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Post-Movement Beta Rebound Is Related to Movement Connection

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Abstract

After 300 - 500 ms of various movements, a significant rebound in beta rhythm power is observed. This phenomenon is called Post-Movement Beta Rebound (PMBR). Previous studies have been carried out in a single movement context in the exploration of its functional significance, and few studies have been conducted in connected movements. Therefore, this study used the cue-induced delayed task paradigm to examine the PMBR change in the motor cortex of the 20 adults when they were moving under the single or connected movements condition. It was found on right-hand movements that the PMBR of the first movement in a connected condition was stronger than that of a single movement, and it was also observed on both left- and right-hand movements that the PMBR of the first movement was stronger than that of the last movement in a connected condition. The results show that the PMBR after the connected movement was stronger than the no movement connection, reflecting that PMBR plays an important role in the preparation of subsequent movements.

Keywords

Motor Preparing, Post-Movement Beta Rebound, EEG Recording, Movement Connection

1. Introduction

Brain function can be regulated by the rhythmic activity formed by the firing of different neurons. After movement, a significant increase in 17 - 24 Hz beta rhythm activity is recorded in the sensorimotor cortex, a phenomenon known as Post-Movement Beta Rebound (PMBR), which is stably observed in various types of movements such as voluntary, passive, and imaginative [1] [2] [3] [4] [5]. However, the functional significance of the PMBR is ambiguous.

Some researchers have suggested that PMBR is associated with bottom-up sensory input processing of movement [6] [7]. Cassim, Monaca [8] observed the PMBR phenomenon after passive exercise, and Fry, Mullinger [2] also found that the power of PMBR was modulated by the strength and speed of contractile exercise. Another view is that PMBR seems to be associated with process of top-down inhibition, which can be demonstrated by the evidence that in Go/NoGo tasks, PMBR is stranger after NoGo signal requiring active inhibition than after Go signal [5]. Consistent with this, the dynamic activity of the PMBR is consistent with decreased excitability of motor cortical neurons [9], suggesting that PMBR activity is closely associated with motor control.

Given the inseparability of sensory and motor control, some research have suggested that the function of the PMBR may not be limited to sensory input and motor inhibition, but may combine both functions and play an important role in the integration and updating of motor information [10] [11] [12]. Gaetz and Cheyne [13] observed a PMBR phenomenon in the corresponding sensorimotor area of the hand following tactile stimulation of the lips or toes, suggesting that PMBR may reflect the preparation process for subsequent hand movements. Also, Tan *et al.* (2016) found that the power of PMBR was modulated by confidence in a behavior-based internal feedforward model, increasing with certainty about the subsequent movement.

Taken together, PMBR may be used by the sensorimotor cortex to recalibrate or reset the motor system to new conditions in order to prepare for subsequent movements [11] [14] [15]. Therefore, PMBR is not only related to this current movement, but also to the preparation for the next movement. Moreover, people's movements in real life are coordinated and connected by multiple movements rather than a single movement. Therefore, the present study used a cue-induced delayed task to directly compare PMBR after a single movement with that after a connected movement to investigate the role of PMBR in movement connectivity.

2. Materials and Methods

2.1. Participants

Twenty-three college students (mean age was 19.65 years, SD = 0.57, 10 males) participated in the experiment. All participants were right-handed, had normal or corrected vision, and none reported a history of neurological disorders, alcohol or drug abuse, and no symptoms such as cold and cough during the experiment. Each participant was paid about 55 RMB at the end of the experiment.

2.2. Stimuli and Task

A variation of the Cue-Induced Delay Tasks was used in this study [16] (see **Figure 1**). In one trial, after the 500 ms fixation point disappears, the directional cue indicated by arrow/arrows appears in the center of the screen. And the delay period is set to a random time of 200 ms to 700 ms before the target appears

