Impact of Constraint-Induced Movement Therapy on Brain Functioning in Children with Cerebral Palsy

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**Abstract**

Few studies have examined the effects of Constraint-Induced Movement Therapy (CIMT) in children or its effects beyond sensory-motor domains. Evidence from adult populations suggests that CIMT is linked with cortical restructuring and could have effects on speech, language deficits, and sensory-perceptual processes, domains typically affected by cerebral palsy (CP). Using a five-day camp model, CIMT effects were tested on children age 5-12 with CP using behavioral measures and two event-related potential (ERP) paradigms –speech sound perception and picture-word matching. Data were collected at baseline, immediately after treatment, and 6 months after the camp. We found that paretic limb function improved after CIMT, and ERP waveform patters changed significantly to reflect faster processing and improved organization. These changes persisted at 6 months follow-up.

Impact of Constraint-Induced Movement Therapy on Brain Function in Children with Cerebral Palsy

Cerebral palsy (CP) is a type of motor impairment originating in the brain usually caused by a central nervous system malformation or lesion or by an injury to the developing brain. The current definition of CP often includes impairments in cognition, communication and sensation (Himmelman, Hagberg, Beckung, & Uvebrant, 2010). CP is one of the most prevalent forms of childhood disability, affecting approximately 2 children per 1000 live births annually (Pellegrino, 2007) and this risk is increased for pre-term births.

A distinction is made between CP when the onset is before, during, or soon after birth, which is referred to as congenital CP, and when the onset is later in childhood, which is referred to as acquired CP. Many forms of CP have been described, including diplegic, ataxic and quadraparetic; however, one of the most common types, and the one addressed in this study, is congenital hemiparetic cerebral palsy (HCP). According to Himmelman et al. (2010), hemiparesis occurs in approximately 33% of all individuals diagnosed with CP. HCP is an incomplete paralysis affecting one side of the body and can vary in its degree from person to person (DeLuca, Echols, Law, & Ramey, 2002). Common manifestations of HCP are weakness, lack of control of the affected limb(s) and sensory-perceptual deficits (Cerebral Palsy Source, 2005). In addition to sensory-motor deficits, CP is also associated with problems with learning and language, epilepsy, and hearing and vision impairment (Krageloh-Mann & Horber, 2007; Geytenbeek, 2011).

A study by Sigurdardottir (2010) of the population of all 4-6 year olds with CP in Iceland from 1989 to 2004 found a significant level of impairment in speech, expressive language and verbal cognition. The population of children (N=152) was evaluated by a team including a pediatrician, neuropsychologist and a speech and language therapist. They found that 16% of children were nonverbal communicators and that 16% of children had severe dysarthria. These results are concurrent with the findings in a review of speech and language therapy that 20% of children with CP cannot produce intelligible speech and up to 50% have less severe speech and communication impairments (Pennington, Goldhart & Marshall, 2005). Bottcher, Flachs, and Uldall (2010) found impaired executive functioning and slower performance on timed tasks using standardized neuropsychological measures in children with spastic CP.

The effects of HCP are often exacerbated in children. One explanation for this effect is the theory of learned nonuse (Taub, Crago & Burgio, 1994). The theory of learned nonuse posits that substantial neurologic injury during childhood, like that which is found in HCP, is associated with “more depressed motor function than warranted by actual nervous system damage” because of negative feedback the child receives when using the affected limb early in development (DeLuca et al., pp. 932, 2002). This negative feedback is caused by either an inability to move the affected limb or inefficient, clumsy movements that lead to a conditioned avoidance of using the affected limb. If this learned nonuse or suppression is not overcome, the results could last throughout the child’s life (DeLuca et al., 2002). Related to learned nonuse is developmental disregard, which is a lack of sensory-motor input to the affected limb during developmental periods (Sterr et al., 2002).

No cure exists for HCP; however, studies show that the effects of the condition and of learned nonuse can be minimized through therapy. Of particular interest are the benefit of Constraint-Induced Movement Therapy (CIMT) for improving function of the afflicted limb and its possible benefits to motor and cognitive deficits, alike.

**Constraint-Induced Movement Therapy (CIMT)**

CIMT is a relatively new therapy that was developed for treating adults with hemiparesis due to stroke (Taub, Crago, & Uswatte, 1998). CIMT combines restraint of the unaffected limb - usually via a cast - and exhaustive use of the paretic limb in a range of daily activities, referred to as shaping (Sutcliffe, Logan, & Fehlings, 2009; DeLuca et al., 2002). Additionally, an important part of CIMT is immediate verbal praise and reinforcement, and constant adjustment of expectations to higher levels of performance (DeLuca et al., 2002).

To measure the effectiveness of CIMT, studies have employed questionnaires and observational reports from caregivers and therapists. The most commonly used measures are the Motor Activity Log (MAL) and the Quality of Upper Extremity Skills Test (QUEST). The MAL is a patient interview focusing on the amount of use and the quality of movement of the affected limb (Van der Lee, Beckerman, Knol, de Vet, & Bouter, 2004). The scores range from zero (never use the affected hand/limb or poor quality of use) to five (always use the affected hand/limb or normal functioning). The benefits of the MAL are high levels of internal consistency and limits of agreement (Van der Lee et al., 2004). The MAL is typically used as a predictor of future/lasting gains from CIMT. The Quality of Upper Extremity Skills Test (QUEST; DeMatteo et al., 1992) is the quantitative measure of the quality of movements of the hemiplegic extremity and is administered by an occupational therapist (Sutcliffe et al., 2009). The QUEST is intended to be an objective measure of the improvement in motor activity from CIMT.

Although prior studies have varied on the type of restraint (e.g. removable splint vs. permanent cast), length of intervention (1 week – 6 months), intensity of practice (1 hour- 24 hours/day) and specific evaluation measures, their results suggest that CIMT improves sensory-motor function (Charles & Gordon, 2005; Taub et al., 1998).

In a single-subject study of an adult with hemiplegia caused by stroke, CIMT was administered for two weeks and upper-limb function was evaluated using the Upper Extremity Function Test (UEFT) and Simple Test for Evaluating Hand Function (STEF). After treatment, the motor function of the affected limb increased by 29.1% on the UEFT and 18.4% on the STEF. Those results were maintained and improved upon at a three month follow-up (Bi & Ma, 2009).

