execution dysfunction, but also with impaired motor planning and motor imagery, which involve an important cognitive-motor process and motor control [2]. Nevertheless, contemporary neurorehabilitation approaches emphasize the movement execution aspect of a target motor performance or behavior rather than motor planning processes and associated motor imagery [3]. Neurorehabilitation techniques that address movement execution, cognitive motor planning (including sequence of cortical activation), and imagery processes may be necessary to ameliorate motor impairments in children with CP.

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Table 1
Clinical and demographic characteristics of the children

Subject	Sex	Age	History	Clinical descriptions	[d]MACS (Lt.-Rt.)	Handedness
1	F	13	Normal gestation	None	–	Right
2	F	13	Normal gestation	None	–	Right
3	M	13	Normal gestation	None	–	Right
4	M	13	Normal gestation	None	–	Right
5	F	11	[a]PB 29 wks	Spastic diplegia	I-II	Right
6	M	10	PB 36 wks, [b]BW 2, 800g	Spastic diplegia	II–III	Right
7	F	14	[c]NSVD, 40 wks	Spastic quadriplegia	IV–IV	Right
8	F	6	NSVD, 37 wks	Right hemiplegia	I-II	Left

[a]PB: Premature Birth; [b]BW: Body Weight; [c]NSVD: Normal Spontaneous Vaginal Delivery; [d]MACS: Manual Ability Classification System.

Motor imagery has emerged as an effective technique to augment the current neurorehabilitation practice for upper extremity motor retraining in children with CP. Motor imagery, which selectively stimulates the cognitive facet of motor behavior, is a prerequisite for motor planning processes. For example, both impaired anticipatory control and abnormal timing of grip-load force coordination during grasping contribute to poor manual dexterity in children with CP.

Motor imagery related changes in neural substrates have been reported by previous neuroimaging studies, which used positron emission tomography [4], functional magnetic resonance imaging [5], and transcranial magnetic stimulation [6] to demonstrate involvement of the premotor cortex, supplementary motor cortex, parietal cortical areas, and primary motor cortex. Despite the fact the motor imagery network shares these common neural substrates for both imagined and executed movement, important issues have been raised about the validity of this claimed homology, because these neuroimaging techniques reveal only correlations and often show motion artifacts during gross movement such reaching and grasping. Hence, causal roles of distinct brain areas cannot be directly determined [7].

To overcome this challenge, we recently developed an EEG-based real-time brain mapping system to ascertain the neural mechanism underpinning actual movement execution (ME), such as reaching-grasping motor tasks, and motor imagery tasks including kinesthetic-motor imagery (KMI), observation of hand movement (OOM), and visual-motor imagery (VMI). The specific aim of this study was to compare topographical maps of normal children with those of children with CP using our novel EEG-based brain mapping system to study specific cognitive motor processes during four different motor task conditions (ME, KMI, OOM, and VMI). Our basic premise was that differences in neural network areas exist between normal and children with CP during four different motor task conditions.

2. Materials and methods

2.1. Participation

A convenience sample of eight children (normal children, $n = 4$, mean age $\pm$ SD $= 13 \pm 0$ years; children with CP, $n = 4$, mean $\pm$ SD $= 10.3 \pm 3.3$ years) was recruited from a local elementary school and a community medical center. Informed consent was obtained from all parents prior to participation. The inclusion criteria for children with CP were the ability to sit independently while performing four motor tasks with the affected upper limbs and the ability to understand and follow instructions. The exclusion criteria for children with CP included severe cognitive impairment, visual-perceptual impairment, sensory deficit, or hearing dysfunction, severe spasticity (Modified Ashworth Scale > 3), seizures, and medications that affect performance of tasks. Healthy children were free of any medical problems. All children were right-handed, except one child with hemiparetic CP (subject 8). Demographic and clinical characteristics are shown in Table 1.

2.2. Experimental tasks and procedures

The children were instructed to sit in a comfortable armchair with neutral shoulder position and elbows resting on the table with 90° flexion, about 65 cm from a computer monitor in a quiet room. Each child practiced four tasks (ME, KMI, OOM, and VMI) until they were familiar with the tasks. ME involved reaching and grasping a small ball with the dominant hand while avoiding other body movements. KMI involved imagery or imagining the hand movement (kinesthetic experience) needed to reach and grasp the ball. OOM entailed simply observing an animated reaching and grasping hand movement displayed on the monitor in front of them. VMI included imagery of hand movement, in which the subjects were asked to visualize the