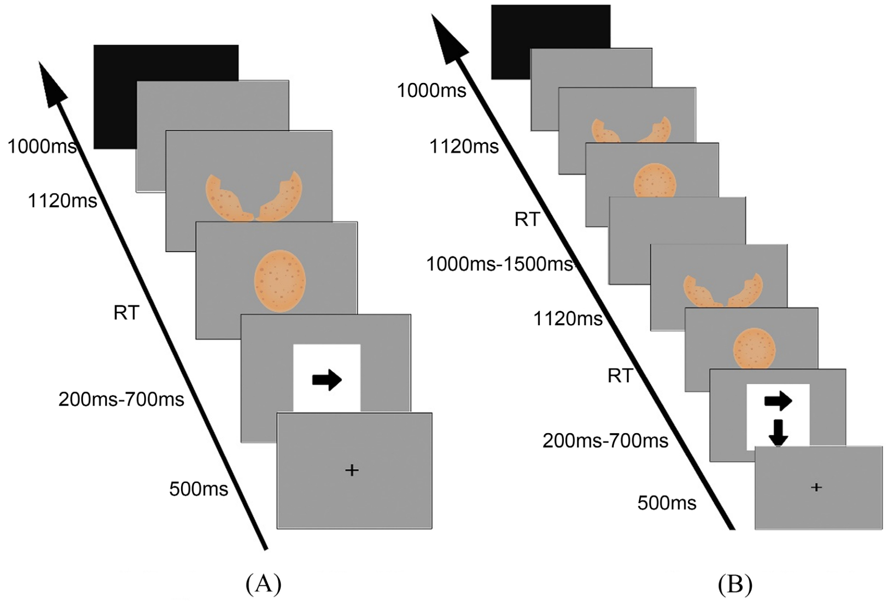

Figure 1. Experimental procedure. Each trial of the single movement condition and the connected movements condition started with a fixation cross followed by a directional cue consisting of a single arrow (A) or two arrows (B). A random delay was followed by one/two occurrences of the target stimulus represented by the yellow egg. The egg cracked after the participant responded. (A) Single movement condition; (B) Connected condition.

represented by a yellow egg, in order to control for participants' anticipation of the GO signal. Participants are asked to press the corresponding key as soon as they see the target. After the subject presses the corresponding key, with that the egg would crack open, accompanied by a cracking sound. And the duration from cracking to disappearance is 1120 ms. This is followed by a random blank screen time of 1000 to 1500 ms. A final fixed black screen of 1000 ms allowed the subject sufficient resting time for the collection phase of the baseline.

The directional cues included three types of arrows, rightward, downward and leftward. The rightward arrow meant that the subject had to press the rightward directional button with the right hand, the leftward arrow meant that the subject needed to press the leftward directional button with the left hand and the downward arrow meant that the subject needed to press the pedal with the left foot.

There are two conditions for the presentation of directional cues: the single movement condition and the connected movement condition. In the single movement condition, the directional cue consisted of only a one-way arrow, including "→", "↓" and "←", and the trial ended with one correct keystroke response by the participant to the target. In the connected movement case, the directional cue contained two directional arrows presented in an up-and-down structure, including "→←", "→↓", "↓→", "↓←", "↓←", "←↓" and "←→" in six cases. In this condition, the first egg will appear after a random delay time, and the participant was asked to press the key indicated by the upper arrow in the cue, and press the key indicated by the arrow at the bottom of the cue after the second egg. Finally, the participants' response time was limited to 600 ms. When the participant's reaction time exceeded 600 ms, the trial would be restarted. The participant's reaction time for each trial is also visualized as a rectangle presented at the top of the screen, which turns red when the participant's reaction time exceeds the limit.

2.3. Procedure

The experiment consisted of seven blocks, each containing three cases of single action and six cases of connected action, with 16 trials for each case of the single movement condition and 8 trials for each case of the connected movement condition, for a total of 96 trials. The total number of trials for the whole experiment was 672.

The different conditions throughout the experiment consisted of three *movement types* ("→" - "right hand"; " ↓ " - "left foot"; and "←" - "left hand") occurring singly and in combinations of two, and for both the single movement and connected movement conditions involving movements, we divide them into three *movement conditions*: a single movement, the first movement of the connected condition (Connected-1st), and the second movement of the connected condition (Connected-2nd). Therefore, the current study was 3 (movement types: right hand, left foot, left hand) × 3 (movement conditions: Single movement, Connected-1st, Connected-2nd) within-subjects design.

After signing an informed consent form, the participants were comfortably seated in a soundproofed room, viewing a computer-controlled display (1920 x 1080 resolution) at a distance of 60 cm, and were asked to keep their eyes on a central fixation point position throughout the experiment. During the experiment, participants were required to use a gamepad and a foot pedal to complete their motor responses.

