

Comparative Analysis of P300 Latency and Amplitude during Real and Imaginary Hand Movements among Healthy Adult Subjects

Jitendra Kumawat¹, Anuradha Yadav², Preeti Sharma³

^{1,2,3}Department of Physiology, SMS Medical College, Jaipur Rajasthan, India.

Corresponding Author: Dr Anuradha Yadav

DOI: <https://doi.org/10.52403/ijhsr.20260134>

ABSTRACT

Background: P300 is an event-related potential, and its amplitude and latency indicate the degree of cortical activation, and the speed of cognitive processing. P300 responses during both real and imaginary motor tasks can provide insight of motor control mechanisms.

Aim: Comparing P300 amplitude and latency during real versus imaginary hand movements helps to identify the differential cortical dynamics underlying motor execution and motor imagery.

Methods: An observational study was conducted on 56 healthy, right-handed male volunteers aged 18–30 years participated after providing written informed consent. Electroencephalography (EEG) was recorded during three phases: baseline, real and imaginary motor task for both hand movements. The P300 component was evaluated for amplitude and latency within the Gamma frequency band across all EEG channels during real and imaginary motor conditions. The median values with interquartile ranges (IQRs) were calculated for right and left-hand movements. Compared across baseline, real, and imaginary conditions were performed using the Kruskal–Wallis test, considering $p < 0.05$ statistically significant.

Results: Real hand movements elicited shorter P300 latencies across widespread parieto-occipital cortical regions, reflecting faster and broader neural engagement. Imaginary movements showed reduced latencies primarily in frontal and parietal midline regions. P300 amplitude was greater in frontal and parietal areas during real movements, whereas imaginary movements predominantly activated occipital regions.

Conclusions: Although motor imagery and motor execution share common neural pathways, their spatial and temporal activation patterns differ significantly. These findings underline the relevance of motor imagery for neurorehabilitation applications.

Keywords: Cognition, Electroencephalography, Event-Related Potential, Motor Imagery, Neurorehabilitation

INTRODUCTION

Event-related potentials (ERPs) provide a non-invasive means to study cortical processing related to sensory, cognitive, and motor functions. Among the ERP

components, the P300 wave has been widely recognized as an indicator of cognitive processing, attention allocation, and stimulus evaluation¹. P300 is typically elicited in response to task-relevant stimuli,

and its amplitude and latency reflect the intensity of cortical activation and the speed of cognitive processing, respectively². In the context of motor control, studying P300 responses during both real and imaginary movements offers valuable insights into the shared and distinct neural mechanisms underlying motor execution and motor imagery³.

Motor imagery, the mental simulation of movement without actual execution activates neural circuits similar to those engaged during real movements, including motor, premotor, and parietal areas^{4,5}. This overlapping activation forms the basis for the use of motor imagery in neurorehabilitation and brain-computer interface (BCI) research^{6,7}. However, despite shared neural substrates, differences in P300 characteristics between real and imaginary movements have been reported, reflecting varying degrees of sensory feedback, attention, and motor preparation⁸.

Previous studies have shown that real movements often produce larger P300 amplitudes and shorter latencies, attributed to greater cortical engagement and immediate sensory feedback⁹. In contrast, imaginary movements are associated with lower amplitudes and delayed responses, suggesting reduced sensory input and increased cognitive load¹⁰. Furthermore, hemispheric and regional variations in P300 parameters have been observed during left- and right-hand movements, providing additional insights into lateralized motor processing¹¹.

Thus, a comparative study aims to evaluate P300 amplitude and latency during real and imaginary hand movements can clarify the differential cortical dynamics involved in motor imagery and execution. Such understanding holds implications for optimizing motor imagery paradigms in cognitive neuroscience and rehabilitation settings.

MATERIALS & METHODS

The present study was a laboratory-based, comparative, analytic observational study

conducted in the Electrophysiology Laboratory of the Department of the Institute. Ethical approval was obtained from the Institutional Ethics Committee (No.:1110/MC/EC/2021) before the commencement of the study. Participant confidentiality was maintained by assigning anonymous identification numbers. All procedures adhered to the ethical standards of the Declaration of Helsinki.