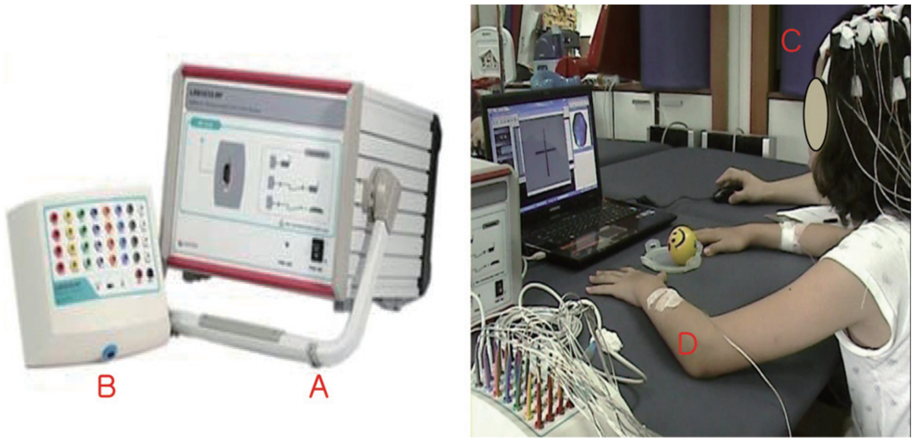

Fig. 1. The EEG set up. A: Main box; B: Junction box; C: 30 Ag-AgCl electrodes; D: 2 Electromyography electrodes. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/NRE-2012-00803)

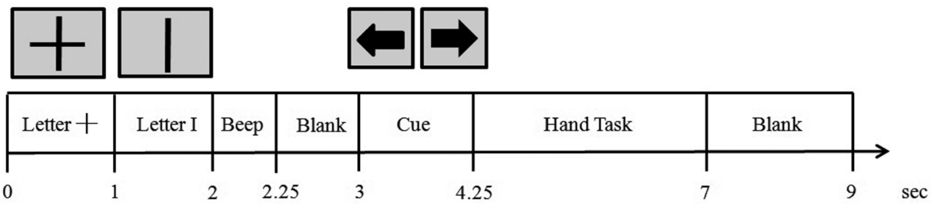

Fig. 2. Experimental paradigm for EEG measurement during a reaching-grasping hand motor task: The letters "+" and "I" were presented for 2 seconds so that the child can be ready for the test. A black arrow cue signaling either the left or right side of the screen was randomly appeared with a beep sound to perform either the left or right hand motor task. The starting sequence for the motor imagery task was randomized. The EEG data were recorded for the motor task, which lasted for approximately 3 seconds and used for further analysis.

right-handed reaching and grasping movement and create a "mental video" of the virtual hand movements as in the previous task (Fig. 1).

The motor imagery experiment was divided into two blocks and the sequence of the two blocks was counterbalanced. One started with the ME and was followed by KMI, and the other started with OOM and was followed by VMI. Thus, imagery tasks were preceded by the corresponding actual motor tasks to enhance acquisition of the corresponding motor imagery. Each child practiced the reaching-grasping motor task, which involves reaching and grasping a small ball while avoiding other body movements [8].

The motor task experiment consisted of 40 trials (9 s each). Each child was presented with a fixation cross in the center of the computer monitor at 0 s. Upon hearing a beep tone (at 2 s), the child was asked to perform the reaching-grasping hand movement. The double beep tone signaled the end of the task (at 7 s), and the child rested for 2 s while the monitor screen remained blank. All children were allowed to rest for 3 to 5 min as needed between tasks or trials to avoid mental fatigue (Fig. 2).

2.3. EEG data acquisition

An EEG-based brain mapping system with 30 scalp sites (Ag–AgCl electrodes, extended 10–20 system) (Laxtha L, Daejeon, Republic of Korea) was used to record electrical potentials. An EEG-based cortical rhythmic activity monitoring system [9], which consisted of pre-processing and real-time processing parts, was used to monitor task procedures. To monitor muscle activity associated with movement artifacts during motor imagery tasks, we also recorded electromyography signals from the two electrodes attached to the bilateral flexor carpi radialis [10]. When undesirable muscle activation due to movement artifact was observed, the data were discarded, and the test was repeated.