2.4. EEG and Behavioral Data Recording

The Stimulation and Neuroscience Application Platform (SCCN, Christian A. Kothe), based on Python was used to programing and present the experimental procedures. The EEG signals were recorded at a sampling rate of 5000 Hz from 64 Ag-AgCI (silver-silver chloride) electrodes mounted in ActiCap electrode cap (Brain Product, Germany). The electrode impedance was kept below 10 kΩ. The experiment was performed using Lab Stream Layer (LSL, SCCN, Christian A. Kothe) to record behavioural responses and EEG data simultaneously.

The reaction time of a subject's action was defined as the time interval between the moment when the GO signal (in this experiment, the egg) appeared and the moment when the key was pressed or the pedal was depressed. The correct response of the subject was defined as the corresponding action performed within the specified time (600 ms). After excluding timeouts and incorrect movements, the percentage of correct key presses was calculated for the different conditions.

2.5. EEG Data Analyses

The MATLAB-based EEGLAB toolbox was used to analyse the offline EEG data. The sampling rate of the EEG data was reduced from 5000 Hz to 500 Hz, after which the data was then high-pass filtered at 3 Hz and low-pass filtered at 35 Hz. The leads with a signal different from the normal EEG signal pattern due to excessive impedance or other reasons were removed as bad leads, and 4 electrooculograms were removed. High-frequency EMG activity and other artefacts in the EEG data after removal of the re-reference were identified by visual observation. The de-artifacted data is used in Adaptive Mixture Independent Component Analysis (AMICA). AMICA separates the beta components of the motor cortex located in the left and right hemispheres by maximising the separation of the independent components of the EEG signal. All trials time locked at response, intercepting −4 s - 4 s as the time window. Trials with timeouts and wrong response were removed from the data. After epoch, the data were automatically rejected in EEGLAB to remove trials that exceeded 800 μV. The average number of trials remaining after rejection was 106 for each condition (SD = 5). For the single movement condition and the Connected-1st condition, time window from −2550 ms to 2050 ms was used to baseline correction; and for the Connected-2nd condition, time window from 2620 ms to 3120 ms was used to baseline correction.

During the data analysis phase it was found that one subject was found to blink during each movement during manual deactivation, so this subject's data was excluded. The data from the other two subjects did not find a component with a high signal-to-noise ratio at the Cz position after independent component analysis. We therefore excluded the data from these three subjects (females).

We extracted the data from the C3 channel corresponding to the right hand, the C4 channel corresponding to the left hand, and the Cz point corresponding to the left foot for time-frequency analysis. Using the short-time Fourier calculation ERSP, according to the frequency distribution obtained from the time-frequency analysis, we extract 17 - 24 Hz as the beta rhythm frequency band. The PMBR phase was taken to be 250 ms before and after the peak moment of the PMBR.

We used SPSS version 20.0 for 3 (movement type: right hand, left foot, left hand) × 3 (movement condition: Single movement, Connected-1st, Connected-2nd) two-way repeated measures ANOVA to test the significance of the main effects of movement type and movement condition, and the interaction between the two. Significance level was 0.05, with partial eta^2 (η_p^2) as a measure of effect size.

3. Results

3.1. Behavioral Results

Subjects' correctness was greater than 90% (92.01% to 95.32%) in all conditions.

To analyse subjects' behavioural performance, a repeated measures ANOVA was conducted with reaction time as the dependent variable, which showed a significant main effect of action type; $F(2, 18) = 29.744$, $p < 0.001$, $\eta_p^2 = 0.768$. A significant main effect of action condition, $F(2, 18) = 15.968$, $p < 0.001$, $\eta_p^2 = 0.640$. The interaction between action type and action condition was significant; $F(4, 16) = 13.437$, $p < 0.001$, $\eta_p^2 = 0.771$.

Simple effects analysis showed that, In the right hand movement, reaction time for Single movement was significantly faster than for Connected-1st ($RT_{single\text{-}Connected1st} = -12.84$, $p = 0.004$) and for connected-2nd actions ($RT_{single\text{-}Connected2nd} = -29.494$, $p = 0.001$), and Connected-1st movement was faster than Connected-2nd movement ($RT_{Connected1st\text{-}Connected2nd} = -16.647$, $p = 0.025$). In the left hand movement, the reaction time of Single movement was significantly faster than that of the Connected-1st ($RT_{single\text{-}Connected1st} = -36.003$, $p = 0.002$) and Connected-2nd movement ($RT_{single\text{-}Connected2nd} = -20.509$, $p < 0.001$), but the reaction time of the Connected-1st movement was not significantly different from that of the Connected-2nd movement ($RT_{Connected1st\text{-}Connected2nd} = -14.506$, $p = 0.126$). In the left foot movement, reaction time of Single movement was not significantly different from that for the Connected-1st movement ($RT_{single\text{-}Connected1st} = 14.885$, $p = 0.254$), but was significantly faster than that for the Connected-2nd movement ($RT_{single\text{-}Connected2nd} = -28.122$, $p = 0.001$); and reaction time for the Connected-1st movement was significantly faster than that for the Connected-2nd movement ($RT_{Connected1st\text{-}Connected2nd} = -43.007$, $p = 0.025$) (see **Figure 2**).

