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Mu Wave Suppression and Enhanced Predictive Motor Control: Insights from Neurofeedback Training

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Abstract

Prediction of the actions of others is an integral aspect of human interaction. Indeed, our survival depends on our understanding of others' activities, intentions, and emotions. The objective of this study was to explore the impact of neurofeedback training on the enhancement of predictive motor control. The population of the research comprised all students at Urmia University, from which 36 individuals (age = 23.20±1.96) were selected as available samples. They were then randomly assigned to three groups, neurofeedback, control, and training. The neurofeedback protocol involved activation of the right primary motor cortex and suppression of Mu waves (8-12 Hz) at the C4 point during a 30-minute session. Predictive motor control was assessed using variables indicative of performance and success on a manual tracking task. Participants were asked to trace a moving target along a circular path by adjusting the movement of the pointer by the target displayed on the monitor. This task was executed by manipulating game joysticks held in the nondominant hand, where the direction of the joystick movements mirrored the intended path of the target. The results of the repeated-measures analysis of variance revealed a significant difference between the training and neurofeedback groups compared to the control group in predictive control indicators, including total time on target ($p=0.003$), consecutive time on the target ($p=0.02$), distance from target ($p=0.023$), and movement speed ($p=0.002$). However, no significant difference was observed between the two training groups ($p>0.05$). The findings of this study suggest that a single practice session and a single session of the neurofeedback program can be used interchangeably to acquire skills in predictive motor control.

Keywords: Predictive motor control, Neurofeedback training, Manual tracking

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Introduction

Within the framework of computational neuroscience, internal models are neural mechanisms within the central nervous system (CNS) that play a vital role in motor learning, adaptation, and control. There are two main types of internal models: forward (or predictive) models and inverse models. These models are essential for predicting the outcomes of actions and generating the motor commands required to achieve specific goals (Adams et al., 2016; Yavari et al., 2013). From a perception-action perspective, predictive motor control is a critical component of motor control (Von Hofsten & Rosander, 2012), as it supports skill development and learning (Marshall et al., 2020; Von Hofsten, 1983). For example, the skillful manipulation of objects depends on the ability to control and predict their consequences. Experts' ability to anticipate future events is fundamental to situational awareness and effective reactions (Wilson & Knoblich, 2005). Skilled individuals demonstrate enhanced predictive abilities and faster reactions when interpreting environmental cues, as well as the posture and movements of others. Predictive motor control is employed in various tasks including postural control (Jover et al., 2010; Jucaite et al., 2003), eye movement control (Katschmarsky et al., 2001; Langaas et al., 1998; Marshall et al., 2020), and manual and visual tracking (C. Hyde & P. Wilson, 2011; C. Hyde & P. H. Wilson, 2011), and daily life activities. Predictive motor control plays a crucial role in performing everyday activities, and deficiencies in this area can lead to significant challenges, ultimately affecting quality of life. Research indicates that Mu wave activity serves as a marker for the mirror neuron system (MNS). Consequently, neurofeedback training aimed at suppressing these waves offers an innovative and promising approach to enhancing MNS functionality and its role in predictive motor control. The significance of this study lies in its emphasis on a non-invasive, targeted, and clinically applicable intervention designed to improve motor performance and overall quality of life.

Studies have suggested that mirror neurons play an important role in recognizing actions, understanding action intentions, and facilitating social interactions by creating predictive models (Balser et al., 2014; Csibra, 2008; Kilner, 2011; Molenberghs et al., 2012; Rizzolatti et al., 2014). Psychological, cognitive, and neurophysiological studies aim to model the factors influencing behavior and motor control methods in order to enhance performance or justify behavioral approaches. Experienced individuals can simulate and represent movements in their motor systems by observing movements or scenes, thus enabling them to make predictions (Calvo-Merino et al., 2005; Rizzolatti & Craighero, 2004). Additionally, evidence has demonstrated that, in the realm of prediction, motor experiences outperform observational experiences (Wolpert & Flanagan, 2001). When an individual observes a moving target, they can better predict its trajectory and adjust their behavior accordingly. Alternatively, they may choose to wait for additional information, but this waiting period is often accompanied by delay (Mann et al., 2007). According to the computational neuroscience framework, effective feedback control involves three key computations: 1) accurate prediction of sensory outcomes resulting from motor commands (predictive modeling). 2) Integrating and comparing this prediction with actual sensory feedback. 3) Adjustment of sensory-motor feedback loops for optimal control (Popa & Ebner, 2019). Cerebellar regions are crucial for integrating predictive modeling with sensory feedback, providing an estimate of the body state. Simultaneously, the premotor cortices may utilize generalized control predictions (Yarrow et al., 2009).

The mirror neuron system comprises a network of brain areas in the parietal and inferior frontal gyrus (Thompson et al., 2022). Neurons within this system exhibit regular and coordinated activity during rest, which intensifies during both execution and observation of actions (Fox et al., 2016; Von Hofsten & Rosander, 2012). The heightened activity of mirror neurons aligns with the decrease in the range of brain Mu waves (12-8 Hz) in the sensorimotor region (Dastgheib et al., 2024; Shin et al., 2024). Consequently, it has been acknowledged as an indicator of mirror neuron activity and serves as a noninvasive approach for studying their function in humans (Dastgheib et al., 2024). This method has been validated by recording brain waves in numerous studies (Fox et al., 2016; Hobson & Bishop, 2016; Pineda, 2005; Von Hofsten & Rosander, 2012).

Mu waves serve as indicators of integrated sensory-motor processes, stemming from the activity of mirror neurons within the parietal and premotor networks connecting perception and action (Pineda, 2005). These waves were detected using electrodes positioned around the central sulcus, specifically at points C4, C1, C2, C3, and Cz, while the brain was resting. In this state, these areas remain inactive and lack sensory-motor information processing or motor control (Dastgheib et al., 2024). Brainwave desynchronization is associated with the stimulation of neural networks and the activation of cortical regions, occurring alongside cortical deactivation (Pineda, 2005; Pineda et al., 2014). Several researchers have proposed a correlation between Mu waves and mirror neuron activity(Dastgheib et al., 2024). Similar to Mu waves, mirror neurons display low activity during rest, and the Mu waves in this region demonstrate synchronous and symmetrical patterns. However, with increased mirror neuron activity, Mu waves were suppressed and desynchronized (Kilner et al., 2007). Furthermore, when individuals execute or observe actions performed by others, these waves exhibit desynchronization and suppression (Genzer et al., 2022). Brain imaging studies have also indicated a correlation between the suppression of Mu waves and activation of mirror neurons (Cuevas et al., 2014; Muthukumaraswamy & Johnson, 2004; Pineda et al., 2014). In certain studies, researchers have manipulated Mu brain waves, thereby influencing the activity of mirror neurons. Fox et al. (2016) conducted a meta-analysis of 85 studies and suggested alterations in Mu waves as a viable method for investigating the activity of the mirror neuron system (Fox et al., 2016). Similarly, Ernestine et al. (2011), using brain imaging techniques and recording brain waves, illustrated that the suppression of Mu waves aligns with the activation of the mirror neuron system within the relevant brain regions (Arnstein et al., 2011).