The study included 56 right-handed male participants, aged 18–30 years who were apparently healthy and provided written informed consent, on the basis of non-random selection. Individuals were excluded if they had a history of neurological or psychiatric disorders, were addicted to alcohol or drugs, were taking medications that could affect the nervous system, or had any illness detected during examination. Participants who were uncooperative during testing were also excluded.

EEG Recording: EEG data were recorded using the BESS (Brain Electro Scan System) software, version 4.0 (Axxonet Systems Technologies Ltd, India). Saline-soaked Ag/AgCl surface electrodes (immersed 24 hours prior to testing) were mounted on a silicon electrode cap positioned according to standard anatomical landmarks. Electrodes were placed at Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, O2, and Oz sites, following the International 10–20 System¹². The reference electrode was attached to the left earlobe, and the ground electrode was placed on the forehead. Electrode impedance was maintained below 5 k Ω . A notch filter (50 Hz) was used to eliminate line noise, and a band-pass filter (1–65 Hz) was applied to smooth the signal. EEG data were amplified and digitized at a sampling rate of 512 Hz.

Prior to data collection, a brief baseline EEG was recorded to ensure signal stability. Once stable, the stimulus protocol was initiated.

Participants were seated comfortably about 1 meter from a computer screen in a sound-attenuated, dimly lit room with forearms resting on a table, palms downward, and eyes open. The target detection task was explained and practiced in a training session involving both real and imagined motor tasks before data acquisition.

Experimental Procedure: The experimental protocol consisted of three sequential phases (Figure 1):

1. Basal Recording: Participants maintained gaze on the screen's center

to minimize eye movements and refrained from any motor or cognitive activity. Baseline EEG activity was recorded for 15 minutes, divided into three 5-minute segments with 1-minute rest intervals between each.

2. Real Motor Task: Participants performed actual wrist extension movements, involving rapid extension followed by brief relaxation.

3. Imaginary Motor Task: Participants imagined performing the same wrist extension and relaxation movement without any physical muscle activity.

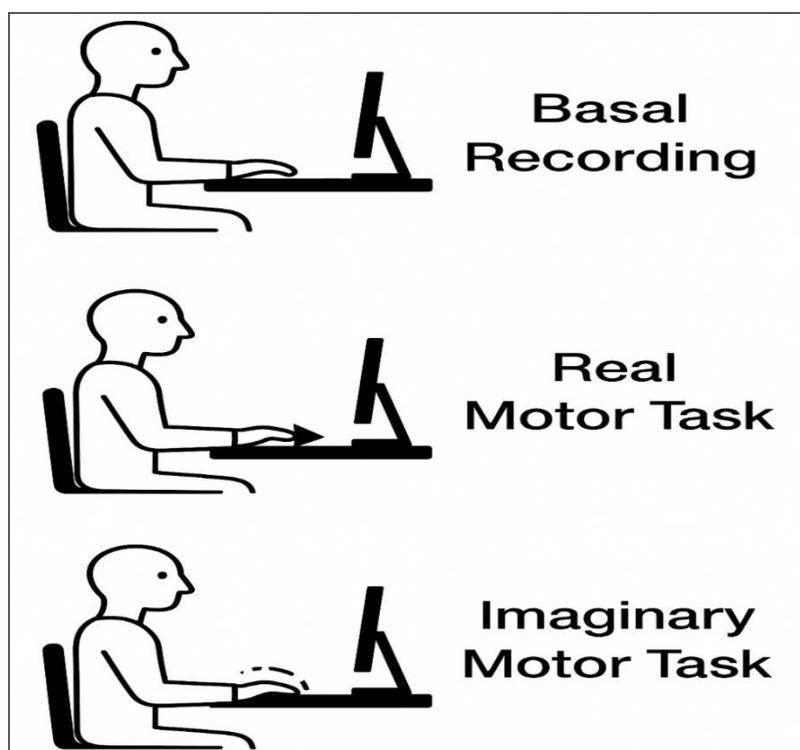


Figure 1: Sequential Phases of the Experimental Procedure Showing Basal Recording, Real Motor Task, and Imaginary Motor Task.