One of the promising effects of CIMT in adults is evidence of cortical reorganization. Using intracortical micro-stimulation, Taub et al. (1998) found that somatosensory representation of the affected limb in stroke patients was larger after CIMT, suggesting that improvements in behavioral functioning of an affected limb are reflected in changes in brain structure. Using transcranial magnetic stimulation, DeLuca et al. (2002) found that, after 12 days of therapy, the excitable cortex of the affected limb in their adult patients with HCP doubled in size. Similar results were reported by Sutcliffe et al. (2009) in a fMRI study where all participants, ages 7-15 (n=5), showed increased contralateral activity for affected hand movement after CIMT. Of their five patients, three improved by ≥ 0.7 on the Pediatric MAL (PMAL) and one improved on the QUEST but not the PMAL. Furthermore, because contralateral activity was present in all 5 participants, even the one who did not improve by clinical measures, the authors suggested that cortical change may be unrelated to clinical improvements and may be more sensitive to the benefits of constraint therapy.

**CIMT in Children**

Given the evidence of the beneficial outcomes of CIMT in adults, this therapy has recently been extended to work with children. The same measures of effectiveness, QUEST and MAL, can be used. The Pediatric Motor Activity Log (PMAL; Wallen, Bundy, Pont & Ziviani, 2009) is a modified version of the MAL and is a parental interview.

The first paper on pediatric CIMT was published in 2002 on a sample of 18 children, average age 41.5 months (DeLuca et al., 2002). The study consisted of two groups, a control and a group that received 21 consecutive days of CIMT for 6 hours per day. The children’s less involved upper extremity was casted (bivalve for weekly removal) from upper arm to fingertips. The day after casting a pediatric therapist began the intervention. After the 21 days the control group and the therapy group switched. The results indicated significant positive change in upper extremity function in response to CIMT. Assessments of motor function using PMAL and QUEST were performed one to three days prior to treatment, one to three days after treatment, and at a 3-week follow-up. Treatment was associated with an increase in PMAL scores (quality of movement and frequency of use) and improvement in QUEST scores that approached significance. Similar results were found in the second phase of the study, after crossover, for the initial control group.

Child participants who undergo constraint-induced therapy show improvement in measures of paretic limb use and function (Smania et al., 2009; Naylor & Bower, 2005). Moreover, the improvement they see from CIMT is greater than the improvement seen for patients in control studies that used non-constraint physical therapy techniques. Both studies used a crossover design that reconfirmed greater improvements seen after constraint therapy. Smania et al. (2009) used two groups of five participants with congenital HCP that each participated in CIMT and conventional physiotherapy in opposite orders over a five month period. They were measured on 16 exercises focusing on extent of use and three types of function (bimanual, paretic, and unaffected). Significant improvement was seen in the use-tests after CIMT and in paretic arm function. Bimanual function showed changes close to significance and no change was found in unaffected arm function, as was expected.

A review of 15 pediatric CIMT studies, reported “increased frequency of use of the upper extremity following CIMT for children with hemiplegic CP” (Huang, Fetters, Hale, & McBride, 2009, pp. 126). They also noted that more rigorous conditions, such as longer lengths of intervention and more hours of therapy, were correlated with increased frequency of use of the upper extremity, following CIMT.

**Current Study**

While both adult and pediatric studies demonstrate that CIMT improves sensory-motor functioning of the affected limb and may result in cortical reorganization even after just one week of CIMT, no study to date has investigated whether CIMT may offer benefits for other domains typically affected by CP, such as language and sensory-perceptual processes. In this study, we addressed this question.

To ensure a comprehensive assessment of treatment effects, the study utilized the traditional behavioral measures (PMAL and QUEST) as well as measures of brain activity. event-related potentials (ERP) were chosen as the measure of brain activity because it is noninvasive, easily repeatable, sensitive to aspects of language, attention, and memory and can be used to compare changes in brain activity pre- and post-treatment (Connolly & D’Arcy, 2000).

An ERP is a measure of the electrochemical response to a stimulus presentation (e.g., visual, auditory). Such responses can be recorded from multiple locations on the scalp and are represented as a waveform depicting voltage over time. When analyzing the waveform of an ERP, three things are taken into consideration: time course, amplitude, and distribution across the scalp. Differences in ERP waveforms across conditions lend themselves to the assumption that the underlying brain processes associated with each condition differ in some respect (Otten & Rugg, 2004). By analyzing these three elements, ERP can provide insights into the underlying differences between cognitive as well as sensory and motor processes.

The temporal resolution of ERP can be made in the order of milliseconds (Otten & Rugg, 2004). By comparing differences between waveforms in time, researchers can draw inferences about the timing of brain and cognitive processes relative to one another. When applied to CIMT, ERP allows us to observe if treatment improved the response time of brain processes.

Differences in amplitude, like differences in latencies, are treated as quantitative. If two waveforms were identical in terms of temporal characteristics and distribution across the scalp but differed in amplitude, the waveforms would be considered to reflect the same cognitive process but at varying degrees, such as level of attention (Otten & Rugg, 2004). An increase in the amplitude of the waveforms post-CIMT can be seen as a stronger response to the stimuli due to more cells firing in temporal synchrony, possibly because of cortical reorganization.

Although ERPs offer valuable information concerning functional processes, limitations exist. Two weaknesses of ERPs are their correlational nature and low spatial resolution. ERPs are created by matching the constant electrical signal the brain emits with the precise moment a stimulus is presented. Because multiple parts of the brain are always active and emitting a signal, and only signals that are in temporal synchrony will be strong enough to reach the scalp, it is impossible to trace the spatial origin of an ERP to a single specific source.

We used ERPs to examine whether CIMT can affect processes like language and speech perception in addition to sensory-motor functioning. ERP recordings in children with HCP were obtained immediately pre- and post- one week of constraint treatment as well as at 6 month follow-up to determine lasting effect. We hypothesized that CIMT results in (1) quantifiably improved sensory-motor functioning of the affected limb indicated by better PMAL, QUEST, two-point discrimination (TPD), and relative grip strength (GS) scores, and (2) increased efficiency of brain functioning as reflected in the amplitude and latency of ERPs in response to speech and language stimuli. We believe the measures of sensory-motor functioning will show quantifiable improvements in behavioral functioning after treatment. The biological principles behind the ERP tasks that are being tested are that behavioral improvements require changes in the brain and, because cortically diffuse processes like speech and language utilize multiple cortical areas, these brain changes will affect speech and language processes as well.