Neurofeedback training is a novel method for modifying and regulating electrical brain activity (brainwaves) to facilitate mindful adjustments in individuals (Young et al., 2017). It seems that by altering the activity and rhythm of brainwaves, desired behaviors can be encouraged, whereas inappropriate behaviors can be reduced. A notable advantage of neurofeedback training is its sustained effect (Steiner et al., 2014). The dysfunction of mirror neurons can pose challenges to individuals. Research in this area indicates that synchronization between Mu waves and the activity of the mirror neuron system is disrupted in children with autism (Pineda et al., 2014). The crucial focus lies in the modulation of brain waves to enhance the function of the mirror neuron system, which benefits both healthy individuals and those with autism (Hobson & Bishop, 2016). Exploring the influence of motor experience and skill level on mirror neuron function, Orgs et al. (2008) discovered that skilled players, compared to novices, exhibited greater Mu wave desynchronization during rhythmic movements. Additionally, Wolf et al. (2014) showed a correlation between skill levels in tennis players and the extent of Mu wave desynchronization in the (10-8 Hz) frequency range.

In their study on the effectiveness of neurofeedback training for treating autism spectrum disorder, Steiner et al. (2014) found that neurofeedback regulates brainwave activity and significantly influences the performance of mirror neurons by inducing neural plasticity (Steiner et al., 2014). Keuken et al. (2011) also observed enhanced reaction times and reduced suppression of the 8–12 Hz EEG Mu rhythm in healthy individuals following repetitive transcranial magnetic stimulation (Keuken et al., 2011). Some studies have indicated that humans can volitionally regulate the spectrum of Mu wave frequencies (LaMarca et al., 2023; Pineda, 2005). Pineda et al. (2008) proposed that irregular Mu wave rhythms may signify dysfunction in mirror neurons. Their study revealed that employing neurofeedback techniques, involving desynchronization of Mu waves at the C4 point for 30 sessions, each lasting 30 minutes, in children with autism resulted in enhanced information processing within mirror neurons. They interpreted the suppression of Mu waves as an indicator of the heightened activation of mirror neurons. They also found that the suppression of Mu wave activity in the right hemisphere, specifically in the C4 region, was superior to that in other areas. They observed that individuals could learn to control Mu wave patterns over a relatively short period (Pineda et al., 2008).

Hence, the utilization of neurofeedback training techniques to suppress or desynchronize Mu waves has been employed to modify the function of mirror neurons and regulate brainwave patterns in individuals with autism or athletes (Steiner et al., 2014). The neurofeedback program has been effective in rectifying mirror neuron network dysfunction in children with autism (Pineda et al., 2014).

The Present Study: Several studies have investigated the impact of neurofeedback programs or direct cortical stimulation on Mu wave activity and mirror neuron function in individuals with autism and athletes. However, there remains a gap in the understanding of how this training technique influences predictive motor control. Recent studies have shown that supplementing traditional training methods with innovative approaches, such as neurofeedback involving brain wave regulation, has accelerated advancements in cognitive and motor performance. In these studies, individuals received feedback on their performance through visual or auditory cues, allowing them to control their brainwaves. This established a closed-loop neurofeedback system. The process of reorganizing neural connections and training to control specific brain waves through neurofeedback can prove beneficial in enhancing performance across diverse areas, such as learning, focus of attention, and sports achievement (Afrash et al., 2023; Wang et al., 2019). In the present study, predictive control is assessed through a tracking task. Successful performance in the rotating tracking task requires predicting both target movement and corresponding hand movements. Successful completion of the rotating pursuit task necessitates accurate anticipation of both the target and corresponding hand movements. This research evaluated manual tracking performance through a novel approach to the rotatory pursuit task, focusing on staying consecuatively time on the target. This duration serves as an indicator of the predictive control model (Adams et al., 2014; Ferguson et al., 2015; Sparaci et al., 2015), enabling an examination of the capacity to learn, recognize, and rectify momentary fluctuations. To ascertain whether participants employed anticipatory or step feedback, we determined the most prolonged consecutive duration spent tracking the target during each trial. This approach reveals whether individuals employ a phased tracking strategy that involves the planning and execution of shorter movement path segments, or if they utilize a feedforward control strategy to anticipate, plan, and execute more extended movement paths with smoother transitions (Sparaci et al., 2015; Van Roon et al., 2008). Therefore, the current study aimed to examine the effect of neurofeedback training on the acquisition of predictive motor control by modulating the function of mirror neurons and Mu waves. Based on the hypothesis that employing neurofeedback techniques to suppress and desynchronize Mu waves (12-8 Hz) can potentially induce plasticity in neural networks, such as the mirror neuron system. This improvement may effectively enhance the predictive control. The findings of this study offer insight into the intrinsic mechanisms, causes, and processes governing individual movements within the realm of motor control. These insights hold the potential to address and enhance underlying processes, particularly in instances of disorders or within educational settings. By considering the activation of the mirror neuron system in both actual execution and neurofeedback training, along with the suppression of Mu waves, this study aims to compare the efficacy of these two methods in learning predictive motor control. Enhancement in predictive control performance was assessed using manual tracking tasks conducted before and after the training program and neurofeedback sessions.

Methodology

Population and Sampling

This study followed a semi-experimental design, employing a randomized controlled trial featuring one between-group factor (comprising three levels) and one within-group factor comprising two levels. Pre- and post-test assessments were conducted along with a single intervention session involving training exercises. The sample size of the 33 participants was determined using the G*Power 3.1. This determination considered a minimum power of 0.95, effect size of 0.33, and alpha level of 0.05, which is consistent with previous studies (Ring et al., 2015; Wang et al., 2022). A two-way ANOVA statistical analysis, incorporating three levels of groups and the number of measurements (pre-post and 24-hour retention), was utilized to calculate the minimum required sample size. Thirty-six participants were purposefully selected to maintain statistical power and prevent participant dropout, 36 participants were purposefully selected. Following the initial screening, participants were randomly assigned to three distinct groups using a random sampling method. Each group comprised 12 participants and was allocated to one of the following study groups: neurofeedback training (age: 23.8±8.0), motor training (age: 22.7±4.2), and a control group (age=23.2±8.2). All participants fulfilled the following criteria: 1)-Absence of

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learning, psychological, or neurological disabilities in their medical history, 2)-Exclusively right-handed males, 3)-non-usage of medications that could affect brain function, 4)-Normal vision and eyesight, 5)-No prior exposure to neurofeedback training. The participants were instructed to avoid consuming caffeinated beverages, alcoholic drinks, or food within 24 h before the examination. Following an explanation of the research objectives, participants attended scheduled laboratory sessions. After completing the informed consent form, the participants independently commenced their respective group's program. The neurofeedback program involved a 30-minute session providing biological feedback just before engaging in the manual tracking task. Each individual's training and examination session lasted approximately one and a half hours.