3.2. ERP Results

As shown in **Figure 3**, we found that the beta rhythm was clearly modulated by the movement process throughout the movement. We can clearly observe a decrease in beta power before the onset of movement and an enhanced return of beta rhythm energy after movement at C3, Cz, and C4. The data from the time window of 250 ms before and after the peak of each conditional beta rhythm were taken and averaged to calculate the average power of the PMBR (see **Figure 3**).

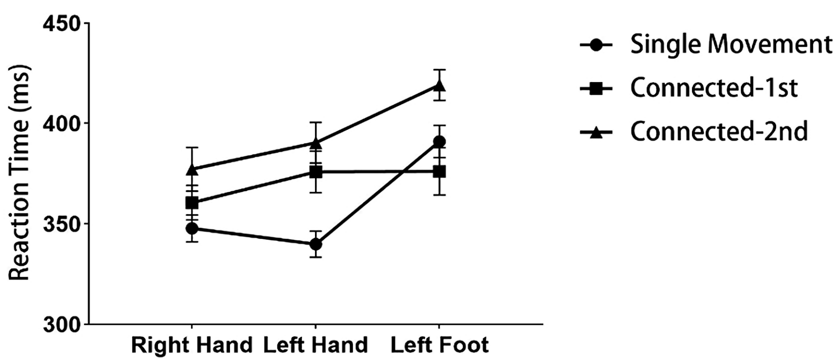

Figure 2. Reaction time results. The average reaction time of participants completing Single movement, connected-1st and connected-2nd movements with their right hand, left hand, and left foot. The error bar represents the standard error of the mean (SE).