During both motor and imagery tasks, physical settings remained identical to the baseline recording. Task cues were displayed on the screen: black cues indicated a real motor task, and grey cues indicated an imaginary motor task. The cue's position (left or right) corresponded to the hand to be used.

Each trial lasted 2 seconds, consisting of a 150 ms visual cue followed by a static white screen for 1,850 ms. Each experiment comprised four runs per hand, with 40 trials

per run. To minimize fatigue, right and left-hand tasks were alternated between runs.

Data Processing and Analysis

EEG Data Analysis: Raw EEG data were processed using BESS software (version 4.0). Data were segmented into epochs of 2000 ms per trial. Artifacts, including eye blinks and noise, were removed manually by visual inspection. Data were then averaged for each electrode site, condition, and participant.

ERP Recording: Trigger points were time-locked to stimulus onset (100 ms before cue presentation). Epochs were baseline-corrected using the average voltage of the 100 ms pre-stimulus period. Event-Related Potentials (ERPs) were averaged across trials for each condition and then across all participants.

Outcome Measures: The P300 component was analyzed for amplitude and latency within the Gamma frequency band across all EEG channels for:

- a. Real motor movements
- b. Imaginary motor movements

Median values with interquartile ranges (IQRs) were calculated for both right and left-hand movements.

STATISTICAL ANALYSIS

Data were entered in Microsoft Excel and analyzed using STATA version 14. Continuous variables were expressed as median (IQR) due to non-normal data distribution, verified using the Shapiro–Wilk (W) test. Since normality assumptions were not met, non-parametric tests were

applied. Comparisons across the three conditions (baseline, real, and imaginary) were performed using the Kruskal–Wallis test. A p-value < 0.05 was considered statistically significant.

RESULT

The significant differences in P300 peak latency were observed between left- and right-hand movements across multiple brain regions. During real movements, shorter latencies were noted over frontal (F4), central (CZ), temporal (T6), parietal (P3, P4), and occipital (O1, O2, OZ) areas, indicating hemispheric specialization depending on the movement side. For imaginary movements, reduced latencies were predominantly seen over frontal (FP1, FP2, F3, FZ) and parietal (PZ) regions, suggesting differential cortical activation during motor imagery.

Real movements showed broader cortical involvement, whereas imaginary movements predominantly engaged frontal and parietal regions, reflecting distinct neural processing patterns for executed versus imagined actions. (Table 1).

Table 1: Brain regions showing significant differences in P300 peak latency (ms) between left- and right-hand movements

Brain Area	Channel(s)	Real Movements (p < 0.05)	Imaginary Movements (p < 0.05)
Frontal	F4, FP1, FP2, F3, FZ	F4 (0.040)-Lower latency during left-hand movement	FP1 (0.002), FP2 (0.007), F3 (0.006), FZ (0.026)- Lower latency during left-hand movement
Central	CZ	CZ (0.016)-Lower latency during left-hand movement	–
Temporal	T6	T6 (0.011)- Lower latency during Right-hand movement	–
Parietal	P3, P4, PZ	P3 (0.025), P4 (0.019)-Lower latency during Right-hand movement	PZ (0.004)- Lower latency during Right-hand movement
Occipital	O1, O2, OZ	O1 (0.003), O2 (0.023), OZ (0.046)- Lower latency during Right-hand movement	O1 (0.030)-Lower latency during Right-hand movement

During the different movement conditions, P300 peak latency varied notably among brain regions. The Right side has lower latency than the left side. When comparing real with imaginary, imaginary movements have shorter latency than real movements. During real left-hand movements, the

shortest latency was recorded at CZ (378.42 ms) and the longest at F7 (435.55 ms), while real right-hand movements showed the shortest latency at O2 (358.89 ms) and the longest at CZ (446.29 ms). For imaginary movements, the shortest latency occurred at FZ (353.52 ms) for the left hand and at O1

(339.36 ms) for the right hand, with the longest at PZ (417.97 ms) and FP2 (447.27 ms), respectively (Table 2).