**Methods**

**Participants**

Twenty children (15 male, 5 female), between the ages of 5 and 12 years (*M* age = 6.8, *SD* = 2.00), were recruited from the Monroe Carell Jr. Children’s Hospital at Vanderbilt University. Eligibility criteria were a diagnosis of hemiparesis and asymmetrical upper extremity use on a standardized assessment using consensus definitions (Rosenbaum, Paneth, Leviton, Goldstein & Bax, 2006) within the 6 months prior to the intervention, and the ability to complete the 60-month Ages and Stages Questionnaire (ASQ; Squires & Bricker, 2009). Requirements for participation in the study were that all answers on the ASQ were “yes” and a maximal score (60) in the Communication, Problem-solving and Personal-Social domains. Exclusion criteria were uncontrolled seizure disorder or cognitive ability more than 2 standard deviations below the mean on standards tests, as determined by school systems or specialized psycho-educational testing. The study was approved by the University’s Institutional Review Board and consent was obtained from each child’s parents and pediatrician. Each child provided a verbal assent. Study population characteristics are presented in Table 1.

**Study Design and Procedure**

The study was run in a 5 day, day-camp format. On Day 0, the day preceding the start of the camp, participants completed neurobehavioral and ERP assessments at the Pediatric Rehabilitation Center. Then the upper extremity, contralateral to their brain lesion, was fitted with a non-removable cast covered in a soft sleeve.

The total time of constraint was 120 hours (Day 1 – Day 5) and allowed for 22 hours of combined group and individual therapy. Activities were aimed at improving the fine motor skills and use of the affected limb. Sensory activities targeted tactile stimulation (e.g., making dough, placing hand in rice), and vestibular control (e.g., dancing and spinning). Motor activities included jumping, running and playing with water guns. A novel component of this camp was that CIMT intervention incorporated fine and gross motor activities in equal proportion to sensory exposures and stimulation; this has not been done before in other CIMT camp models. Instructions were given to the children for each activity, and positive feedback was a critical component. Parents were given a program on Day 0 to help maximize intervention in the home setting and cope with initial child frustration.

Neurobehavioral and ERP assessments were repeated on Day 5 after the cast was removed and at a follow-up visit 6 months after the camp.

**Neurobehavioral Assessments**

Motor function assessments were conducted by pediatric physical therapists. Assessments of motor function were grip strength (GS), QUEST, PMAL [total and spontaneous use (SU)], and two-point discrimination (TPD).

Grip strength was measured using a calibrated Jamar Dynamometer. Therapists administered QUEST to measure function in four domains: dissociated movement, grasps, protective extension, and weight bearing. The PMAL (Wallen et al., 2009) was completed by the patient’s parents during a semi-structured interview to assess the amount of hand/arm use. TPD was assessed by placing either one or two points of a Disc-Criminator on the finger tip pulp of the index finger. The minimum distance (mms) that a participant could correctly distinguish between one or two points of contact in five consecutive trials was recorded.

**Electrophysiological Assessments**

Electroencephalogram (EEG) was recorded using a Geodesic Sensor Net with a high-density array of 124 Ag/AgCl electrodes (EGI, Inc., Eugene, OR) with filters set to 0.1 – 100 Hz, (filtered offline to 0.1 – 30 Hz) and a sampling rate of 250 Hz. Electrode impedance levels were adjusted to less than 40 kOhm. During data collection, all electrodes were referred to Cz (re-referenced offline to an average reference). Two paradigms were used over a 20 minute testing period. ERPs were recorded in response to picture-word pairs and speech-sound tasks to measure effect on language perception and comprehension.

**Speech sound processing task.** To assess auditory perceptual processes three speech sounds (/ba/, /ga/, /pa/) produced by a female native speaker of English were randomly presented 40 times each, for a total of 120 trials. Inter-stimulus intervals varied randomly between 1400 and 2400ms to prevent habituation to sound onset. The stimuli were presented binaurally at 75 dB SPL(A) through speakers positioned two feet in front of the participant. Participants were asked to listen to the stimuli while keeping their heads still and avoiding blinking as much as possible. No behavioral responses were required. During sound presentation, a silent video was presented on a computer screen in front of the participant to hold their attention. The task lasted approximately 10 minutes.

**Picture-word matching task.** This paradigm was adapted from the Peabody Picture Vocabulary Test – IV (PPVT-IV; Dunn, Dunn, Williams, & Wang, 2007) and examined receptive vocabulary. In this task, pictures were presented on a computer monitor for 1700ms followed by a target spoken word beginning 700ms after picture onset. On 50% of trials the word matched the picture and the remaining 50% were mismatches. All auditory stimuli were presented at 75 dB SPL(A) through stereo speakers positioned on the table in front of the participant. Inter-stimulus intervals varied randomly between 1400 and 2400ms to prevent habituation to sound onset. Participants were instructed to decide whether the spoken word matched the picture correctly but no behavioral response was required. Two levels of vocabulary were used in the test (known words in the child’s vocabulary and novel words from adult vocabulary). This task lasted approximately 8 minutes.

**Analysis**

**Neurobehavioral measures.** Changes in the behavioral outcomes as measured by the QUEST and PMAL were the primary measures of the CIMT effects. Pairwise T-tests were conducted from baseline to posttest and from baseline to 6 month follow-up to determine if there was a significant difference in scores.

**ERP measures.** Individual ERPs were derived by segmenting the ongoing EEG on each stimulus onset to include a 100ms pre-stimulus baseline and a 900ms post-stimulus interval. Resulting segments were screened for artifacts using computer algorithms included in NetStation and then followed by a manual review. Trials contaminated by eye or movement artifacts were excluded from the analysis. The remaining ERPs were averaged, re-referenced to an average reference, and baseline corrected. For a data set to be included in the statistical analyses, individual condition averages had to be based on at least 10 trials.

To reduce the number of variables in the statistical analyses, only electrodes corresponding to the a priori defined regions of interest were analyzed. These electrode clusters were selected based on the scalp locations identified in previous studies as the optimal sites for the targeted ERPs. Latency and mean amplitude measures were taken using the NetStation statistical extraction tool. These data were derived for each selected electrode and then averaged within each cluster. Latency windows were determined based on the examination of the grand-averaged waveform and the intervals used in prior studies.

**Speech sounds.** Analyses focused on the differences in the ERP for the /ba/-/ga/ and /ba/-/pa/ contrasts as reflected by the amplitude of the first positive (150-250ms after stimulus onset) and negative (250-550ms) ERP responses at temporal, central, and frontal scalp areas.

**Picture-word matching.** Data analyses focused on the amplitude and latency of the frontal and central N200 responses, and the centro-parietal and fronto-central N400 responses of matching vs. mismatching picture-word pairs. The mismatching words were expected to generate a larger N200 and N400 than the matching words.

