Published in final edited form as:

Conf Proc IEEE Eng Med Biol Soc. 2019 July ; 2019: 5156–5159. doi:10.1109/EMBC.2019.8857945.

EEG Based Analysis of Cortical Activity during Mirror Visual Feedback Target - Directed Movement

Maryam Rohafza,

Dept. of Biomedical Engineering, NJIT, 323 Dr. Martin Luther King Jr. Boulevard, Newark, NJ 07101, and Rutgers New Jersey Medical School, Newark, NJ, USA;.

Soha Saleh,

Center of Mobility and Rehabilitation Engineering Research, Kessler Foundation, 1199 Pleasant Valley Way, West Orange, NJ, 07047, and Rutgers New Jersey Medical School, Newark, NJ, USA.

Sergei Adamovich [Member, EMBS]

Dept. of Biomedical Engineering, NJIT, 323 Dr. Martin Luther King Jr. Boulevard, Newark, NJ 07101, and Dept. of Rehabilitation and Movement Science, Rutgers Univ., Newark, NJ, USA.

Abstract

In mirror visual feedback (MVF) based rehabilitation, the illusion of mirror reflection of volitional movement of non-paretic limb tends to have a modulatory effect on visuomotor and sensorimotor brain activations. This paper presents EEG based analysis of hemispheric activation asymmetry within the beta band (15–28 Hz) when MVF is combined with a target-directed hand motor task in a block design versus a similar task without any target requirements. MVF coupled with target-directed movement was associated with a decrease in hemispheric asymmetry in both preparation and execution phases of movement. These results emphasize the potential importance of incorporating visuomotor goals into the task to maximize the rehabilitation outcomes of MVF-based training activities.

I. INTRODUCTION

Mirror visual feedback (MVF) provides the observation of mirror reflection during volitional movement of one limb to induce a visual illusion of the opposite limb movement. This illusion effect has been used in MVF-based rehabilitation where a person with hemiplegia due to stroke exercises the less affected limb while observing its reflection in a sagittally-oriented mirror, perceived as the motion of their hemiplegic limb [1]. However, the rehabilitation outcomes of these studies vary greatly, with one potential source of variability being the type of the sensorimotor task [2].

Numerous neuroimaging techniques, such as TMS, fMRI, MEG, in healthy and stroke population, have shown a modulatory effect of MVF, like increasing activation of the ipsilateral hemisphere or rebalancing abnormal interhemispheric dominance [3–5]. TMS

studies investigating the effect of MVF on ipsilateral motor cortex excitability revealed cortical disinhibition of the ipsilateral hemisphere [6]. Our group has shown that MVF can activate and strengthen effective connectivity within sensorimotor areas of the lesioned hemisphere in stroke survivors [3, 7]. Several studies have reported a decrease in lateralization of brain activity during movements coupled with MVF, estimated by measuring the Lateralized Readiness Potential [4, 5, 8], or the Event Related Desynchronization (ERD) of contralateral and ipsilateral motor cortices [9].

Surprisingly, the task used in the majority of MVF investigations (i.e. finger tapping, oscillatory movement) did not necessarily require vision to complete the task [4, 5, 9–11]. Very few studies have used target-directed movements that do require vision [4, 12–15]. To date, our group was the first group that specifically investigated the neurophysiological effects of sensorimotor task selection for MVF [12, 15]. In a study by Yarossi et al., [12] TMS was used to probe cortical spinal excitability following MVF conducted with and without movement targets, and the authors reported a decrease in cerebrospinal excitability (CSE) ipsilateral to the trained hand in non-target conditions and a significant increase only when MVF was combined with a visual target during training. These results are novel but not surprising, knowing the robust modulatory effect visual targets have on sensorimotor networks [16, 17]. In this study, authors are more interested in the temporal-spatial processing of MVF that may have led to increased CSE when MVF was provided during a target-directed movement. Hence, the investigators studied the interaction between movement goal (target, no target) and visual feedback (veridical, MVF) in a 2×2 factorial design. Investigators used EEG technology to record whole brain activation and to study the temporal processing of MVF in different beta EEG waveforms, which may correspond to unique sensorimotor processes in correlation with MVF and visuomotor goals.

II. METHODS

A. Participants

Seventeen healthy right-handed individuals with normal or corrected-to-normal vision (17 males, mean age = 22 ± 3 years) participated in the study and provided an informed consent approved by New Jersey Institute of Technology Human Research Institutional Review Board.

B. Task and procedure

Data collection was conducted in a quiet room, where participants were seated in a comfortable chair with the elbow and forearm resting on the armrest. Both hands were hidden from view under an LCD screen. Subjects were asked to perform right index finger movements with visual feedback presented as VR-rendered hand models actuated by real-time kinematic data at a 60 Hz rate streaming from 18-sensor gloves (CyberGlove) worn on each hand. A visual “move” cue was used to instruct participants to flex the right index finger and hold their position until they see a visual “return” cue to go back to the starting position. Subjects had 1 second to make the flexion movement and 3 seconds to return to the starting position and wait for the next trial. In each session, participants completed four 2-min blocks of 30 trials, separated by one-minute rest.