Assessments

predictive motor control

Predictive motor control was evaluated through a manual tracking task using a modified hand-tracking software test (EbrahimiSani et al., 2020; Ferguson et al., 2015; Sparaci et al., 2015). Participants tracked a one-centimeter diameter red circular target on a 15.6-inch computer screen (1366×768 pixels resolution) in a clockwise direction. They used a wireless mouse (2.4 GHz, havit-k501G) in an inverted position, following a circular path with a 535-millimeter radius and focusing on a 25-millimeter radius target. The participants aimed to keep the mouse cursor on the red target, which brightened upon cursor overlap. The task involved a visible circular white path that guided the movement of the target and offered clear cues for its trajectory. It was organized into nine blocks, each containing six practice trials. Throughout the task, the participants exclusively used their nondominant left hand. They were instructed to execute inverted mouse movements, in which the relationship between mouse movements and the cursor was reversed. For instance, moving the mouse left corresponded to the cursor moving right, and downward mouse movements resulted in upward cursor movements and vice versa. Blocks 1-8 were completed on a single day, while Block 9 was conducted after a 24-hour delay and rest period to assess the consolidation and learning of predictive motor control. Across all blocks, participants followed a designated circular path at predetermined speeds (0.7 and 0.8 Hz), completing two laps within a 15-second interval in each trial. A five-second rest period was allotted between practice trials, and each block lasted approximately two minutes. In experimental group one (practice group only), participants underwent a pre-test in Block 1 under the reversed condition. Subsequently, they engaged in six blocks of targeted task practice, without instructional guidance. Post-tests were conducted on Block 8 following a ten-minute interval and on Block 9 after a 24-hour rest period. In experimental group two (neurofeedback only), similar to the first group, participants underwent a pre-test followed by a 30-minute neurofeedback training session. Immediate and delayed posttests were performed. The third group (control) underwent pseudo-training, which involved watching a video program of neurofeedback, without any direct influence on the participants. They did not receive actual neurofeedback training and were assessed in Blocks 1 (pre-test), 8, and 9 (post-tests). These experimental conditions were established to determine the impact of the neurofeedback program in contrast to other experimental conditions. Learning to track occurs in three steps: 1) learning to stay on the target, 2) predicting the trajectory and direction of the target's movement, and 3) learning to decrease reliance on simultaneous visual feedback, thereby reducing the occurrence of minor movements. Each component was identified using the TOT, CTT, and DT. Dependent variables, such as the total time on the target (in milliseconds), were recorded by the program. Information regarding CTT (milliseconds), DT (pixels), and V (indicator movement speed, pixels per millisecond), which was not directly recorded, were subsequently calculated using MATLAB. During each phase, the results of each effort were documented. In the retention phase, which occurred at two intervals—10 min (immediate) and 24 h (consolidation test) after the practice phase—evaluations akin to those in the pre-test stage were performed.

Neurofeedback Training Program

The neurofeedback program suppressed Mu waves in the frequency range of 8–12 Hz in the right motor cortex (C4), as outlined in the training protocol of Ros et al. (2014). EEG signals were captured using a FlexComp system equipped with an EEG amplifier and a 24-bit analog-to-digital converter. The visual representation of neurofeedback training was facilitated by the BioGraph program, which was integrated with the software, and run on a dual-core Intel computer with a 15-inch screen. Brain waves were collected and recorded for biological feedback by using blue reference electrodes at a sampling rate of 256 Hz in the right primary motor cortex (C4). The reference electrode was positioned on the contralateral side, behind the ear, on the mastoid bone. The electrode placement sites on the skull were prepared using NuPrep abrasive gel, and the electrodes were affixed with Ten20 electrode paste. The ground electrode is connected to the right earlobe. The Reward thresholds were set such that, in 70% of the instances, the amplitude of the Mu was below the initial Mu mean amplitude (baseline). In a serene setting, each intervention was initiated with five minutes dedicated to concentration. Subsequently, baseline brainwave data (initial baseline) were recorded for 3 min while the participants had their eyes open and remained relaxed. Following this, the neurofeedback protocol began, and immediately after its completion, another 3 min session of brainwave recording took place. Participants were not given explicit verbal instructions or training strategies during the neurofeedback session; instead, they were informed that guidance would be provided through the neurofeedback process. The electrode receivers, which capture brain electrical activity, converte these data into the primary unit of the neurofeedback system. Subsequently, this information was transmitted to a computer. The computer simulated brainwaves and presented them to the participants in the form of a computer game or video. Five random feedback games, each lasting six minutes, were played using the Canadian software Biograph Infiniti. These games include bowling, flying mazes, gorillas, windsurfer races, and bee flights (Ros et al., 2014). In each game, the movement and stopping of symbols depended on whether the brainwave levels were above or below the reward threshold, requiring individuals to regulate their brain activity. A range of games were used in this protocol to prevent fatigue and enhance participants' involvement in the tasks.

Statistical Analysis

The mean and standard deviation were used to summarize the results, whereas the Shapiro-Wilk test was used to assess variable normality. Data analysis was performed using the repeated measures analysis of variance (ANOVA) technique. The three assumptions of the analyses (normality of residuals distribution assessed by the Shapiro-Wilk test, homogeneity of residuals variances evaluated through Levene's test, and sphericity of residuals covariances determined via Mauchly's test) were verified and supported ($p > 0.05$). A 3x3 repeated measures two-way analysis of variance (ANOVA) was used to assess learning levels among the three groups across pre-test sessions, 10-minute retention, and 24-hour retention. Statistical computations were conducted using SPSS software (version 26), with significance set at ($p < 0.05$).

Results

A one-way analysis of variance (ANOVA) was used to examine age distribution across three groups (NF, MT, and Control). The findings revealed no significant difference in the age index among the participants, suggesting that age did not affect the outcomes $F(3{,}46) = 0.59;\ P = 0.62$).

Successful tracking depends on several key factors: total time on target (TOT), distance from target (DT), consecutive time on target (CTT), and movement velocity (V). Successful tracking requires individuals to spend more time on the target, maintain a consistent and minimal distance from it, and ensure smooth, incremental changes in tracking speed. In the pre-test session, one-way analysis of variance (ANOVA) revealed no significant differences among the three groups in TOT ($p = 0.37$), CTT ($p = 0.47$), DT ($p = 0.88$), and V ($p = 0.27$). To assess consolidation and predictive motor learning across the three groups using the measured indices, a repeated-measures ANOVA was performed. This analysis incorporated a between-subjects factor (group) and a within-subjects factor (time) over three periods: pre-test, immediate, and delayed retention. According to Table 1 and Figure 1, the results revealed significant differences in the total time on target, indicating main effects for both group and time, as well as an interaction effect. Considering the interaction effect's significance and examining the simple main effects, a one-way ANOVA indicated significant differences among the three groups during the immediate retention phase (10 minutes) ($p = 0.007$). Further pairwise comparisons using the Bonferroni test revealed a significant difference between the two training groups and the control group. However, no significant difference was observed between the two training groups during this phase. In addition, in the delayed retention phase (24 hours), which is similar to the immediate retention phase, no significant difference was observed between the two training groups. However, both training groups exhibited a significant difference from the control group. The repeated measures one-way ANOVA within each group revealed significant differences among the three test phases within the training group. This disparity was mainly observed between the pre-test and the immediate/delayed retention sessions. Notably, no significant difference was observed between the immediate and delayed retention sessions (refer to Figure 1A and Table 1).

The index of consecutive time on target (CTT) demonstrated significant main effects for group, time, and their interaction. Upon conducting one-way ANOVA for group comparisons in each phase, a significant difference was observed among the three groups in both the immediate and delayed retention sessions ($p < 0.05$). Notably, the distinction in both retention phases lay between the training and control groups, whereas no difference was found between the two training groups.

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Additionally, within-group analysis using repeated measures ANOVA revealed significant differences among the test phases in both the training and non-feedback groups. In the training groups, a disparity was observed between the pre-test phase and the two retention phases. However, no significant difference was found between the immediate and delayed retention phases (refer to Figure 1B and Table 1).

Regarding the distance from the target index, the group and time main effects were significant, whereas the interaction effect did not reach significance. As the interaction effect was not significant, pairwise comparisons using the Bonferroni test revealed a significant difference between the control group and the two training groups. However, no significant difference was observed between the two training groups. Additionally, a significant difference was observed between the pre-test and immediate and delayed retention phases. However, no significant difference was found between the retention phases themselves (refer to Figure 1C and Table 1).

In the volecity index, both the group and time main effects were significant, whereas the interaction effect did not reach significance. Post hoc testing using the Bonferroni test revealed significant differences between the pre-test and immediate and delayed retention phases. However, no significant difference was observed between the retention phases. Moreover, a notable difference existed between the two training groups and the control group. Interestingly, no significant difference was observed between the two training groups (refer to Figure 1D and Table 1).