For both tasks, the resulting ERP variables were analyzed using a repeated measures ANOVA [Speech Sounds - Time (3) x Sound Contrast (2) x Electrode (7) x Affected Side (2); Picture-word matching - Time (3) x Condition (2) x Match (2) x Electrode (3) x Hemisphere (2) x Affected Side (2)] and corrected using the Huynh-Feldt Method. Where appropriate, post hoc analyses were conducted using Bonferroni Correction. Significance level of 0.05 (two-tailed) was used.

**Results**

**Neurobehavioral data**

There was a significant increase in PMAL scores from baseline measures to post-test, *t*(19) = -6.342 *p* < 0.001, and from baseline to 6 months follow-up, *t*(16) = -3.962 *p* < 0.001. QUEST scores showed a significant increase from baseline to post-test, *t*(18) = -2.958 *p* = 0.008 and from baseline to 6 months follow-up, *t*(17) = -2.316 *p* = 0.033. Grip Strength scores showed a significant increase from baseline to post-test *t*(19) = -4.538 *p* < 0.001, but no significant results from baseline to 6 month follow-up. There was no significant change in TPD scores from baseline to post-test or baseline to 6 month follow-up. See Table 2 for behavioral results.

**ERP data: Sound Contrast**

**Baseline to posttest.** Analysis of Variance (ANOVA) of the 100-300ms amplitude differences showed a significant interaction of Time x Electrode x Hemisphere x Affected Side, *F*(2,32) = 3.930 *p* = 0.036. Post hoc analysis revealed no significant results for participants with either Affected Side.

ANOVA of the 100-300ms latency of the negative peak showed a significant interaction of Sound Contrast x Electrode, *F*(2,32) = 3.659 *p* = 0.037. Post hoc analysis of the interaction revealed that the latency difference of the BG sound contrast was significantly greater than the difference for the BP sound contrast at the Right Frontal electrode, *t*(17) = 2.175 *p* = 0.044.

ANOVA of the 100-300ms latency of the positive peak showed an interaction of Sound x Time x Electrode x Hemisphere that was nearly significant, *F*(2,32) = 3.282 *p* = 0.052. Post hoc analysis revealed that the BG latency difference of the positive peak was significantly greater than the BP latency difference at baseline for the Central electrode, *t*(17) = 6.194 *p* < 0.001; Left Frontal electrode, *t*(17) = 7.496 *p* < 0.001; Right Frontal electrode, *t*(17) = 7.788 *p* < 0.001; Left Temporal electrode, *t*(17) = 5.851 *p* < 0.001; Right Temporal electrode, *t*(17) = 5.462 *p* < 0.001; Left Posterior-Temporal electrode, *t*(17) = 2.971 *p* = 0.009; The BG – BP difference approached significance for baseline at the Right Parietal Temporal electrode, *t*(17) = 2.080 *p* = 0.053. At posttest the BG latency difference of the positive peak was significantly greater than the BP difference at the Right Frontal electrode, *t*(17) = 3.257 *p* = 0.005; Left Temporal electrode, *t*(17) = 2.754 *p* = 0.014; Right Temporal electrode, *t*(17) = 2.528 *p* = 0.022; and Left Parietal-Temporal electrode, t(17) = 2.757 *p* = 0.013. Post hoc also showed that the baseline latency difference of the positive peak was significantly greater than the difference for the BG Sound Contrast at the Central electrode, *t*(17) = 5.589 *p* < 0.001; Left Frontal electrode, *t*(17) = 3.144 *p* = 0.006; Right Frontal electrode, *t*(17) = 3.995 *p* = 0.001; and Left Temporal electrode, *t*(17) = 2.158 *p* = 0.046.

ANOVA of the 300-500ms amplitude differences showed a significant interaction of Time x Affected side, *F*(1,16) = 4.332 *p* = 0.035. Post hoc analysis revealed no significant results for participants with a left affected side. For participants with a right affected side, the baseline amplitude difference was greater than the posttest difference and approached significance, *t*(9) = 2.067 *p* = 0.069.

ANOVA of the 300-500ms latency of the negative peak showed no significant differences.

ANOVA of the 300-500ms latency of the positive peak showed a significant interaction of Sound Contrast x Time x Electrode x Hemisphere, *F*(2,32) = 3.494 *p* = 0.042. Post hoc analysis revealed that the baseline positive peak latency difference was greater than the posttest difference for the BG contrast at the Central electrode, *t*(17) = 24.319 *p* < 0.001; Left Frontal electrode, *t*(17) = 2.425 *p* = 0.027; Right Frontal electrode, *t*(17) = 4.898 *p* < 0.001; the Left Temporal electrode approached significance, *t*(17) = 1.949 *p* = 0.068; and the Right Temporal electrode, *t*(17) = 4.685 *p* < 0.001. For the Right Parietal Temporal electrode the direction of difference was reversed, *t*(17) = -15.983 *p* < 0.001. The baseline positive peak latency difference was greater than the posttest difference for the BP contrast at the Central electrode, *t*(17) = 19.251 *p* < 0.001; Left Frontal electrode, *t*(17) = 5.204 *p* < 0.001; Right Frontal electrode, *t*(17)=5.467 *p* < 0.001; Left Temporal electrode, *t*(17) = 2.321 *p* = 0.033; Right Temporal electrode, *t*(17) = 4.198 *p* = 0.001; and the Left Parietal Temporal electrode, *t*(17) = 3.460 *p* = 0.003. For the Right Parietal Temporal electrode the direction of difference was reversed, *t*(17) = -8.669 *p* < 0.001. Also, at posttest the BG positive peak latency difference was significantly greater than the BP latency difference at the Central electrode, *t*(17) = 2.370 *p* = 0.030.

**Baseline to 6-month follow-up.** ANOVA of the 100-300ms amplitude revealed a main effect of Time, *F*(2,28) = 5.461 *p* = 0.010. Post hoc analysis revealed the follow-up amplitude difference was significantly smaller than the baseline difference, *t*(14) = 2.718 *p* = 0.018.

ANOVA of the 100-300ms negative peak latency revealed no significant effects.

ANOVA of the 100-300ms positive peak latency revealed a main effect of Time, *F*(2,26) = 3.830 *p* = 0.043. Post hoc analysis revealed the follow-up positive peak latency difference was significantly smaller than the baseline difference, *t*(15) = 4.229 *p* = 0.001.

ANOVA of the 300-500ms amplitude revealed a main effect of Time, *F*(2,26) = 7.347 *p* = 0.003. Post hoc analysis revealed the follow-up amplitude difference was significantly smaller than the baseline difference, *t*(14) = 3.390 *p* = 0.004.