These findings indicate that latency variations are task- and region-specific, with

faster responses in occipital and frontal areas during imagery, reflecting differential cortical activation between real and imagined motor tasks.

Table 2: Maximum and minimum P300 peak latency (ms) differences across movement conditions

Condition	Brain Area (Min Latency)	Min Latency (ms)	Brain Area (Max Latency)	Max Latency (ms)
Real – Left Hand	CZ	378.42	F7	435.55
Real – Right Hand	O2	358.89	CZ	446.29
Imaginary – Left Hand	FZ	353.52	PZ	417.97
Imaginary – Right Hand	O1	339.36	FP2	447.27

The scalp distribution Figure- 2 shows significant P300 peak latency differences between left- and right-hand movements. Real movements (red) exhibited latency differences mainly over central, parietal, and occipital regions (CZ, P3, P4, T6, OZ, O2). Imaginary movements (blue) demonstrated effects over frontal and midline areas (FP1, FP2, F3, FZ, PZ).

Overlapping significance (purple) was observed at O1, indicating shared occipital involvement. Real movements primarily influenced posterior and central latencies, while imaginary movements affected frontal and midline sites, suggesting differential temporal processing of motor execution and imagery.

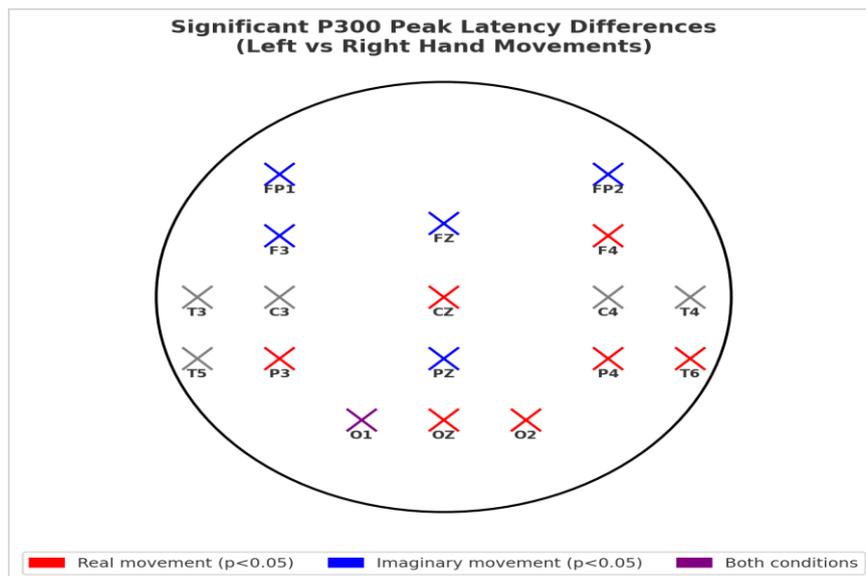


Figure 2: Schematic brain map showing significant sites of P300 peak latency from frontal to occipital regions

Note: ● Red = Real movements significant ($p < 0.05$), ● Blue = Imaginary movements significant, ● Purple = Significant in both conditions (notably O1)

This figure illustrates the visual clearly in the differences between left and right-hand movements under real and imagined tasks. The figure depicts that imaginary movements are more prominent in the frontal area while real in the parietooccipital area of the brain.

The significant differences in P300 amplitude were observed between left- and right-hand movements in specific brain regions. During real movements, higher amplitudes were noted at F3 ($p = 0.015$), FZ ($p = 0.049$), and PZ ($p = 0.048$) for left-hand movements. In contrast, during imaginary

movements, significant differences appeared only in the occipital region, with higher amplitudes at O2 ($p = 0.009$) and OZ ($p = 0.032$) for right-hand imagery. Real movements predominantly engaged frontal

and parietal regions for the left hand, whereas right-hand imagery activated occipital areas, indicating distinct cortical activation patterns for real and imagined motor tasks (Table 3).