2.4. Regions of interest (ROI)

Regions of interest (ROIs) were drawn around the primary sensorimotor cortex (SMC), premotor cortex (PMC), and supplementary motor area (SMA), which

Table 2
EEG electrode locations activated and corresponding activation areas in the extended 10–20 system during movement execution

	Movement execution			
	Left hand tasks		Right hand tasks	
Subject	Electrode locations	Corresponding activation areas	Electrode locations	Corresponding activation areas
1	CP3, C4	Inferior parietal Lobe, Postcentral Gyrus	C3, CP3	Postcentral Gyrus, Inferior parietal Lobe
2	CP3, P1	Inferior parietal Lobe, Precuneus	CP3, P1	Inferior parietal Lobe, Precuneus
3	FC4	Middle frontal Gyrus	C4, CPz	Postcentral Gyrus
4	C3, CP3, C4	Postcentral Gyrus, Inferior parietal Lobe	C3	Postcentral Gyrus
5	C4	Postcentral Gyrus	C4	Postcentral Gyrus
6	CP3, CP1	Inferior parietal Lobe, Postcentral Gyrus-Superior parietal Lobe	P1, PO3	Precuneus, Middle occipital Gyrus
7	CP3	Inferior parietal Lobe	AF3	Superior frontal Gyrus
8	C4,C2	Postcentral Gyrus, Precentral Gyrus	C4, C2	Postcentral Gyrus, Precentral Gyrus

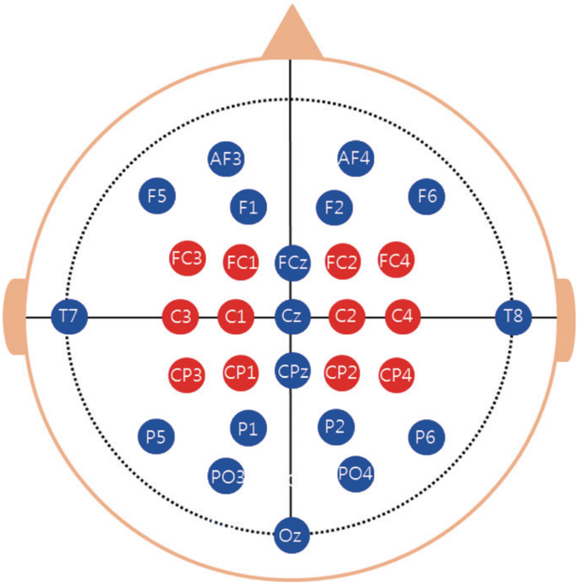

Fig. 3. 30 EEG electrodes sites and the regions of interest (ROIs: Red color electrodes). (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/NRE-2012-00803)

were reported to have neuroplastic potential (Fig. 3). Additionally, the visual cortex (VC) area responsible for visual-motor control during OOM and VMI was selected [11,12]. Electrode locations and anatomical brain areas were described relative to the anatomical locations of cortical projections [13].

2.5. *EEG data analysis*

We used event-related spectral perturbation (ERSP), which measures the average change of spectral power (i.e., event-related desynchronization [ERD] and synchronization [ERS]) to evaluate changes in cortical electrical activity in the brain ROIs. Our EEG monitoring system can instantly display topographical maps on the computer monitor to observe task performance in real time, but the recorded EEG data were analyzed offline. The ERSP analysis was implemented in EEGLAB [14,15]. A time segment of 7 s was extracted for each epoch, in which the first 2 s of EEG data (0 to 2 s) were taken before the cue onset for the reference period. The mu frequency band (8–12 Hz) related to limb movements that was previously calculated was used to portray topographic power maps. Topographic power maps were displayed to evaluate spatial perturbations in the ROIs as the tasks were performed. The mu band power values recorded from 0 s to 5 s after the cue onset were averaged for each electrode position, and the mean values were displayed in the predefined color map. Descriptive analysis was used to examine the topographical brain map.

3. Results

3.1. *EEG brain mapping during ME*

In normal children, commonly activated cortical areas during ME were near the SMC (C3, CP3; post central gyrus and inferior parietal lobes), whereas the activated areas in children with CP were near the SMC, PMC, SMA (AF3, C2; superior frontal gyrus, precentral gyrus), and VC (P1, PO3; precuneus and middle occipital gyrus) (Table 2).

3.2. *EEG brain mapping during KMI*

Electrodes overlying the SMC and VC areas were activated in normal subjects, whereas electrodes near the SMC, SMA, PMC (FC4, F1; middle frontal gyrus and superior frontal gyrus), and VC (middle occipital gyrus) areas were activated in children with CP (Table 3).