ANOVA of the 300-500ms negative peak latency difference revealed a main effect of Time, *F*(2,26) = 3.774 *p* = 0.042, and a significant interaction of Time x Electrode, *F*(12,156) = 2.189 *p* = 0.028. Post hoc analysis of the interaction revealed that the follow-up latency difference of the negative peak was significantly smaller than the baseline difference at the Central electrode, *t*(14) = 2.568 *p* = 0.022; and the Left Posterial-Temporal electrode, *t*(14) = 2.909 *p* = 0.011.

ANOVA of the 300-500ms latency difference of the positive peak revealed a main effect of Time, *F*(2,26) = 5.227 *p* = 0.012, and a significant interaction of Sound x Time x Electrode x Affected Side. Post hoc analysis of the interaction revealed, for participants with a right affected side, the BG difference at follow-up of the Left Frontal electrode was smaller than the baseline difference, *t*(5) = 6.710 *p* = 0.001. The BP positive peak difference at posttest was smaller than the baseline difference at the Left Temporal electrode, *t*(7) = 2.532 *p* = 0.039. Additionally, at baseline, the BP difference was smaller than BG difference at the Right Temporal electrode, *t*(7) = 2.411 *p* = 0.047; at posttest, the BG difference was smaller than the BP difference at the Right Frontal electrode, *t*(7) = -3.048 *p* = 0.019; the BP difference was smaller than the BG difference at the Left Parietal Temporal electrode, *t*(7) = 2.998 *p* = 0.020 and at the Right Parietal Temporal electrode, *t*(7) = 2.672 *p* = 0.032. For participants with a left affected side, the BG difference at baseline was smaller than the posttest difference at the Left Temporal electrode, *t*(9) = -2.388 *p* = 0.041.

**Picture-Word**

**Baseline to posttest.** Analysis of Variance of the N200 amplitude showed a significant interaction of Condition x Match x Electrode x Hemisphere x Affected side, *F*(2,30) = 4.125 *p* = 0.026; and an interaction of Time x Condition x Affected side for the N200 amplitude that was nearly significant, *F*(1,15) = 4.502 *p* = 0.051. Post hoc analysis on the first interaction revealed no significant results for participants with either Affected Side. Post hoc analysis on the second interaction revealed that the N200, in response to the Novel condition at posttest, was significantly more negative than at baseline at the midline electrodes for participants with a left affected side, *t*(7) = 2.910 *p* = 0.023. There were no significant findings for participants with a right affected side.

ANOVA of the N200 latency showed a significant interaction of Time x Match x Affected Side, F(1,15) = 7.119 p = 0.018. Post hoc analysis on the interaction revealed no significant results for participants with either Affected Side.

ANOVA of the N400 amplitude showed a significant interaction of Time x Match x Electrode x Hemisphere, *F*(2,30) = 3.747 *p* = 0.045. Post hoc analysis revealed that at baseline, the Match condition was significantly less negative than the Mismatch condition at the Right Frontal electrode, *t*(16) = 3.635 *p* = 0.002; and Right Parietal electrode, *t*(16) = -2.374 *p* = 0.030. At posttest, the Match condition was significantly less negative than the Mismatch condition at the Left Frontal electrode, *t*(16) = 2.474 *p* = 0.025.

ANOVA of the N400 latency showed a significant interaction of Time x Condition x Affected side, *F*(1,15) = 5.010 *p* = 0.041; and a significant interaction of Time x Match x Electrode, *F*(2,30) = 3.746 *p* = 0.047. Post hoc analysis found no significant results of the first interaction. Post hoc analysis on the second interaction revealed the latency difference at posttest was significantly greater than the baseline difference for the Match condition at the Frontal electrode, *t*(16) = -2.334 *p* = 0.033; the latency difference at follow-up was significantly smaller for the Match condition at baseline at the Temporal electrode, *t*(13) = 2.787 *p* = 0.015; the latency difference was significantly smaller for the Mismatch condition than for the Match condition at posttest for the Frontal electrode, *t*(16) = 2.230 *p* = 0.040; and the latency difference of the Match condition was significantly smaller than the Mismatch condition at follow-up at the Temporal electrode, *t*(13) = -2.557 *p* = 0.024.

**Baseline to 6-month follow-up.** ANOVA of the N200 amplitude revealed a significant interaction of Time x Electrode, *F*(4,48) = 3.866 *p* = 0.019, a significant interaction of Time x Condition x Affected Side, *F*(2,24) = 3.730 *p* = 0.049,and a significant interaction of Condition x Match x Electrode x Hemisphere x Affected Side, *F*(2,24) = 3.855 *p* = 0.035.Post hoc analysis on the interaction of Time x Electrode revealed that the follow-up amplitudes were significantly less positive than the baseline at the Frontal electrode, *t*(13) = 3.610 *p* = 0.003. The baseline amplitudes were significantly more negative than the follow-up at the Parietal electrode, *t*(13) = -2.254 *p* = 0.042. Post hoc analysis of the interaction of Time x Condition x Affected Side revealed that, for participants with a right affected side, the amplitude of the Known condition was significantly less positive than the Novel condition at baseline, *t*(7) = -2.612 *p* = 0.035. There were no significant results for participants with a left affected side. Post hoc analysis on the interaction of Condition x Match x Electrode x Hemisphere x Affected Side revealed that, for participants with a left Affected Side, the Novel Mismatch response was significantly less positive than the Novel Match response at the Frontal electrode for the left Hemisphere, *t*(8) = 2.607 *p* = 0.031, and the right Hemisphere, *t*(8) = 2.321 *p* = 0.049. No significant results were found for participants with a right Affected Side.

ANOVA of the N200 latency showed a significant interaction of Condition x Match, F(1,12) = 6.592 p = 0.025, a significant interaction of Time x Match x Affected Side, F(2,24) = 3.787 p = 0.037, a significant interaction of Condition x Electrode x Affected Side, F(2,24) = 4.610 p = 0.029, and a significant interaction of Match x Hemisphere x Affected Side, F(1,12) = 10.612 p = 0.007. Significant post hoc results were present only for the interaction of Match x Hemisphere x Affected Side where, for participants with a left Affected Side, the Mismatch response was significantly more negative than the Match response in the left hemisphere, t(8) = 2.489 p = 0.038; no significant results were found for participants with a right Affected Side.

ANOVA of the N400 amplitude revealed a significant interaction of Condition x Match x Electrode x Hemisphere x Affected Side, *F*(2,24) = 4.356 *p* = 0.024. Post hoc analysis revealed, that for participants with a left Affected Side, the amplitude difference of the response to the Known Mismatch condition was significantly less positive than the response to the Known Match condition at the Frontal electrode in the left Hemisphere, *t*(8) = 3.384 *p* = 0.010; and approached significance at the Frontal electrode in the right Hemisphere, *t*(8) = 2.246 *p* = 0.055; but the amplitude difference of the response to the Known Match condition was significantly less positive than the response to the Known Mismatch condition at the Parietal electrode in the left Hemisphere, *t*(8) = -2.548 *p* = 0.034; and at the Parietal electrode in the right Hemisphere, *t*(8) = -2.416 *p* = 0.042. No significant results were found for participants with a right Affected Side.