Table 1. The results obtained from the repeated measures analysis of variance (ANOVA) and subsequent Bonferroni post hoc tests were employed to identify disparities between groups and variations within each group across the studied indices.

variables	**Group**	**Pre intervention**	**Post intervention (10 min)**	**Follow up (24 hour)**	**sig**		
					group	time	Interaction
TOT	1	1940/7±1033/9 Ba	5880±2299/2 Aa	6475/4±2345/2 Aa	P=0.003*	P<0.001*	P=0.002*
	2	2558/8±1559/4 Ba	5650/3±2251/4 Aa	6416/6±2654/4 Aa			
	3	19480/08±965/4 Aa	2992/1±2371/9 Ab	3488/4±1534/4 Ab			
CTT	1	800/2±462/8 Ba	1741/6±664/8 Aa	1852/2±519/6 Aa	P=0.02*	P<0.001*	P=0.001*
	2	1107± 943/9 Ba	1832/1±706/8 Aa	1899/9±1055/9 Aa			
	3	849/3±435 Aa	1016/5±718/6 Ab	1002/9±406/5 Ab			
DT	1	92/6±49/3 a	21/17±17/7	14/3±8/2	P=0.023*	P<0.001*	P=0.55
	2	82/7± 63/99 a	23/2±14/6	21/2±14/2			
	3	93/9±68 a	78/3±93/1	45/3±28/1			
V	1	0/31±0/08 a	0/11±0/012	0/16±0/02	P=0.002*	P<0.001*	P=0.08
	2	0/26±0/09 a	0/17±0/02	0/17±0/03			
	3	0/28 ±0/06 a	0/25±0/07	0/23±0/04			

-Dependent variables categorized into three groups: TOT (total time on target), CTT (continuous time on target), DT (distance from target), and V (velocity); Group (1): Exercise, Group (2): Neurofeedback, Group (3): Control
-In each measured indicator, dissimilar uppercase Latin letters in a row and dissimilar lowercase Latin letters in a column indicate a significant difference (P<0.05).

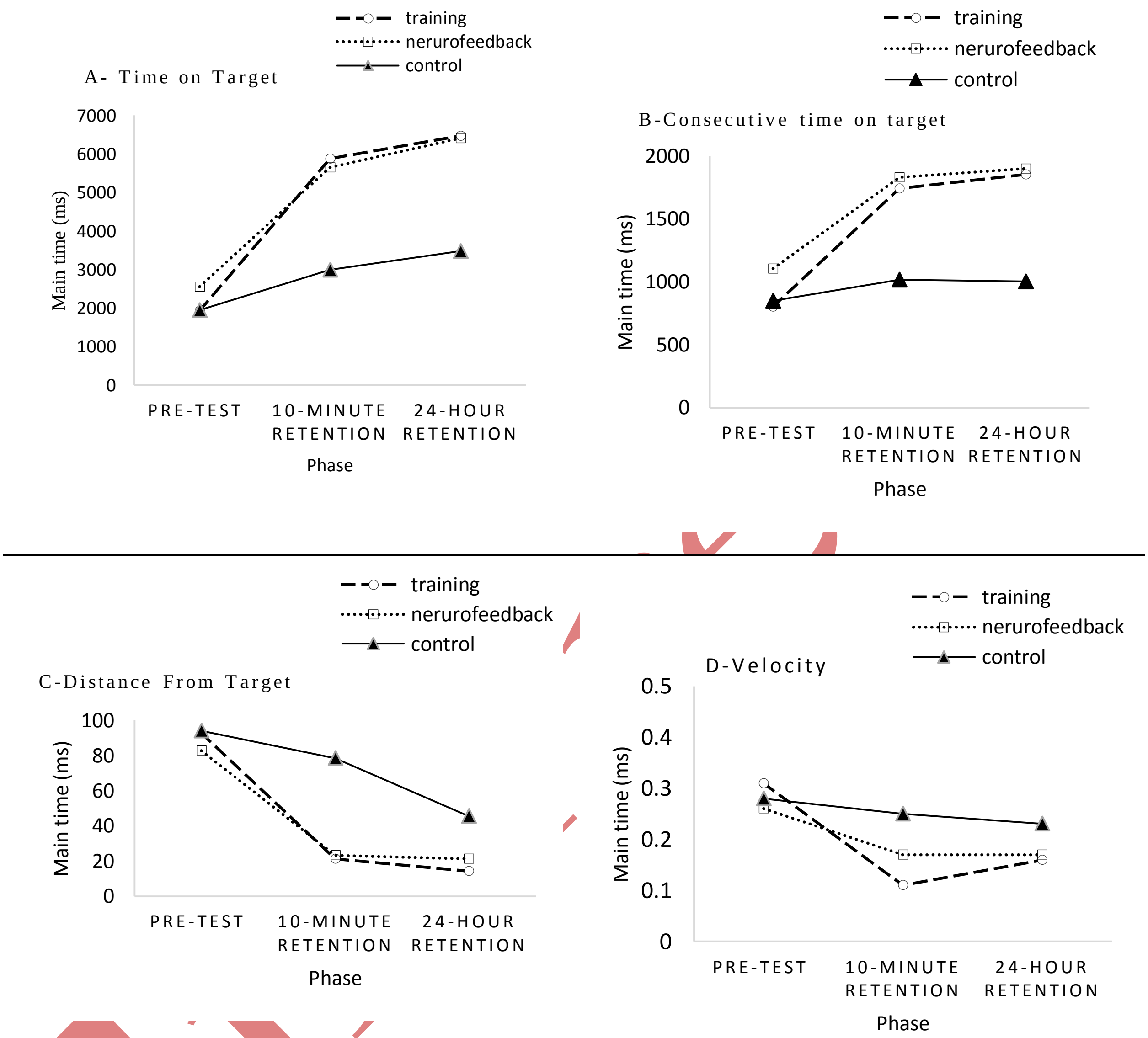

Figure 1. The performance chart depicts the performance of three groups—exercise, neurofeedback, and control—regarding indices associated with predictive motor learning.

Discussion and conclusion

This research aimed to explore the influence of neurofeedback training and exercise on pre-predictive motor learning and control within a complex visual-motor task. In order to achieve this, Predictive motor control was compared among three groups" neurofeedback training, motor exercise, and a control group" across pre-test, acquisition, and retention stages in this study. Based on the results of all dependent variables (TOT, CTT, DT, and V), no significant difference was found between the motor exercise and neurofeedback groups during the acquisition and retention stages. However, both these groups exhibited a meaningful difference compared to the control group. Furthermore, there were no observed differences among the three groups in the dependent variables during the pre-test session. Within the control group, no differences were observed between the test stages. The results indicate that interventions targeting all selected indicators had a significant positive impact on improving predictive motor control. Moreover, the experimental groups successfully acquired internal representations during the learning process. Both neurofeedback training and motor practice appear to contribute to the activation of the mirror neuron system, thereby enhancing predictive internal models.

The ability to anticipate a target's movement depends, in part, on stored information about its motion. Consequently, the initial step involves creating an accurate internal representation of the mobile target's location and motion. This representation facilitates seamless tracking of the moving target. The subsequent stage involves updating this constructed model, enabling individuals to track the moving target smoothly. According to the theory of computational neuroscience, the simultaneous control of actions relies on the capacity to integrate internal representations (Ferguson et al., 2015). Consequently, the advancement of internal model functions has also contributed to enhancing the efficiency of experimental groups in utilizing internal action representations for the concurrent control of manual tracking tasks. According to Wilson et al. (2016), anticipatory motor control plays a pivotal role in simultaneous action control, ensuring the stability of the overall motor system and facilitating learning through prior estimations of limb movement location and trajectory.