Table 3
EEG electrode locations activated and corresponding activation areas in the extended 10–20 system during kinesthetic-motor imagery

	Kinesthetic-motor imagery			
	Left hand tasks		Right hand tasks	
Subject	Electrode locations	Corresponding activation areas	Electrode locations	Corresponding activation areas
1	CP3,CP1	Inferior parietal Lobe, Postcentral Gyrus	CP3, CP1	Inferior parietal Lobe, Postcentral Gyrus-Superior parietal Lobe
2	Oz, PO4	Cuneus, Middle occipital Gyrus	Oz	Cuneus
3	Oz, PO4	Cuneus, Middle occipital Gyrus	C3	Postcentral Gyrus
4	C4, C2	Postcentral Gyrus	C3	Postcentral Gyrus
5	C4	Postcentral Gyrus	T7	Middle temporal Gyrus
6	CP2, CP4	Postcentral Gyrus, Inferior Parietal Lobe	CP2	Postcentral Gyrus
7	PO3	Middle occipital Gyrus	PO3	Middle occipital Gyrus
8	C4, FC4,	Postcentral Gyrus, Middle frontal Gyrus,	F1, FC3	Superior frontal Gyrus, Middle frontal Gyrus

Table 4
EEG electrode locations activated and corresponding activation areas in the extended 10–20 system during observation of movement

	Observation of movement			
	Left hand tasks		Right hand tasks	
Subject	Electrode locations	Corresponding activation areas	Electrode locations	Corresponding activation areas
1	PO4	Middle occipital Gyrus	PO4	Middle occipital Gyrus
2	PO4	Middle occipital Gyrus	CPz, CP2, P2	Postcentral Gyrus, Precuneus
3	P2, FC4	Precuneus, Middle frontal Gyrus	PO4, P6	Middle occipital Gyrus, Middle temporal Gyrus
4	Oz, PO4	Cuneus, Middle occipital Gyrus	PO3	Middle occipital Gyrus
5	C4, P1	Postcentral Gyrus, Precuneus	C4, CP4, PO4	Postcentral Gyrus, Inferior parietal Lobe, Middle occipital Gyrus
6	PO4	Middle occipital Gyrus	PO3	Middle occipital Gyrus
7	PO3	Middle occipital Gyrus	PO3, F6	Middle occipital Gyrus, Middle frontal Gyrus
8	P2, PO3	Precuneus, Middle occipital Gyrus	P2	Precuneus

3.3. *EEG brain mapping during OOM*

In normal children, the most commonly activated cortical area was the VC, whereas in children with CP, commonly activated areas were near the VC and SMC (subject 5) (Table 4).

3.4. *EEG brain mapping during VMI*

In normal children, activated cortical areas were near the visual or occipital area and the SMC, whereas in the children with CP, the primary activated areas were near the VC (subjects 7 and 8), SMC (subject 5), and auditory cortex (middle temporal gyrus in subject 6) (Table 5).

4. Discussion

This is the first study reporting topographical brain mapping using a novel EEG-based system to evaluate specific cognitive motor processes in normal children and children with CP during four different motor imagery tasks (ME, KMI, OOM, and VMI). As hypothesized, different cortical areas were activated in the two groups of children during the motor imagery tasks. In particular, normal children showed increased activation primarily in the SMC during ME and KMI tasks and in the VC during the OOM and VMI tasks, whereas children with CP showed activation in various cortical regions.

It was difficult to compare our findings with those of previous studies, because there is little EEG brain mapping data for children with CP. In the present study, EEG signals recorded during the ME and KMI tasks showed that the SMC was commonly activated in normal children. This finding was consistent with that of a previous study, which described similar topographic maps for normal adults [16]. During KMI, both SMC and VC areas were activated in normal children. However, in children with CP, the SMC, PMC, SMA, and VC were activated during the ME and KMI tasks. In particular, children with mild to moderate CP (subjects 5, 6 and 8) showed SMC activation along with other motor network areas (PMC, SMA). A child with severe CP (subject 7) showed increased activation in the VC

Table 5
EEG electrode locations activated and corresponding activation areas in the extended 10–20 system during visual motor imagery

	Visual motor imagery			
	Left hand tasks		Right hand tasks	
Subject	Electrode locations	Corresponding activation areas	Electrode locations	Corresponding activation areas
1	FC2, C2, C4, CP4	Superior frontal Gyrus, Postcentral Gyrus, Inferior parietal Lobe	AF3, PO3	Superior frontal Gyrus, Middle occipital Gyrus
2	PO3	Middle occipital Gyrus	FC4	Middle frontal Gyrus
3	AF3, FC3, C3	Superior frontal Gyrus, Middle frontal Gyrus, Postcentral Gyrus	F1	Superior frontal Gyrus
4	C4	Postcentral Gyrus	C3	Postcentral Gyrus
5	C4, CP4	Postcentral Gyrus, Inferior parietal Lobe	C4, CP4	Postcentral Gyrus, Inferior parietal Lobe
6	T7	Middle temporal Gyrus	T7	Middle temporal Gyrus
7	PO3	Middle occipital Gyrus	PO3	Middle occipital Gyrus
8	P2, PO4	Precuneus, Middle occipital Gyrus	F1, FC3	Superior frontal Gyrus, Middle frontal Gyrus