All subjects completed four feedback conditions in 4 separate sessions: Veridical No-target (M-T-): subjects flexed the right index finger as fast as possible to the perceived mid-range of motion (no target presented) while observing the same hand on the screen. Veridical Target (M-T+): subjects flexed right index finger as fast and accurate as possible to specific targets (pseudorandomly assigned to 20, 40, 60 degrees) while observing the same hand. Mirror No-target (M+T-): subjects flexed right index finger as fast as possible to perceived mid-range of motion (no target presented) while observing opposite hand. Mirror Target (M+T+): subjects flexed right index finger as fast and accurate as possible to specific targets (pseudorandomly assigned to 20, 40, 60 degrees) while observing opposite hand.

C. Data acquisition

Continuous EEG data were recorded using a 64-channel WaveGuard™ EEG cap and ASALAB 4.7.3 software (Advanced Neurotechnology, ANT™, WaveGuard™ Active Shield). The cap was positioned using the 10–20 system, ensuring Cz is on the top center of the head, and C3 and C4 electrodes cover the cortical areas representing the movement of the active (contralateral) and mirrored (ipsilateral) hands. Impedances were kept below 10 K Ω . Data were sampled at 2048 Hz.

EMG data were recorded with a surface electrode (Delsys Inc., Natick, MA) placed on the first dorsal interosseous (FDI) muscle of the active hand and was used to determine the onset of movement in each trial. Kinematics recorded from the data gloves were used for realtime actuation of virtual hand, and for offline analysis where trials with incorrect or absence of movement response were eliminated from the EEG/EMG analysis.

D. Data analysis

Kinematics data were used to identify trials that should be removed from analysis due to a missed cue resulting in no movement. EMG data were band-pass filtered (2nd order, 10 – 300 Hz), band-stop filtered (2nd order, 55 – 65 Hz) and rectified after baseline removal. Envelope generated by RMS filter (time window of 20 ms) was used to identify the onset of finger movement. EMG onset was defined as the first time point exceeding the threshold (threshold is defined as the mean $\pm$ 3*standard deviation of the envelope during the phase of inactivity prior to movement cue). EEG data were analyzed offline using EEGLAB toolbox version 13.2.2b (www.sccn.ucsd.edu/eeglab/) and custom-written Matlab scripts. Raw EEG data were referenced to average, then band-pass filtered (2nd order, 1–70 Hz), and band-stop filtered (4th order, 55–65 Hz), to remove 60 Hz line noise. Data from the mastoid electrodes and EOG electrodes were rejected. To study the event-related EEG dynamics, EEG epochs of –2 to 2 s were extracted, 0 being movement onset, acquired from the EMG data analysis. Mean baseline value from each trial was removed because of the inter-trial baseline differences. EEG epochs were then visually inspected and erroneous trials were removed. Independent Component Analysis (ICA) was used to remove artifacts caused by eye blinks, saccades, muscle contractions, and ECG. To reduce inter-subject and inter-trial variability in the duration of preparation and execution epochs, the data during preparation and execution were time-normalized.

Event-Related Desynchronization / Synchronization (ERD/ERS) within the beta band (15–28Hz), which is the relative power change compared to baseline (1500 – 1000ms before EMG onset), was calculated based on a method implemented by Pfurtscheller [18]. Negative values show more event-related desynchronization and positive values show more event-related synchronization.

A previous fMRI study has shown a significant effect of MVF on primary motor cortices [3]. Hence, ERD/ERS time locked to movement onset was calculated at C3 and C4 electrodes that largely reflect activity from contralateral and ipsilateral primary motor cortex areas [19]. The difference (sum squared error, SSE) in ERD within the beta band (15–28 Hz) between ipsilateral and contralateral sites, was quantified during planning (between cue presentation and movement onset), and at movement execution.

Statistical analysis: A $2 \times 2 \times 4$ repeated measure ANOVA with factors Feedback (Mirror, Veridical), Target (Target, No Target), and Block (1–4), was performed on reaction time, movement duration and amplitude. In addition, A 2×2 rmANOVA on Asymmetry index with factors Feedback (Mirror, Veridical) and Target (Target, No Target) was used to evaluate the effect of visual feedback on cortical activation asymmetry.

III. RESULTS

A. Finger kinematics

Kinematics data were analyzed to identify any training-related changes in movement execution across conditions. Repeated measure ANOVA showed no significant effect of feedback or condition on reaction time, movement duration peak velocities, and amplitude, indicating that the results in ERD are not confounded by variations in finger movement velocity.