Through motor prediction, these individuals can anticipate the outcomes of their actions in manual tracking tasks, thereby improving their movement stability and decreasing their dependence on slow feedback control. The duration of consistently staying on target reflects an individual's motor control strategy, employing either anticipatory or incremental feedback for guiding and controlling movements. In motor tracking, an individual who consistently stays on target (e.g., CCT) implies the utilization of anticipatory feedback (Adams et al., 2014). The study outcomes revealed a significant difference between the experimental and control groups regarding the duration of consecutive time spent on target in both the post-test and retention phases. These results imply that the experimental group employed continuous and seamless target-tracking strategies via anticipatory mechanisms (e.g., constructing internal predictive models to anticipate the trajectory and location of subsequent movements). Conversely, the control group relied on feedback-dependent approaches (e.g., utilizing visual and movement feedback to detect the target's location and then making partial adjustments accordingly). Porficient motor behavior necessitates an individual's ability to create coordinated movements following dynamic external conditions. This ability is a fundamental aspect of the motor system's proficiency in acquiring its dynamics, using this framework as a model at every moment, allowing individuals to make swift adjustments based on prior predictions. Most studies conducted so far have focused on comparing mirror neuron activity between individuals with typical and atypical development, as well as exploring the correlation between mirror neuron activity and brain Mu waves. Nevertheless, there has been a lack of research on training interventions about the plasticity of mirror neurons and the modulation of brain Mu waves via neurofeedback, and how these factors might impact the enhancement of motor control functions and action planning in individuals. Although this aspect signifies a strength in the current study, it does complicate direct comparisons with previous studies, posing challenges in drawing direct parallels. Further studies must validate these results comprehensively and ensure a more robust confirmation.

The findings of the current study align consistently with prior research regarding the effectiveness of neurofeedback training programs in desynchronization and suppression of Mu waves, leading to increased action preparation, motor control, and related performance (Afrash et al., 2023; Cooke et al., 2015; Ros et al., 2014; Wang et al., 2022). In this field, Ros et al. (2014) demonstrated the efficacy of a neurofeedback training session in suppressing Mu waves, thereby enhancing procedural learning. The findings of this study also align with the findings of Cannon et al. (2014) and Dastgheib et al. (2024), which indicated a modulation of Mu wave activity shortly after motor training. Therefore, it seems plausible that interventions targeting the regulation of motor programming processes could potentially impact outcomes and related processes.

When interpreting the observed outcomes, specific effects can be ascribed to the impact of motor training interventions, while others are attributable to neurofeedback training programs. Additionally, some effects display similarities between these two modes of training. According to Afrash and colleagues (2023), both neurofeedback training and experiential learning from motor training contribute to neural plasticity by promoting the formation of new connections among nerve cells across various brain regions. These structures are crucial in developing memory, attention, and motor learning (Afrash et al., 2023). Moreover, while the mirror neuron system activates through the observation of purposeful actions, specific learning processes, such as acquiring practical experience, are crucial in shaping this system and improving sensorimotor performance. These experiences lead to variations in the activity levels of mirror neurons and the development of refined internal models in skilled individuals compared to novices (Aglioti et al., 2008). This implies that the precision of predictive action simulation hinges upon an individual's level of experience (Aglioti et al., 2008; Wuang et al., 2011). Consequently, consistent practice, repetition, and experience acquisition have collectively shown the capacity to enhance predictive motor control comprehensively.

In addition, according to EEG studies, the activity pattern of brain waves is different in beginners and skilled people, and the range of activity and power of Mu waves (8-12 Hz) is reported to be lower in skilled people than in beginners. Therefore, it is possible that by practicing and training neurofeedback, the pattern of brain Mu wave activity of beginners will be closer to that of skilled people, and the range of Mu waves will decrease (Denis et al., 2017).

Hervault and colleagues (2021) linked the continuous desynchronization of Mu waves during the execution of ongoing movements to the closed-loop control necessary for simultaneous and predictive movement regulation (Hervault et al., 2021). Consequently, utilizing neurofeedback training to suppress and desynchronize Mu waves might facilitate the activation of sensorimotor areas and enhance predictive motor control. Additionally, the effectiveness of neurofeedback training aligns with the motor neuron hypothesis, as proposed by Hatfield (2018), attributing its efficacy to the inhibition of irrelevant cognitive and motor processes while enhancing the processing of pertinent information in the brain, thus reducing noise (Hatfield, 2018). Also, following the research conducted by Nitsche et al., (2003), which investigated the impact of transcranial direct current stimulation (tDCS) on the motor cortex opposite to the body and noted enhancements in the serial reaction time task, it can be inferred that employing neurofeedback protocols to stimulate the primary motor cortex and desynchronize Mu waves might heighten cortical-spinal excitability. This approach could potentially alleviate intracortical inhibition, with effects lasting for at least 20 minutes (Ros et al., 2014; Ros et al., 2010), thereby potentially facilitating more effective learning processes. Moreover, these findings are consistent with cognitive theories concerning exercise and the impact of training experiences. According to these theories, heightened cognitive activity characterizes the initial stage of motor skill learning. As individuals progress from novice to expert performance, there is a natural decline in Mu wave activity patterns (Wang et al., 2019; Wang et al., 2020). Thus, in the initial stages of motor learning, characterized by higher error rates and increased cognitive activity, neurofeedback training appears well-suited to accommodate the performer's needs. Furthermore, the acquired results on consolidation effects are consistent with Hsu and Bishop's (2014) observations of improved learning effects in a visuomotor task among children aged 7 to 11 after a 7-5 day interval (Hsu & Bishop, 2014). Likewise, these findings correspond with Sparaci et al., (2015) research, demonstrating improved performance in pursuit tracking tasks among children following a 24-hour rest period (Sparaci et al., 2015). Understanding the connection between an action and its sensory feedback is crucial for precise and swift control. This capability relies on internal models that simulate all controllable features of objects. The predictive model relies either on prior perception within an internal model or, when previous perceptual information is unavailable, replicating of motor commands and the specification of their resulting sensory consequences. Subsequently, it compares these anticipated consequences with actual feedback, using prediction errors to adjust and refine the internal model. Consequently, in manual tracking scenarios where the target maintains a constant speed and follows a clearly defined trajectory, individuals pre-select their predictive model in advance. However, when the target accelerates or alters its path" similar to the observed conditions in the current study where the target's movement and the indicator were mirror-inverted" the refinement of the predictive model relies on minimizing prediction errors.