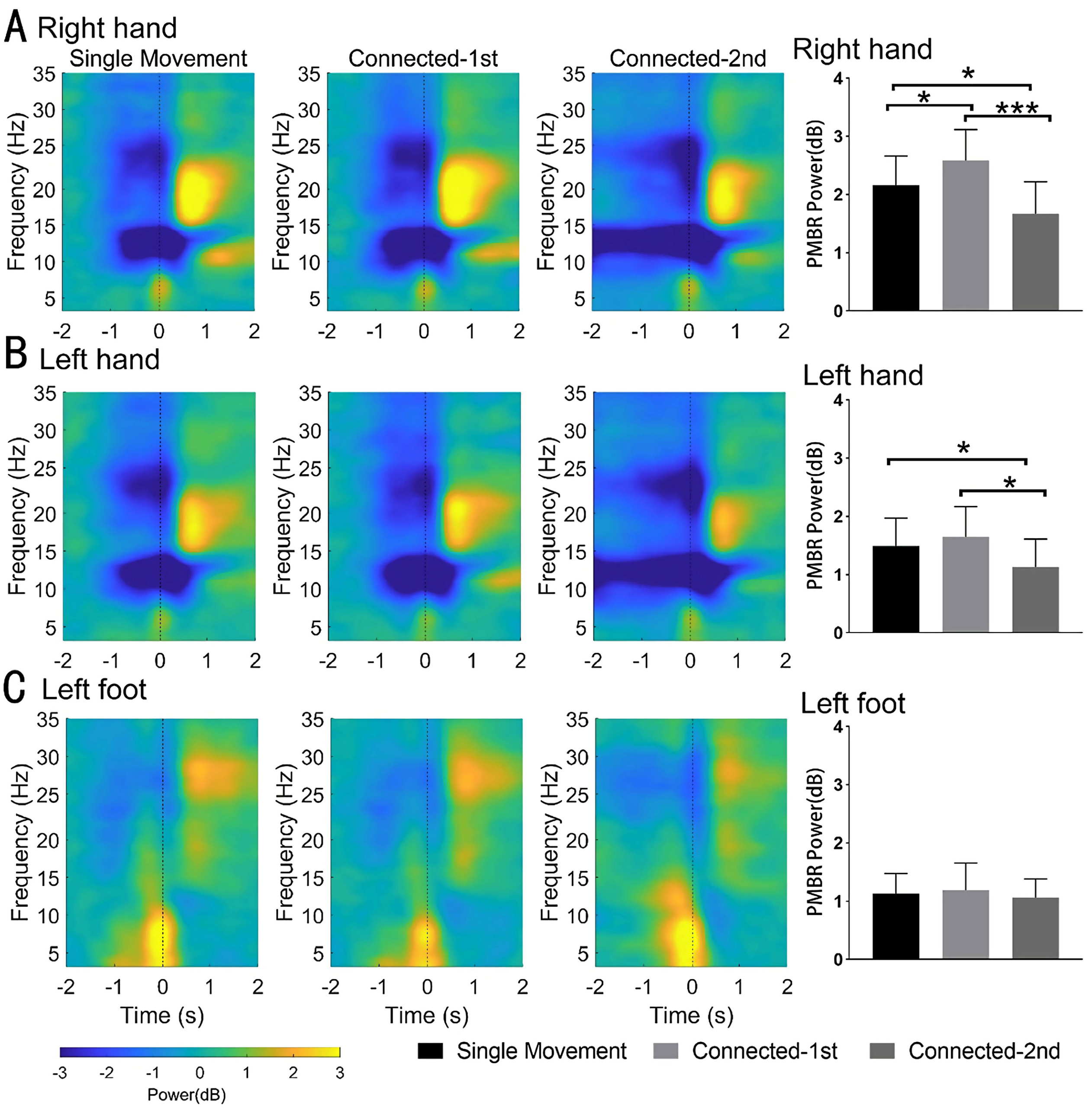

Figure 3. Power changes of the beta rhythm (17 - 24 Hz) after the reaction and mean PMBR power (extracted during the 425 - 925 ms interval following response) in three movement conditions: Single movement, Connected-1st and Connected-2nd movements for the three main movement types separately: right hand (A), left hand (B), and left foot (C).

A repeated measures ANOVA was performed with PMBR power as the dependent variable, and the results showed a significant main effect of action type, $F(2, 18) = 3.854$, $p = 0.040$, η_p^2 $p = 0.300$, significant differences between right hand, left hand, and left foot actions, and post-hoc comparisons showed that PMBR power was significantly greater for left hand movement than for right hand movement ($PMBR_{right\text{-}left} = 0.716$, $p = 0.032$), whereas the differences between PMBR between right hand and left foot, and left hand and left foot movements were all non-significant ($ps > 0.05$). The main effect of action condition was significant, $F(2, 18) = 5.461$, $p = 0.014$, $\eta_p^2 = 0.378$, and post hoc comparisons indicated that PMBR was significantly stronger for the Single movement condition than for the Connected-2nd movement condition ($PMBR_{single\text{-}Connected2nd} = 0.306$, $p = 0.008$) and significantly stronger after the Connected-1st than after the Connected-2nd action ($PMBR_{Connected1st\text{-}Connected2nd} = 0.520$, $p = 0.007$), while the difference in PMBR between Single movement and Connected-1st was not significant ($p < 0.05$). Finally, the interaction of movement type × movement condition was not significant, $F(4, 16) = 2.146$, $p = 0.122$, and $\eta_p^2 = 0.349$).

Although there was no statistically significant interaction between movement type × movement condition, to further explore the effects of the two independent variables on PMBR, we conducted further simple effects analyses. In the right hand movement, it was found that the PMBR for the Single action condition was significantly weaker than the Connected-1st condition ($PMBR_{Single\text{-}Connected1st} = -0.427$, $p = 0.045$) but significantly stronger than the Connected-2nd condition ($PMBR_{Single\text{-}Connected2nd} = 0.492$, $p = 0.014$), and the PMBR for the Connected-1st condition was significantly stronger than the Connected-2nd condition ($PMBR_{Connected1st\text{-}Connected2nd} = 0.920$, $p < 0.001$).

In the left hand movement, PMBR was significantly stronger in the Single movement condition than in the Connected-2nd condition ($PMBR_{Single\text{-}Connected2nd} = 0.360$, $p = 0.045$) and significantly stronger in the Connected-1st condition than in the Connected-2nd condition ($PMBR_{Connected1st\text{-}Connected2nd} = 0.541$, $p = 0.040$), while PMBR was not significantly different in the single movement and Connected-1st conditions ($p < 0.05$). Finally in the left foot movement, no significant differences between movement conditions were shown ($ps > 0.05$).