Table 3: Brain regions showing significant differences in P300 Amplitude (μV) between left- and right-hand movements

Brain Area	Channel(s)	Real Movements ($p < 0.05$)	Imaginary Movements ($p < 0.05$)
Frontal	F3, FZ	F3 ($p = 0.015$) – Higher amplitude during left-hand movement; FZ ($p = 0.049$) – Higher in left-hand movement	No significant difference
Parietal	PZ	PZ ($p = 0.048$) – Higher amplitude during left-hand movement	No significant difference
Occipital	O2, OZ	No significant difference	O2 ($p = 0.009$), OZ ($p = 0.032$) – Higher amplitude during right-hand imagery

Across all movement conditions, the maximum P300 peak amplitude was consistently observed at the frontal site FP2, while the minimum amplitude was found in posterior regions. During real left-hand movement, FP2 showed the highest amplitude ($0.85 \mu\text{V}$) and O2 the lowest ($0.21 \mu\text{V}$). For real right-hand movement, FP2 again had the highest ($0.64 \mu\text{V}$) and OZ the lowest ($0.10 \mu\text{V}$). Similarly, in

imaginary conditions, FP2 showed maximal amplitudes ($0.72 \mu\text{V}$ and $0.56 \mu\text{V}$), whereas posterior regions (PZ, O2, T5, P3) exhibited minimal responses. Frontal regions, particularly FP2, demonstrated the strongest P300 responses across all movement conditions, indicating dominant frontal activation during both real and imagined motor tasks (Table 4).

Table 4: Maximum and minimum P300 peak amplitude (μV) differences across movement conditions

Condition	Brain Area (Min Amplitude)	Min Amplitude (μV)	Brain Area (Max Amplitude)	Max Amplitude (μV)
Real – Left Hand	O2	0.21	FP2	0.85
Real – Right Hand	OZ	0.10	FP2	0.64
Imaginary – Left Hand	PZ, O2	0.21	FP2	0.72
Imaginary – Right Hand	T5, P3, O2	0.14	FP2	0.56

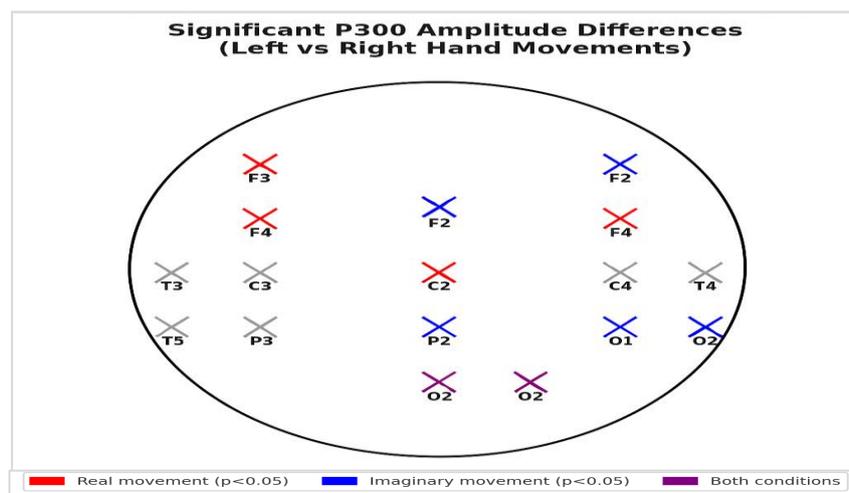


Figure 3: Schematic brain map showing significant sites of P300 Amplitude from frontal to occipital regions:

Note: ● Red = Real movements significant ($p < 0.05$), ● Blue = Imaginary movements significant ($p < 0.05$), ● Purple = Significant in both conditions (notably O2)

The scalp topography illustrates significant P300 amplitude differences between left- and right-hand movements. Real movements (red) showed significant activation in frontal (F3, F4, C2) areas, while imaginary movements (blue) primarily engaged frontal and occipital regions (F2, P2, O1, O2). Overlapping effects (purple) were observed at occipital sites (O2), indicating shared cortical processing between conditions. Real movements predominantly activated frontal regions, whereas imaginary movements involved both frontal and occipital cortices, reflecting distinct yet overlapping neural mechanisms for motor execution and imagery (Figure 3).