The mirror neuron system, located in the premotor cortex, inferior parietal, and superior temporal sulcus regions, plays a pivotal role in human interaction and behavior prediction (Jeon & Lee, 2018). It facilitates the inference of observed action goals while minimizing prediction errors (Bach et al., 2011). This system is activated during both action observation and performance, operating through predictive sensory outcome models (Maranesi et al., 2014; Zhang et al., 2018). Functional magnetic resonance imaging (fMRI) studies have shown that the premotor cortex and inferior frontal sulcus exhibit mirror-like properties (Marshall & Meltzoff, 2014). The posterior parietal and frontal regions are crucial for predicting trajectory and movement direction in manual tracking tasks (Field et al., 2007; Mulliken et al., 2008). In addition to the structural and functional characteristics of these regions, skilled individuals demonstrate proficiency in internal and predictive models that help identify environmental information. The efficiency of these models correlates with Mu rhythm desynchronization, which is notably less developed in novices (Denis et al., 2017). Research has indicated that greater Mu rhythm desynchronization in skilled individuals strengthens the perception-action coupling within the mirror neuron system (Sanchez-Romero & Cole, 2021; Yang et al., 2020). Furthermore, previous studies suggest that individuals find it easier to learn mu rhythm suppression than mu rhythm enhancement (Pineda et al., 2003). Consequently, neurofeedback training aimed at improving or facilitating Mu rhythm suppression in regions associated with the mirror neuron system appears to support the development of internal models in this study. Regarding motor training and the development of internal models, studies have shown that left-sided body movements lead to Mu rhythm suppression and desynchronization in the right sensorimotor region (Derambure et al., 1999). Additionally, task complexity amplifies this effect. As demonstrated in this study, motor training promoted Mu rhythm suppression in these areas. Mu rhythm desynchronization activates cortical networks responsible for sensorimotor processing, selective attention, and motor preparation in the anterior parietal region (Pineda, 2005). This process enhances motor recognition (Denis et al., 2017), execution (Fox et al., 2016), corrective actions (Cooke et al., 2015), adaptability, and stability (Cooke et al., 2015). Wang et al. (2019) also associate reduced Mu rhythm power with corrective actions and controlled processing, which require heightened alertness, working memory engagement, and attentional control during complex tasks (Wang et al., 2019). Furthermore, Mu movement capacity is influenced by past execution errors, indirectly emphasizing the significance of suppressing Mu rhythms to allocate cognitive resources for motor response planning during action execution or observation (Bertollo, 2016; Wang et al., 2019). Therefore, the observed Mu rhythm desynchronization and suppression in this study, facilitated through neurofeedback and motor training, likely enhanced mirror neuron activity and perception-action coupling. Given the complexity of the visuomotor task, Mu rhythm suppression and reduced activity amplitude may have enabled greater cognitive resource allocation for motor planning. This improvement in predictive motor control allowed participants to refine their actions in a controlled manner, focusing on positional and trajectory adjustments, relative body movement coordination, and goal awareness.

Similar to any previous research, this study has certain limitations in addition to its strengths. Although the improvement in motor planning performance was inferred to result from the suppression of mu waves, enhanced mirror neuron activity, or activation of specific neural regions, the lack of direct recording of mu wave activity or neuroimaging to capture the activation of brain areas affected by the training intervention represents a limitation of the present study. Providing such information in future studies may be crucial for validating these findings. One of the limitations of the current study is the lack of data regarding the long-term durability of the effects of neurofeedback training. It is possible that the effects of prolonged training may not be sustained over time or that a longer duration of training may be required to achieve more enduring results. Therefore, future studies should extend the duration of training and reassess the outcomes using delayed retention tests to better evaluate the persistence of the effects. Although neurofeedback training was employed to suppress mu waves and enhance predictive motor control, it should be noted that psychological and cognitive factors also significantly influence mu wave activity (Rusalova & Kostyunina, 2004). Controlling for their impact on the results is challenging; thus, caution is required when generalizing the findings. To better understand the underlying processes of motor control, future research should explore the impact of neurofeedback training on disinhibition of neural networks and action planning. This could be achieved by analyzing antisaccadic eye movements at different stages of learning while accounting for participants' expertise levels, ranging from novices to individuals with advanced motor skills. Furthermore, a detailed investigation of the allocation of cognitive resources for motor planning and the functioning of attentional networks is essential. While the findings of this study demonstrate the efficacy of neurofeedback training in improving predictive motor control during manual tracking tasks, future research should broaden these investigations to encompass other activities such as visual tracking, postural control, driving, and both discrete and continuous sports tasks. Additionally, this study focused solely on the independent effects of motor training and neurofeedback training without examining their combined influence. It is conceivable that integrating these two approaches would produce synergistic benefits. Therefore, future studies should employ a combined training approach to assess the collective impact of motor and neurofeedback training on predictive control performance. Our findings provide support for interventions involving motor experience or innovative approaches, such as neurofeedback training. These interventions influence action perception through activation of mirror neurons. These findings offer practical implications for individuals experiencing difficulties with social interactions or deficits in internal modeling. Furthermore, this study provides support for the effectiveness and applicability of a single neurofeedback session in enhancing motor control, which may benefit coaches, educators, and healthcare professionals engaged in training or therapeutic practice. In brain-computer interface (BCI) studies, where visual feedback is provided, individuals learn to control mu waves, establishing a closed-loop neurofeedback system. This method, which does not require muscular activity, is particularly beneficial for individuals with neuromuscular disorders or injuries. This neural reorganization, achieved through neurofeedback training to enhance performance in various domains, including athletic performance, has significant potential for practical applications. Given that both the neurofeedback training group and the group practicing the primary task showed comparable performance gains, the two training methods appeared functionally equivalent. Where physical practice is not feasible, neurofeedback training targeting brainwave modulation can significantly enhance individual performance.

Conclusion

As both the physical execution of an action and mu wave suppression via neurofeedback can activate the mirror neuron system, this study compared these methods in learning predictive motor control. Performance improvement was assessed using a manual tracking task, before and after a single neurofeedback training session. The results demonstrated the effectiveness of this single session in enhancing predictive motor control learning. These findings suggest a significant role for mirror neurons in domains including predictive motor control and that neurofeedback, leveraging mirror neuron system plasticity, may modulate their function, facilitating behavioral adjustments and predictive motor control acquisition. Sports contexts offer a valuable setting for investigating actions, movement prediction, and training program efficacy. Therefore, future research should explore the underlying changes resulting from training and learning in real-world settings.

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References

Adams, I. L., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2014). Compromised motor control in children with DCD: a deficit in the internal model?—A systematic review. *Neuroscience & Biobehavioral Reviews*, *47*, 225-244. https://doi.org/10.1016/j.neubiorev.2014.08.011

Afrash, S., Saemi, E., Gong, A., & Doustan, M. (2023). Neurofeedback training and motor learning: the enhanced sensorimotor rhythm protocol is better or the suppressed alpha or the suppressed mu? *BMC Sports Science, Medicine and Rehabilitation*, *15*(1), 93.

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nat Neurosci*, *11*(9), 1109-1116. https://doi.org/10.1038/nn.2182

Arnstein, D., Cui, F., Keysers, C., Maurits, N. M., & Gazzola, V. (2011). μ-suppression during action observation and execution correlates with BOLD in dorsal premotor, inferior parietal, and SI cortices. *Journal of Neuroscience*, *31*(40), 14243-14249.

Bach, P., Bayliss, A. P., & Tipper, S. P. (2011). The predictive mirror: interactions of mirror and affordance processes during action observation. *Psychonomic bulletin & review*, *18*, 171-176.

Balser, N., Lorey, B., Pilgramm, S., Stark, R., Bischoff, M., Zentgraf, K., Williams, A. M., & Munzert, J. (2014). Prediction of human actions: expertise and task-related effects on neural activation of the action observation network. *Hum Brain Mapp*, *35*(8), 4016-4034. https://doi.org/10.1002/hbm.22455

Bertollo, M. (2016). Proficient brain for optimal performance: the MAP.

Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: an FMRI study with expert dancers. *Cerebral cortex*, *15*(8), 1243-1249.

Cannon, E. N., Yoo, K. H., Vanderwert, R. E., Ferrari, P. F., Woodward, A. L., & Fox, N. A. (2014). Action experience, more than observation, influences mu rhythm desynchronization. *PloS one*, *9*(3), e92002.

Cooke, A., Gallicchio, G., Kavussanu, M., Willoughby, A., McIntyre, D., & Ring, C. (2015). Premovement high- alpha power is modulated by previous movement errors: Indirect evidence to endorse high- alpha power as a marker of resource allocation during motor programming. *Psychophysiology*, *52*(7), 977-981.

Csibra, G. (2008). Action mirroring and action understanding: An alternative account. *Sensorymotor foundations of higher cognition. Attention and performance XXII*, 435-459.