B. EEG data

ERD and hemispheric asymmetry, the difference (sum squared error, SSE) in event-related desynchronization (ERD) in the beta band (15–28Hz) between motor cortices (electrodes C3, C4), was quantified over epochs during planning (between cue presentation and movement onset), and movement execution. The main effect of visual feedback and the target x visual feedback interaction on asymmetry index was significant during both preparation ($F(3,48) = 9.80, p = 0.003$) and execution ($F(3,48) = 13.25, p = 0.001$). Although there was no significant main effect of Target during planning or execution, the presence of a target in the veridical condition was associated with increased lateralization of activity during planning.

The top row in Figure 1 shows the grand average event-related spectral perturbation, within the beta band. A significant decrease in ERD is observed (more pronounced in M+T+) during mirror conditions in C3 only. While ERD at C4 is relatively similar across conditions, the desynchronization is slightly greater in M+T+ during preparation.

M-T+ shows the highest asymmetry index value and M+T+ shows the lowest. Two by two repeated measure ANOVA at C3/C4 electrodes revealed a significant main effect of visual

feedback on asymmetry index during both preparation ($F(3, 48) = 9.80, p = 0.003$) and execution ($F(3, 48) = 13.25, p = 0.001$). There was also a significant target x visual feedback interaction effect during planning ($F(3, 48) = 4.47, p = 0.039$) and execution ($F(3, 48) = 7.13, p = 0.01$). The highest symmetry was observed when MVF was combined with target directed movement. There was no significant main effect of Target during planning or execution, however, the presence of a target in the no-mirror condition was associated with increased lateralization of activity during planning.

IV. DISCUSSION

The aim of the current study was to understand the neurophysiology behind MVF related brain modulations and the temporal processing of MVF in beta waveforms. These understandings may help in explaining task phase dependent differences in sensorimotor processing, and in examining the effect of incorporating visuomotor goals with the MVF task. For that purpose, we examined the difference in hemispheric activation symmetry in a group of healthy individuals while different visual feedbacks were presented with the presence or absence of targets. Overall results showed no significant difference in movement kinematics across conditions. MVF coupled with the target-directed movement was associated with higher beta desynchronization and a decrease in hemispheric asymmetry in both preparation and execution phases of the task.

In line with previous studies, our data show a significant effect of feedback (mirror vs. no mirror) on hemispheric asymmetry in the sensorimotor cortex [4, 9]. The main effect of visual feedback on hemispheric asymmetry was significant for C3/C4 electrodes, during both preparation and execution. As shown in Figure 1, MVF caused a decrease in hemispheric asymmetry during the movement execution phase. More importantly, the decrease in asymmetry caused by mirror feedback was significantly higher in the preparation phase during target directed sessions. In the absence of a visual target, a slight decrease in the hemispheric activation asymmetry was observed in the MVF condition only during the execution phase. However, in the presence of a target, a significant decrease in hemispheric asymmetry was observed during both preparation and execution phases of the MVF-guided movement. This decrease in hemispheric asymmetry may be due to stronger activation in ipsilateral hemisphere and more inhibition on contralateral hemisphere elicited by observation of reflected hand on the screen.

The results emphasize the importance of combining MVF with target-directed movement on modulating brain activation and lateralization in an MVF-based intervention as it was confirmed by the two previous studies conducted by our group [12, 15]. In this study, we benefit from the high temporal resolution of EEG to understand the effect of incorporating target directed movements into MVF tasks, in the preparation and execution phases of the movement (). In the future, investigation of task-based functional connectivity, and ERD at each electrode can clarify the possible sources of the decreased asymmetry in hemispheric activation.

V. CONCLUSION

The results from this pilot study can guide clinicians and researchers in this field to improve the neuromodulatory and therapeutic effects of MVF by incorporating goal-based tasks in the intervention. This information will also guide future rehabilitation studies of training in VR environment conducted by our group.

ACKNOWLEDGMENT

This work was supported in part by the NIH/NICHD grant # R01HD58301 (SA), and by the NIDILRR funded Rehabilitation Engineering Research Center, grant # 90RE5021 (SA).

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Figure 1.

Top: Grand average Event Related Spectral Perturbation in the beta frequency band is shown across different sessions. Bottom: Hemispheric asymmetry is shown as the grand average differences (sum squared error) in the event-related desynchronization (ERD) between C3 and C4 calculated in the beta band during the Preparation and Execution phases of the finger movement. Error bars show standard errors.

Table 1.

Four experimental conditions

Session	Feedback	Target	VR hand (Presented on screen)	Moving hand (hidden from view)
M-T-	No Mirror (Veridical)	No target

Session	Feedback	Target	VR hand (Presented on screen)	Moving hand (hidden from view)
M+T-	Mirror	No target

Session	Feedback	Target	VR hand (Presented on screen)	Moving hand (hidden from view)
M-T+	No mirror	Target

Session	Feedback	Target	VR hand (Presented on screen)	Moving hand (hidden from view)
M+T+	Mirror	Target