ANOVA of the N400 latency showed an interaction of Time x Condition x Match x Electrode x Hemisphere x Affected Side that approached significance, F(4,48) = 2.430 p = 0.060. Post hoc analysis revealed that, for participants with a right Affected Side, the negative peak latency response to the Novel Match condition at follow-up was significantly greater than the at baseline at the Right Frontal electrode, t(5) = -2.566 p = 0.050; and the Known Match latency was significantly greater than the Known Mismatch difference at the Left Temporal electrode at baseline, t(7) = 2.581 p = 0.036. For participants with a left Affected Side, the negative peak latency response to the Known Mismatch condition was significantly smaller at follow-up than at baseline at the Right Temporal electrode, t(7) = 3.312 p = 0.013; the negative peak latency was significantly greater at follow-up than at baseline for the Novel Match response at the Left Frontal electrode, t(7) = -2.678 p = 0.032; the negative peak latency of the Novel Match response was significantly greater than the Novel Mismatch response at the Right Frontal electrode at posttest, t(8) = 3.225 p = 0.012; and the negative peak latency of the Novel Mismatch response was significantly greater than the response of the Novel Match at the Right Temporal electrode at follow-up, t(7) = -2.640 p = 0.033.

**Correlations: Sound Contrast**

To examine the relationship between neurobehavioral and neural measures, a bivariate correlations analysis was performed focusing on changes in both types of measures. The most consistent correlations between the sound contrast data and behavioral measures are shown in Table 3. From baseline to post-test, as ERP amplitude difference increased after treatment, PMAL, GS and SU scores increased as well – positive relationship – while TPD scores decreased, generally – negative relationship. From baseline to 6 month follow-up the GS reversed its trend, resulting in no change in GS between baseline and follow-up, but SU remained improved. Better behavioral performance was associated with bigger, faster, and more organized brainwave measures.

Other correlations include conflicting results between the negative peak latencies and QUEST scores in the 100-300ms time frame from baseline to posttest, and two correlations with TPD in the 300-500ms time frame from baseline to follow-up that linked worse behavioral scores to faster latencies.

**Correlations: Picture-Word**

The most consistent correlations, as measured by bivariate correlations analysis, between the N400 Picture-Word data and behavioral measures are shown in Table 4.

The change from baseline to posttest showed negative correlations between the N200 amplitude Known Match data and TPD, and as the N200 amplitude became larger (more negative) after treatment there was a concurrent increase in QUEST scores. No correlations were found for the PMAL change after treatment, however, and conflicting results were found for TPD. The N200 peak latency had a negative correlation with PMAL and mostly negative correlations with TPD, which were unexpected results. However, it did have a negative correlation with QUEST, indicating that as the peaks became more negative, QUEST scores improved. From baseline to follow-up the Known Match data showed positive correlations between N200 amplitude and GS and QUEST and negative correlations between the N200 negative peak latency and QUEST, all supportive of our hypothesis. From baseline to follow-up the Known Mismatch data showed negative correlations between N200 amplitude and PMAL, which was not expected, and negative correlations between the N200 negative peak difference and QUEST and SU, which was expected.

From baseline to posttest the N400 amplitude had negative correlations with PMAL and TPD, which supported our hypothesis; a more negative N400 amplitude and a more positive PMAL score indicates better measures of cognitive processing and behavioral function. However, a negative correlation between the N400 amplitude and TPD and conflicting correlations with GS did not support our hypothesis. From baseline to posttest the Known Mismatch data showed a negative correlation between N400 peak latency and PMAL, which was supportive of our hypothesis. There was a negative relationship with QUEST but not PMAL, and no consistent relationships with TPD. The N400 negative peak latency had a negative relationship with PMAL. The correlations with QUEST and TPD were inconsistent and inconclusive. The results from baseline to follow-up show that as the N400 latency decreased QUEST scores increased.

**Discussion**

This project was designed to examine the effects of CIMT on sensory-motor functioning and brain functioning of children with hemiparetic cerebral palsy. For the most part, the results were in line with our hypothesis - sensory-motor functioning improved after treatment, and changes in brain functioning were present. However, not all findings showed changes in the expected direction.

From baseline to posttest, camp participants scored higher on PMAL, QUEST, and GS. Higher PMAL scores indicate that according to the parental report, the amount of use of the affected limb increased in a range of daily actions like opening doors or eating with utensils. Similarly, an improvement in quality of use could include having an easier time in tasks like brushing their teeth. Increase in the QUEST scores provided an objective evidence of the improved quality of use of the affected extremity (e.g., improved flexion and extension, greater weight bearing, and improved grasp coordination) as assessed by occupational therapists. Increased PMAL and QUEST scores also indicate participants’ greater awareness of their affected extremity after treatment. The reason for this improvement likely stems from the increased amount of sensory-motor input to the affected limb. The increased stimulation to an area that generally receives very little was enough to counteract the trend of learned nonuse. At 6 month follow-up, these improvements were still present, for the most part, suggesting lasting treatment effects. The only behavioral measure that did not show better scores at follow-up was GS, which returned to its baseline level.

In addition to the improvements in behavioral measures, the results of the ERP paradigms showed gains in brain functioning. In a sensory-perceptual task of speech sound discrimination we observed changes in the speed of information processing. Prior to treatment there was no significant difference in latency for the BG and BP sound contrasts. After treatment, an increased difference in the latency for the BG than BP sound contrasts was observed. This latency change was seen for both the positive and negative peaks in the 100-300ms and 300-500ms time frames. Both sound contrasts became processed quicker after treatment. At follow-up the faster processing still remained evident by shorter positive and negative peak latencies. Additionally, the amplitude differences were smaller at follow-up than at baseline within 100-300ms for participants with a left affected side and 300-500ms for those with a right affected side.