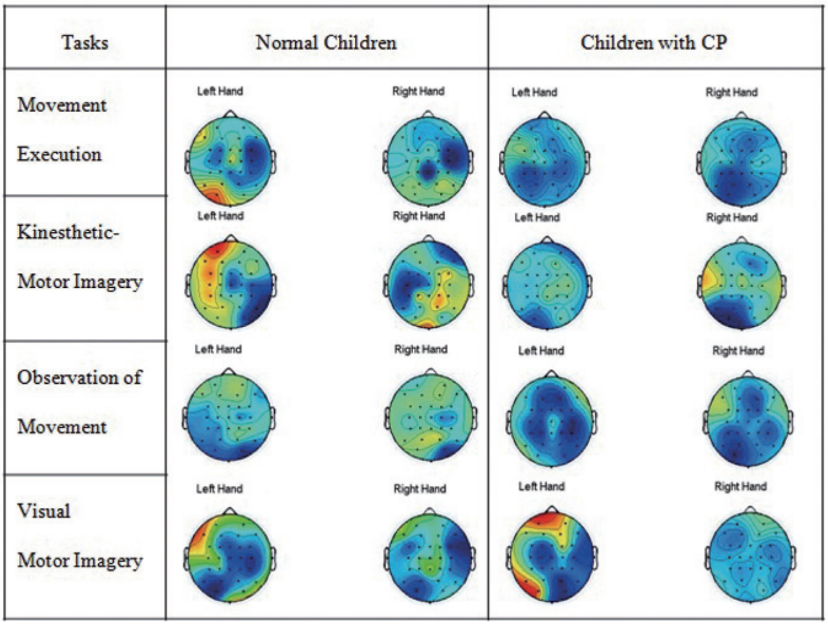

Fig. 4. An overview of topographical maps during four different motor imagery tasks. (Colours are visible in the online version of the article; http://dx.doi.org/10.3233/NRE-2012-00803)

during KMI with the more involved limb, and increased activation in the SMC and PMC during ME. Cortical activation patterns differed not only between normal children and children with CP, they also differed between the involved and uninvolved (or less involved) sides in children with CP during the ME and KMI tasks. A more global activation rather than a focal activation was observed when the task was performed with the more involved limb. This global cortical activation may be related to adaptive or compensatory cortical reorganization associated with increased efforts of the more involved arm (i.e., association reaction) during the motor task [17].

EEG brain mapping data recorded during the OOM and VMI tasks showed that the most commonly activated cortical areas in normal children were near the VC or occipital area, whereas activated areas in children with CP were near the VC and SMC (subject 5) and bilateral auditory cortices (middle temporal gyri in subject 6), which may have been due to hypersensitivity to auditory stimulation (i.e., beep sign). This finding suggests that the VC was activated together with the motor cortex.

Regardless of the motor imagery task, most normal children showed relatively symmetrical and focal topographical maps of the ERD power spectrum in the bilateral hemispheres. However, in children with CP, asymmetrical and global topographical maps were observed, suggesting less cortical activation in the involved area than in the less involved area (Fig. 4).

Our data were in agreement with previous studies that investigated brain activation during motor execution and imagery in adults with hemiplegic stroke [18, 19]. Kimberley et al. [18] demonstrated that contralateral SMC were activated in healthy controls during wrist tracking motor imagery tasks, whereas contralesional activation in primary motor areas and SMA was more common in patients with hemiparetic stroke using the affected hand. Similarly, Jang et al. [19] found that contralesional PMC, bilateral SMA, and the SMC were activated in adults with hemiparetic stroke when performing the hand grip motor task with the affected hand before intervention. Together with other neuroimaging studies of motor imagery, our EEG brain mapping technique is useful to compare topographic maps and cortical activation patterns during motor tasks in normal children and children with CP.

In conclusion, we have presented a novel real-time EEG-based brain mapping system. Although evaluation of its efficiency in rehabilitation has just begun, our brain mapping system shows potential as an alternative neuroimaging technique to probe underlying neural recovery mechanisms. It may also serve as a powerful real-time neurofeedback system for individuals with CP or patients recovering from a stroke. Further studies with larger samples are warranted for generalization of our findings.

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