DISCUSSION

The present study demonstrates clear distinctions in P300 latency and amplitude during real and imaginary hand movements, reflecting differential cortical activation associated with motor execution and motor imagery. Real movements exhibited shorter P300 latencies across widespread cortical regions—particularly central, parietal, and occipital areas—whereas imaginary movements showed reduced latencies mainly over frontal and parietal midline areas. This suggests broader and faster cortical engagement during actual motor execution, and selective frontal–parietal involvement during motor imagery. Moreover, right-hand movements generally produced shorter latencies than left-hand movements, indicating hemispheric specialization in motor processing. Scalp maps confirmed that imaginary movement effects were concentrated in frontal areas, whereas real movements were dominant in parieto-occipital regions. For amplitude, real movements elicited greater P300 responses in frontal and parietal areas, whereas imaginary movements mainly activated occipital sites. Across all conditions, maximum amplitude consistently occurred at FP2, indicating dominant frontal involvement.

These findings align with previous work demonstrating both distinctions and functional similarities between real and imagined movements. Salvaris and Sepulveda (2010)¹³ reported high classification accuracy for both types of movement in P300-based BCI paradigms, with real movements outperforming imaginary movements. Similar to their results, the present study also shows stronger cortical engagement during real motor execution, though imaginary movements still evoke robust and measurable P300 responses—highlighting their applicability for BCI systems. Machado et al. (2013)¹⁴ likewise supported overlapping neural integration across conditions, identifying similar functional networks for real and imagery tasks, despite subtle amplitude differences between hemispheres. The present results further reinforce this overlap, as shared activation was detected at occipital sites in both tasks. Latency patterns from earlier work by Ragot (1984)¹⁵, who related P300 dynamics to spatial stimulus–response conflict rather than motor programming, partially correspond with the present findings, where latency variations were region- and condition-specific rather than simply motor-driven. More recent studies also demonstrate convergence with our observations. Kurgansky et al. (2024)¹⁶ reported asymmetric motor area activation during imagery, similar with our finding of predominant frontal–parietal activation during imagined movement. Similarly, Galdo-Álvarez et al. (2016)¹⁷ noted comparable P3 patterns between real and imaginary movements with shared inhibitory networks, consistent with the strong frontal amplitudes observed across all movement types in the present study. The comparable scalp distributions reported by Bruno et al. (2019)¹⁸ further support the neural similarity between real and imagined phantom movements. Overall, the present study confirms that although real motor execution engages a wider and faster cortical network, motor

imagery elicits distinct yet comparable P300 responses, dominated by frontal processing. These results reinforce the concept of shared neural substrates for executed and imagined actions and highlight motor imagery as a reliable tool for neurophysiological assessment and brain-computer interface applications.

Strengths and Limitations of the Study: The study provides meaningful insight into differential cortical activation by comparing P300 amplitude and latency during real and imaginary motor tasks. Simultaneous evaluation of both hemispheres, through right- and left-hand movements, strengthens the reliability of motor-related EEG findings. The use of a healthy and homogenous participant group, with controlled age and handedness, minimizes inter-individual variability.

However, the sample comprised only young male volunteers, limiting the generalizability of results to females, older individuals, and clinical populations. Motor imagery ability was not formally assessed, which may have introduced variability in imagery performance. As an observational study, causal mechanisms cannot be established. Additionally, analysis was restricted to the gamma-band P300 response, and inclusion of other frequency bands might offer broader insights. Finally, the controlled laboratory setting may not fully reflect real-world motor or rehabilitation environments.

CONCLUSION

The present study found that real and imaginary hand movements generate distinct yet overlapping P300 responses. Real movements elicited shorter latencies across widespread cortical areas, particularly parietal and occipital areas involved in sensorimotor integration and visuomotor processing. Whereas imaginary movements predominantly activated frontal-parietal midline regions with comparatively shorter latencies in frontal sites, reflecting greater reliance on motor planning and cognitive simulation. P300

amplitudes were consistently maximal at FP2 across all conditions, indicating dominant frontal involvement. These findings indicate that while motor execution and motor imagery share common neural substrates, their temporal dynamics and spatial activation patterns differ. Such insights strengthen the value of motor imagery in neurophysiological assessment, neurorehabilitation, and brain-computer interface applications.