Cuevas, K., Cannon, E. N., Yoo, K., & Fox, N. A. (2014). The Infant EEG Mu Rhythm: Methodological Considerations and Best Practices. *Dev Rev*, *34*(1), 26-43. https://doi.org/10.1016/j.dr.2013.12.001

Dastgheib, S. S., Wang, W., Kaufmann, J. M., Moratti, S., & Schweinberger, S. R. (2024). Mu-Suppression Neurofeedback Training Targeting the Mirror Neuron System: A Pilot Study. *Applied psychophysiology and biofeedback*, 1-15.

Denis, D., Rowe, R., Williams, A. M., & Milne, E. (2017). The role of cortical sensorimotor oscillations in action anticipation. *Neuroimage*, *146*, 1102-1114. https://doi.org/10.1016/j.neuroimage.2016.10.022

Derambure, P., Defebvre, L., Bourriez, J., Cassim, F., & Guieu, J. (1999). Event-related desynchronization and synchronization. Reactivity of electrocortical rhythms in relation to the planning and execution of voluntary movement. *Neurophysiologie clinique= Clinical neurophysiology*, *29*(1), 53-70.

EbrahimiSani, S., Sohrabi, M., Taheri, H., Agdasi, M. T., & Amiri, S. (2020). Effects of virtual reality training intervention on predictive motor control of children with DCD–A randomized controlled trial. *Research in developmental disabilities*, *107*, 103768. https://doi.org/10.1016/j.ridd.2020.103768

Ferguson, G. D., Duysens, J., & Smits-Engelsman, B. C. (2015). Children with Developmental Coordination Disorder are deficient in a visuo-manual tracking task requiring predictive control. *Neuroscience*, *286*, 13-26. https://doi.org/10.1016/j.neuroscience.2014.11.032

Field, D. T., Wilkie, R. M., & Wann, J. P. (2007). Neural systems in the visual control of steering. *J Neurosci*, *27*(30), 8002-8010. https://doi.org/10.1523/JNEUROSCI.2130-07.2007

Fox, N. A., Bakermans-Kranenburg, M. J., Yoo, K. H., Bowman, L. C., Cannon, E. N., Vanderwert, R. E., Ferrari, P. F., & van, I. M. H. (2016). Assessing human mirror activity with EEG mu rhythm: A meta-analysis. *Psychol Bull*, *142*(3), 291-313. https://doi.org/10.1037/bul0000031

Genzer, S., Ong, D. C., Zaki, J., & Perry, A. (2022). Mu rhythm suppression over sensorimotor regions is associated with greater empathic accuracy. *Social Cognitive and Affective Neuroscience*, *17*(9), 788-801.

Hatfield, B. (2018). Brain dynamics and motor behavior: A case for efficiency and refinement for superior performance. *Kinesiology Review*, *7*(1), 42-50.

Hervault, M., Zanone, P. G., Buisson, J. C., & Huys, R. (2021). Cortical sensorimotor activity in the execution and suppression of discrete and rhythmic movements. *Sci Rep*, *11*(1), 22364. https://doi.org/10.1038/s41598-021-01368-2

Hobson, H. M., & Bishop, D. V. (2016). Mu suppression - A good measure of the human mirror neuron system? *Cortex*, *82*, 290-310. https://doi.org/10.1016/j.cortex.2016.03.019

Hsu, H. J., & Bishop, D. V. (2014). Sequence- specific procedural learning deficits in children with specific language impairment. *Developmental science*, *17*(3), 352-365.

Hyde, C., & Wilson, P. (2011). Online motor control in children with developmental coordination disorder: chronometric analysis of double-step reaching performance. *Child Care Health Dev*, *37*(1), 111-122. https://doi.org/10.1111/j.1365-2214.2010.01131.x

Hyde, C., & Wilson, P. H. (2011). Dissecting online control in Developmental Coordination Disorder: a kinematic analysis of double-step reaching. *Brain Cogn*, *75*(3), 232-241. https://doi.org/10.1016/j.bandc.2010.12.004

Jeon, H., & Lee, S.-H. (2018). From neurons to social beings: short review of the mirror neuron system research and its socio-psychological and psychiatric implications. *Clinical Psychopharmacology and Neuroscience*, *16*(1), 18.

Jover, M., Schmitz, C., Centelles, L., Chabrol, B., & Assaiante, C. (2010). Anticipatory postural adjustments in a bimanual load-lifting task in children with developmental coordination disorder. *Dev Med Child Neurol*, *52*(9), 850-855. https://doi.org/10.1111/j.1469-8749.2009.03611.x

Jucaite, A., Fernell, E., Forssberg, H., & Hadders-Algra, M. (2003). Deficient coordination of associated postural adjustments during a lifting task in children with neurodevelopmental disorders. *Dev Med Child Neurol*, *45*(11), 731-742. https://doi.org/10.1017/s0012162203001373

Katschmarsky, S., Cairney, S., Maruff, P., Wilson, P. H., & Currie, J. (2001). The ability to execute saccades on the basis of efference copy: impairments in double-step saccade performance in children with developmental co-ordination disorder. *Exp Brain Res*, *136*(1), 73-78. https://doi.org/10.1007/s002210000535

Keuken, M. C., Hardie, A., Dorn, B., Dev, S., Paulus, M., Jonas, K., Van Den Wildenberg, W., & Pineda, J. (2011). The role of the left inferior frontal gyrus in social perception: an rTMS study. *Brain research*, *1383*, 196-205.

Kilner, J. M. (2011). More than one pathway to action understanding. *Trends in cognitive sciences*, *15*(8), 352-357.

Kilner, J. M., Friston, K. J., & Frith, C. D. (2007). Predictive coding: an account of the mirror neuron system. *Cognitive processing*, *8*(3), 159-166. https://doi.org/10.1007/s10339-007-0170-2

LaMarca, K., Gevirtz, R., Lincoln, A. J., & Pineda, J. A. (2023). Brain–Computer Interface Training of mu EEG Rhythms in Intellectually Impaired Children with Autism: A Feasibility Case Series. *Applied psychophysiology and biofeedback*, *48*(2), 229-245.

Langaas, T., Mon-Williams, M., Wann, J. P., Pascal, E., & Thompson, C. (1998). Eye movements, prematurity and developmental co-ordination disorder. *Vision Res*, *38*(12), 1817-1826. https://doi.org/10.1016/s0042-6989(97)00399-4

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of sport and exercise psychology*, *29*(4), 457-478.

Maranesi, M., Livi, A., Fogassi, L., Rizzolatti, G., & Bonini, L. (2014). Mirror neuron activation prior to action observation in a predictable context. *Journal of Neuroscience*, *34*(45), 14827-14832.

Marshall, B., Wright, D. J., Holmes, P. S., Williams, J., & Wood, G. (2020). Combined action observation and motor imagery facilitates visuomotor adaptation in children with developmental coordination disorder. *Res Dev Disabil*, *98*, 103570. https://doi.org/10.1016/j.ridd.2019.103570

Marshall, P. J., & Meltzoff, A. N. (2014). Neural mirroring mechanisms and imitation in human infants. *Philos Trans R Soc Lond B Biol Sci*, *369*(1644), 20130620. https://doi.org/10.1098/rstb.2013.0620

Molenberghs, P., Cunnington, R., & Mattingley, J. B. (2012). Brain regions with mirror properties: a meta-analysis of 125 human fMRI studies. *Neurosci Biobehav Rev*, *36*(1), 341-349. https://doi.org/10.1016/j.neubiorev.2011.07.004

Mulliken, G. H., Musallam, S., & Andersen, R. A. (2008). Forward estimation of movement state in posterior parietal cortex. *Proc Natl Acad Sci U S A*, *105*(24), 8170-8177. https://doi.org/10.1073/pnas.0802602105

Muthukumaraswamy, S. D., & Johnson, B. W. (2004). Changes in rolandic mu rhythm during observation of a precision grip. *Psychophysiology*, *41*(1), 152-156. https://doi.org/10.1046/j.1469-8986.2003.00129.x

Orgs, G., Dombrowski, J. H., Heil, M., & Jansen- Osmann, P. (2008). Expertise in dance modulates alpha/beta event- related desynchronization during action observation. *European Journal of Neuroscience*, *27*(12), 3380-3384.