The Picture-Word paradigm, a more complex language comprehension task, revealed changes in the higher cognitive functions as the task performance required prediction and verification of an answer, specifically a word label for a picture. As expected, we saw the N400 amplitude of the mismatch response increase (become more negative) after treatment and the match response become more positive for the known words, while no test-retest changes were observed for the novel words (outside of the participant’s vocabulary), indicating that these changes in ERPs were not due to repeated exposure to the stimuli. The N400 response represents the processing of semantic error. Therefore, the increase in amplitude of the N400 suggests a better processing of the picture-word relation (i.e. an improvement in semantic processing). Additionally, the change in N400 latency shows that matching words were processed for a longer time than the mismatching words after treatment. In other words, after treatment, mismatches were detected faster compared to the match condition. We believe this reflects an improvement in the efficiency of word processing. The change could reflect that participants were more engaged in the task or that mismatched picture-word pairs became more obvious to participants after treatment. A similar pattern of latency change was found in the earlier N200 response. The N200 reflects executive cognitive control functions and has been used in the study of language to represent early processing of semantic or phonological information (Folstein & Van Petten, 2008; Schmitt, Munte, & Kutas, 2000). In this analysis, the N200 findings serves to reinforce the N400 results; both are measures of match/mismatch processing at different time-points. A similar pattern in both responses lends credibility to the findings, reducing the chance the results were random occurrence. At follow-up, the latency difference was still present, but the N400 amplitude had conflicting results; some showing more negative amplitude at baseline and some showing more negative amplitude at follow-up.

If the changes in the brain and neurobehavioral responses on tasks used in our study reflect the same underlying process, than a correlation between our measures would be expected. Supportive evidence was found in the correlations between neurobehavioral data and both the Sound Contrast and Picture-Word task ERP data. Improvements in PMAL scores and QUEST scores were correlated with increased amplitude differences of both sound contrasts after treatment. Greater awareness of the affected limb in participants co-occurred with the participant’s greater sensory processing of stimuli, including speech. This result is seen by the sound contrast’s correlations with grip strength and spontaneous use; two basic sensory-perceptual measures. At follow-up, the GS correlation was not significant, as GS values returned to baseline levels. The other correlations remained present and in the same direction.

The Picture-Word correlations with behavioral measures demonstrated a positive relationship between the N400 amplitude to matching stimuli and QUEST scores after treatment. Consistent with expectations, improvements in QUEST scores were associated with reduction of N400 amplitude to matching stimuli, but no conclusive relationships were seen with TPD. Lack of correlations with TPD scores is not surprising because our behavioral data did not show any change from pre- to post-treatment in TPD. At follow-up there were an even greater number of correlations between the N400 amplitude and latency and QUEST scores in the same direction as the baseline to posttest correlations.

Even though the nature of the brain and behavioral measures are different – one set focused on speech perception and word comprehension and the other on sensory-motor function – it is not surprising to see the number of correlations between the results. Language and motor systems share overlapping neuronal representations (Boulenger et al., 2006). This overlap suggests that cortical motor regions are involved in word processing and retrieval. The premotor cortex is known to become active during processing of action-related sounds (Pulvermuller et al., 2005; Boulenger et al., 2006) as well as for words that deal with concrete or manipulable objects or actions (Rueschemeyer et al., 2009; Saccuman et al., 2006), further supporting a link between motor function and language. Boulenger et al. (2006) found that motor and premotor cortexes are involved in early word processing/retrieval – first 200ms. Furthermore, word labels of objects that can be manipulated in different ways show different activation patterns of the sensory-motor areas. This implies conceptual knowledge of an object (e.g., functional information) affects the neural representation of the word. Our stimuli included a number of pictures/words depicting objects that could be manipulated by the participant (e.g., pencil, spoon, etc.), thus, making it plausible that better motor function resulted in better/faster identification of these words. Similarly, because speech sound processing, especially at early ages, relies on activity in a diffuse network of cortical area (Cunningham, Nicol, Bradlow, McGee & Kraus, 1997), improvement in areas like motor function leading to cortical reorganization of the motor cortex, can improve the processing of acoustic speech sounds. Therefore, improvements affecting motor cortex functioning could lead to faster, more efficient word processing.

While a number of our findings were consistent with the hypotheses, there were some cases where participants showed changes different from the predicted direction. For instance, we did not see a significant change in TPD scores from pre- to posttest or 6 month follow-up. This indicates that participants did not get better at distinguishing small changes in tactile stimulation of the affected limb. It is possible that gains were not seen in this measurement because the camp did not allow for enough time to change the cortical representation of such a large area of the sensory-motor cortex - the hand/finger. Perhaps the activities incorporated in to the camp targeted at tactile stimulation were not effective or the specific measures we used were not sensitive enough to capture any changes. In either case, future studies will determine if greater length of treatment is needed to see improvements in TPD.

We saw more conflicting results in the ERP data. In particular, we saw the amplitude differences between speech sounds were greater at baseline than at either posttest or follow-up in both the 100-300ms and 300-500ms latency. Similarly, at least one post hoc in both the baseline to posttest and baseline to follow-up analysis showed the positive peak latency difference in the 300-500ms latency was greater after treatment, rather than smaller. Latency results were expected to have greater differences at baseline than posttest or follow-up because participants would become more efficient at differentiating between sound contrasts. The cause of these findings might be the limited sample size of our study or they could be spurious results due to too many analyses. Another explanation for the greater latency differences after treatment is that more effort or resources were used to process the information.

Although these ERP data were non-supportive of our hypothesis this does not, necessarily, discredit the effects of CIMT; we might simply need more specific brain measures. It has been suggested that cortical changes may be more sensitive to constraint than clinical measures like QUEST and PMAL (Sutcliffe et al., 2009). Even in participants that only showed weak behavioral improvement this could explain benefits to their speech and language processing.

**Limitations and Suggested Improvements**

The full affects of CIMT on HCP patients is still unknown. This study found supportive evidence of the benefits of CIMT. However, further investigation is needed to fill in the gaps. To begin with, the sample size of participants involved in the experiment needs to be expanded. The combination of our two camps included a relatively small number of participants and a greater number would increase the power of our analysis. Furthermore, analyses looking at different variables such as hemisphere differences or left verse right lesions would provide a more thorough picture of the effects the CIMT therapy may have on cognitive and behavioral functioning. Future research is needed to investigate what factors may contribute to greater treatment success such as initial severity of limb impairment, age at onset of therapy, and the relationship between developmental disregard of the affected side and potential for cortical change (Sutcliffe et al, 2009). Improvement in our measurement tools could also be addressed in the future. We saw no significant change in TPD scores, for instance, and a great addition to this research would be a wider array of paradigms that test other functions, such as tactile or visual processing. These could better provide evidence for other areas of cortical reorganization.