4. Discussion

The present study recorded changes in the beta rhythm (17 - 24 Hz) of the sensorimotor cortex in healthy adults during single movement and connected movements using the right hand, left hand buttons, and left foot on the pedal, to investigate whether PMBR plays an important role in the connection motor. Our results support the hypothesis that higher PMBR power was observed after Connected-1st movement relative to single movement condition and Connected-2nd movement without subsequent actions, suggesting that PMBR is not only associated with motor endings but also acts on subsequent motor preparation.

In contrast to the finding that PMBR was observed only at the end of the last movement of the sequence in the study by Alegre, Gurtubay [17], we clearly observed PMBR at the end of each movement of the linking exercise. In our study, the time interval between the two movements in the connected condition was specified as 2 s - 3 s, so that the participants had sufficient time to end the previous movement (recover the contracted muscle) before starting the next action. Moreover, Fischer, Tan [18] observed significant PMBR in both movements with finger taps at an interval of 700 ms, suggesting that a complete end of the motor program is not a necessary condition for PMBR. Thus, PMBR should be related to the next movement to be performed in the connected movements in addition to the end of the movement.

Strong evidence comes from the result that PMBR is significantly stronger after Connected-1st movement than after Single movement and Connected-1st movement, and the stronger PMBR activity in these conditions with subsequent actions can be explained by the maintenance and extraction of working memory, which is important for the accuracy of subsequent action execution [19]. In our experiments, before response, the only difference between the connected condition and the single movement condition was the difference in cues. The single movement condition contains information about only one action, and its action representation is relatively simple. In the connected condition, on the other hand, the cue contains information about the two future movements that need to be performed and the sequence of these two movements, implying a more complex representation. This implies that participants need to maintain this complex movement information until the subsequent movement is accurately executed and that PMBR is stronger in this condition. Similarly, Zavala, Jang [20] observed that PMBR was stronger in the condition with interference relative to the condition without interference in the pre-motion cue information, suggesting that the role of PMBR may be to maintain the target information from interference. Furthermore, it was also observed in the N-back task that enhanced beta rhythm reversion to above baseline, that is a significant PMBR phenomenon, was observed only in the case of target stimulus presentation, whereas beta rhythm reverted only to baseline levels after non-target stimuli. Most importantly, a transient activation of sensorimotor areas associated with motor encoding and execution was also observed after target presentation [21]. Briley, Liddle [21] suggested that this suggests that PMBR is associated with reactivation of task-related information. Taken together, the current findings suggest that the PMBR plays an important role in maintaining the information required for subsequent movements.

The current study also found that the PMBR elicited by the first action in the connected condition was greater than that elicited by a single action, a phenomenon observed only in right-handed actions, while not reaching a significant difference in left-handed actions. We attribute this to the fact that the subjects were all right-handed. Sharpshooter preference influences motor planning and execution processes [22] [23] [24]. Sharpshooters are superior in controlling the accuracy of limb movements and rely more on feed-forward control, whereas non-sharpshooters are more suitable for positional control and rely on feedback control [25]. Of course, it cannot be overlooked that the brain regions corresponding to the sharpshooter are subjected to more motor training. Moreover, in studies on the development of PMBR, it was found that compared to the stable and clear PMBR phenomenon observed at the end of exercise in adults, it was almost absent at the end of exercise in children and adolescents [26] [27] [28].

This suggests that PMBR is subject to developmental influences suggesting that PMBR is associated with acquired motor-psychological processes.

The PMBR for foot movements did not show differences between movement conditions compared to left and right hand movements. We speculate that this may be related to the experimental setup of this experiment. On the one hand, we required subjects to respond as soon as possible, so subjects needed to hover their left foot over the pedal at all times, and on the other hand, the sensitivity of the pedal was high in order to collect subjects' first responses. So the subject sustains the muscle contraction continuously while doing the foot pedal movement, although it is weak, it has been recognized as a movement at the neural network level, making the power of PMBR influenced by the muscle contraction before the movement.

5. Conclusion

The current results show that PMBR plays a role in action connectivity, as demonstrated by the presence of subsequent actions that increase PMBR power, and that enhanced PMBR may be relevant for subsequent movement-related information maintenance and motor execution processes.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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