Pineda, J. A. (2005). The functional significance of mu rhythms: translating "seeing" and "hearing" into "doing". *Brain Res Brain Res Rev*, *50*(1), 57-68. https://doi.org/10.1016/j.brainresrev.2005.04.005

Pineda, J. A., Brang, D., Hecht, E., Edwards, L., Carey, S., Bacon, M., Futagaki, C., Suk, D., Tom, J., Birnbaum, C., & Rork, A. (2008). Positive behavioral and electrophysiological changes following neurofeedback training in children with autism. *Research in Autism Spectrum Disorders*, *2*(3), 557-581. https://doi.org/10.1016/j.rasd.2007.12.003

Pineda, J. A., Carrasco, K., Datko, M., Pillen, S., & Schalles, M. (2014). Neurofeedback training produces normalization in behavioural and electrophysiological measures of high-functioning autism. *Phil. Trans. R. Soc. B*, *369*(1644), 20130183.

Pineda, J. A., Silverman, D. S., Vankov, A., & Hestenes, J. (2003). Learning to control brain rhythms: making a brain-computer interface possible. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *11*(2), 181-184.

Popa, L. S., & Ebner, T. J. (2019). Cerebellum, predictions and errors. *Frontiers in cellular neuroscience*, *12*, 524.

Ring, C., Cooke, A., Kavussanu, M., McIntyre, D., & Masters, R. (2015). Investigating the efficacy of neurofeedback training for expediting expertise and excellence in sport. *Psychology of Sport and Exercise*, *16*, 118-127.

Rizzolatti, G., Cattaneo, L., Fabbri-Destro, M., & Rozzi, S. (2014). Cortical mechanisms underlying the organization of goal-directed actions and mirror neuron-based action understanding. *Physiological reviews*, *94*(2), 655-706. https://doi.org/DOI:10.1152/physrev.00009.2013

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annu. Rev. Neurosci.*, *27*(1), 169-192.

Ros, T., Munneke, M., Parkinson, L., & Gruzelier, J. (2014). Neurofeedback facilitation of implicit motor learning. *Biological psychology*, *95*, 54-58. https://doi.org/DOI: 10.1016/j.biopsycho.2013.04.013

Ros, T., Munneke, M. A., Ruge, D., Gruzelier, J. H., & Rothwell, J. C. (2010). Endogenous control of waking brain rhythms induces neuroplasticity in humans. *European Journal of Neuroscience*, *31*(4), 770-778.

Rusalova, M., & Kostyunina, M. (2004). Spectral correlation studies of emotional states in humans. *Neuroscience and behavioral physiology*, *34*, 803-808.

Sanchez-Romero, R., & Cole, M. W. (2021). Combining multiple functional connectivity methods to improve causal inferences. *Journal of cognitive neuroscience*, *33*(2), 180-194.

Shin, N., Ikeda, Y., Motomura, Y., & Higuchi, S. (2024). Effects of observing own/others hand movement in different perspectives on mu rhythm suppression: an EEG study. *Journal of physiological anthropology*, *43*(1), 21.

Sparaci, L., Formica, D., Lasorsa, F. R., Mazzone, L., Valeri, G., & Vicari, S. (2015). Untrivial Pursuit: Measuring Motor Procedures Learning in Children with Autism. *Autism Research*, *8*(4), 398-411. https://doi.org/10.1002/aur.1455

Steiner, N. J., Frenette, E., Hynes, C., Pisarik, E., Tomasetti, K., Perrin, E. C., & Rene, K. (2014). A pilot feasibility study of neurofeedback for children with autism. *Applied psychophysiology and biofeedback*, *39*(2), 99-107.

Thompson, E. L., Bird, G., & Catmur, C. (2022). Mirror neuron brain regions contribute to identifying actions, but not intentions. *Human brain mapping*, *43*(16), 4901-4913.

Van Roon, D., Caeyenberghs, K., Swinnen, S. P., & Smits- Engelsman, B. (2008). Development of feedforward control in a dynamic manual tracking task. *Child development*, *79*(4), 852-865. https://doi.org/10.1111/j.1467-8624.2008.01163.x

Von Hofsten, C., & Rosander, K. (2012). Perception-action in children with ASD. *Front Integr Neurosci*, *6*, 115. https://doi.org/DOI:10.3389/fnint.2012.00115

Wang, K.-P., Cheng, M.-Y., Chen, T.-T., Chang, Y.-K., Huang, C.-J., Feng, J., Hung, T.-M., & Ren, J. (2019). Experts' successful psychomotor performance was characterized by effective switch of motor and attentional control. *Psychology of Sport and Exercise*, *43*, 374-379.

Wang, K.-P., Cheng, M.-Y., Chen, T.-T., Huang, C.-J., Schack, T., & Hung, T.-M. (2020). Elite golfers are characterized by psychomotor refinement in cognitive-motor processes. *Psychology of Sport and Exercise*, *50*, 101739.

Wang, K. P., Frank, C., Hung, T. M., & Schack, T. (2022). Neurofeedback training: Decreases in Mu rhythm lead to improved motor performance in complex visuomotor skills. *Curr Psychol*, 1-12. https://doi.org/10.1007/s12144-022-03190-z

Wilson, P. H., Adams, I. L. J., Caeyenberghs, K., Thomas, P., Smits-Engelsman, B., & Steenbergen, B. (2016). Motor imagery training enhances motor skill in children with DCD: A replication study. *Research in developmental disabilities*, *57*, 54-62. https://doi.org/10.1016/j.ridd.2016.06.014

Wolf, S., Brölz, E., Scholz, D., Ramos-Murguialday, A., Keune, P. M., Hautzinger, M., Birbaumer, N., & Strehl, U. (2014). Winning the game: brain processes in expert, young elite and amateur table tennis players. *Frontiers in Behavioral Neuroscience*, *8*, 370.

Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology*, *11*(18), R729-R732.

Wuang, Y.-P., Chiang, C.-S., Su, C.-Y., & Wang, C.-C. (2011). Effectiveness of virtual reality using Wii gaming technology in children with Down syndrome. *Research in developmental disabilities*, *32*(1), 312-321. https://doi.org/10.1016/j.ridd.2010.10.002

Yang, G., Deng, N., Liu, Y., Gu, Y., & Yao, X. (2020). Evaluation of glymphatic system using diffusion MR technique in T2DM cases. *Frontiers in Human Neuroscience*, *14*, 300.

Yarrow, K., Brown, P., & Krakauer, J. W. (2009). Inside the brain of an elite athlete: the neural processes that support high achievement in sports. *Nat Rev Neurosci*, *10*(8), 585-596. https://doi.org/10.1038/nrn2672

Young, K. D., Siegle, G. J., Zotev, V., Phillips, R., Misaki, M., Yuan, H., Drevets, W. C., & Bodurka, J. (2017). Randomized clinical trial of real-time fMRI amygdala neurofeedback for major depressive disorder: effects on symptoms and autobiographical memory recall. *American Journal of Psychiatry*, *174*(8), 748-755.

Zhang, J. J., Fong, K. N., Welage, N., & Liu, K. P. (2018). The activation of the mirror neuron system during action observation and action execution with mirror visual feedback in stroke: a systematic review. *Neural plasticity*, *2018*(1), 2321045.