One of the greatest gaps in our knowledge about CIMT is the required threshold for intensity and duration of the therapy to have a significant and lasting effect on behavioral and cognitive functioning. Participants in our camps saw significant improvements in behavioral and brain measures after only 5 days of treatment and 20 hours of therapy. Sterr et al. (2002) found that participants in a 6-hour per day treatment benefited significantly more in motor function improvement than their counterparts in a 3-hour per day treatment. Determining the optimal duration of daily treatments and the overall length and intensity of treatment could improve the quality of care provided for future participants.

Another direction to take CIMT-related research is to determine if there are any ill effects of the treatment (Tarkka & Kononen, 2009). Although Smania et al. (2009) found that unaffected limb use was not affected by treatment of six hours per day for two weeks, if constraint therapy were to increase in duration and longevity then the quality of the unaffected limb could come in to question, especially in younger participants. Muscle atrophy could become a concern with longer constraint and sensory input for the pathways of those limbs could also be afflicted from developmental disregard.

**Conclusion**

This study demonstrated that CIMT in children with HCP results in improved sensorimotor functioning of the affected limb as measured by PMAL, QUEST, and GS scores and also leads to changes in brain processes, evidenced by the faster processing and improved discrimination of the sound contrasts and the improved language comprehension, and many of these improvements remain present months after the treatment period. Therefore, CIMT may be a promising approach for treatment and rehabilitation of neurologic damage like that found in hemiplegia and other childhood disabilities.

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Table 1

*Study Population Characteristics*

|  |  |
| --- | --- |
| Participant Info | 20 Children |
| Gender | 15 M, 5 F |
| Age | 6.8 (2.0) |
| Affected Side L, R | 11, 9 |

Table 2

*Behavioral Data*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Behavioral assessment | | Baseline | Posttest | 6 month |
| PMAL | Total | 4.7 (1.4) | 7.5 (1.5) \*\* | 6.6 (1.5) \*\* |
|  | How Often | 2.2 (0.6) | 4.0 (0.8) \*\* | 3.2 (0.7) \*\* |
|  | How Well | 2.5 (0.8) | 3.5 (0.7) \*\* | 3.4 (0.8) \*\* |
|  | Spontaneous Use | 1.7 (0.6) | 2.4 (0.5) \*\* | 2.2 (0.5) \* |
| QUEST | Total | 71.4 (13.4) | 80.8 (11.8) \*\* | 85.5 (7.4) \* |
|  | Dissociated Movement | 59.8 (24.7) | 78.8 (13.3) \*\* | 79.8 (13.9) \*\* |
|  | Grasp | 67.7 (22.2) | 70.6 (21.7) | 77.3 (20.1) |
|  | Weight Bearing | 87.2 (16.4) | 91.1 (9.1) | 89.8(11.9) |
|  | Protective Extension | 70.9 (21.1) | 82.7 (12.4) \* | 75.2(15.0) |
| Two Point Discrimination | | 4.6 (1.7) | 4.1 (1.9) | 4.4(1.62) ± |
| Relative Grip Strength | | 0.4 (0.3) | 0.6 (0.3) \*\* | 0.4 (0.2) |

Note: Measurement of effect, using behavioral assessments; Means (SD).

± Camp-2 data only. \* significant at p = 0.05. \*\* significant at p = 0.01.

PMAL HO scale and HW scale 0-5, SU 0-3.

QUEST scale 0-100, with 100 representing normal task execution/function..

TPD in mm on affected hand.

Table 3

*Correlations: Sound Contrast*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ERP component | Pre to Post | | | Pre to Follow Up | | |
| 100-300ms | PMAL | Relative Grip | Spontaneous Use | QUEST | Relative Grip | Spontaneous Use |
|
| BG Mean Amplitude | 0.47 \* LT | 0.48 \* RF | -0.54 \* Cz | - | -0.53 \* LF | - |
| 0.49 \* RPT | 0.69 \*\* RPT |
| BP Mean Amplitude | - | - | 0.55 \* RPT | - | -0.53\*\* Cz | -0.54 \* Cz |
| BG Latency | - | -0.59 \* LT | - | -0.56 \* RPT | -0.52 \* LF | 0.61 \* Cz |
| BP Latency | - | 0.47 \* Cz | - | -0.52 \* LPT | -0.72 \*\* LF | - |
| -0.65 \*\* RF |
|  | | | | | | |
| 300-500ms | PMAL | Relative Grip | Spontaneous Use | QUEST | Relative Grip | Spontaneous use |
|
| BG Mean Amplitude | 0.47 \* Cz | 0.51 \* LPT | - | - | - | - |
| BP Mean Amplitude | - | - | - | 0.57 \* LT | - | 0.56 \* LT |
| -0.56 \* RPT |
| BG Latency | -0.49 \* LF | - | -0.64 \* LF | - | - | - |
| -0.51 \* LT | -0.72 \*\* LPT |
| -0.59 \* LPT |  |
| BP Latency | -0.51 \* RT | - | -0.59 \* RT | - | - | - |
| -0.60 \* LPT |

Behavioral assessments and ERP measures quantify sensory and functional improvements in CIMT

Note: R, scalp location. \* p < 0.05 \*\* p< 0.01.

Table 4

*Correlations: Picture-Word*

|  |  |  |
| --- | --- | --- |
| ERP component | Pre to Post | Pre to 6 months |
| Match Condition | QUEST | QUEST |
| N400 Mean Amplitude |  | 0.69 \*\* LP |
| - | 0.68 \*\* RP |
| N400 Latency | 0.60 \* Fz | -0.61 \*\* Fz |
| 0.63 \*\* LF | -0.59 \* Pz |
| 0.49 \* RF | -0.72 \*\* LF |
|  | -0.66 \*\* LP |
|  | -0.72 \*\* RP |
|  | -0.52 \* LT |
|  | -0.57 \* RT |
|  | | |
| Mismatch Condition | QUEST | QUEST |
| N400 Mean Amplitude | 0.50 \* Cz | - |
| 0.50 \* Fz |
| 0.48 \* LF |
| 0.56 \* LT |
| N400 Latency | - | -0.60 \* Cz |
| -0.64 \* Fz |
| -0.59 \* Pz |
| -0.63 \* LF |
| -0.64 \* RF |
| -0.76 \*\* LP |
| -0.73 \*\* RP |
| -0.58 \* LT |
| -0.67 \*\* RT |
|  |  |  |

Behavioral assessments and ERP measures quantify motor and functional improvements after CIMT

Note: R, scalp location. \* p < 0.05 \*\* p< 0.01.

Figure 1. Example of waveform pattern change from baseline, posttest, and 6 months of Sound Contrasts at Left Temporal electrode.

Figure 2. Example of waveform pattern change from baseline, posttest, and 6 months of Picture-Word at Parietal Central electrode.