Declaration by Authors

Ethical Approval: Approved

Acknowledgement: None

Source of Funding: None

Conflict of Interest: The authors declare no conflict of interest.

REFERENCES

1. Polich J. Updating P300: an integrative theory of P3a and P3b. *Clin Neurophysiol.* 2007;118(10):2128-48. doi: 10.1016/j.clinph.2007.04.019.
2. Picton TW. The P300 wave of the human event-related potential. *J Clin Neurophysiol.* 1992;9(4):456-79. doi:10.1097/00004691-199210000-00002.
3. Neuper C, Müller-Putz GR, Scherer R, Pfurtscheller G. Motor imagery and EEG-based control of spelling devices and neuroprostheses. *Prog Brain Res.* 2006; 159:393-409. doi:10.1016/S0079-6123(06)59025-9.
4. Jeannerod M. Mental imagery in the motor context. *Neuropsychologia.* 1995;33(11):1419-32. doi:10.1016/0028-3932(95)00073-C.
5. Lotze M, Halsband U. Motor imagery. *J Physiol Paris.* 2006;99(4-6):386-95. doi: 10.1016/j.jphysparis.2006.03.012.
6. Pfurtscheller G, Neuper C. Motor imagery activates primary sensorimotor area in humans. *Neurosci Lett.* 1997;239(2-3):65-8. doi:10.1016/S0304-3940(97)00889-6.
7. Ma ZZ, Wu JJ, Cao Z, et al. Motor imagery-based brain-computer interface rehabilitation programs enhance upper extremity performance and cortical activation in stroke patients. *J Neuroeng Rehabil.* 2024; 21:91. doi:10.1186/s12984-024-01387-w.

8. Oberman LM, Hubbard EM, McCleery JP, Altschuler EL, Ramachandran VS, Pineda JA. EEG evidence for mirror neuron dysfunction in autism spectrum disorders. *Brain Res Cogn Brain Res*. 2005;24(2):190-8. doi: 10.1016/j.cogbrainres.2005.01.014.
9. Zhang J, Chen W, Gu Y, Wu B, Qi Y, Zheng X. Classifying real and imaginary finger press tasks on a P300-based brain-computer interface. In: 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 2011. p. 6356-9. doi:10.1109/IEMBS.2011.6091569.
10. Hanakawa T, Immisch I, Toma K, Dimyan MA, Van Gelderen P, Hallett M. Functional properties of brain areas associated with motor execution and imagery. *J Neurophysiol*. 2003;89(2):989-1002. doi:10.1152/jn.00132.2002.
11. Haaland KY, Elsinger CL, Mayer AR, Durgerian S, Rao SM. Motor sequence complexity and performing hand produce differential patterns of hemispheric lateralization. *J Cogn Neurosci*. 2004;16(4):621-36. doi:10.1162/089892904323057344.
12. Rojas GM, Alvarez C, Montoya CE, de la Iglesia-Vayá M, Cisternas JE, Gálvez M. Study of resting-state functional connectivity networks using EEG electrodes position as seed. *Front Neurosci*. 2018; 12:235. doi:10.3389/fnins.2018.00235.
13. Salvaris M, Sepulveda F. Classification effects of real and imaginary movement selective attention tasks on a P300-based brain-computer interface. *J Neural Eng*. 2010;7(5):056004. doi:10.1088/1741-2560/7/5/056004.
14. Machado S, Arias-Carrión O, Paes F, Ribeiro P, Cagy M, Piedade R, et al. Changes in cortical activity during real and imagined movements: an ERP study. *Clin Pract Epidemiol Ment Health*. 2013; 9:196-201. doi:10.2174/1745017901309010196.
15. Ragot R. Perceptual and motor space representation: an event-related potential study. *Psychophysiology*. 1984;21(2):159-70. doi:10.1111/j.1469-8986.1984.tb00199.x.
16. Kurgansky ME, Isaev MR, Bobrov PD. Dynamics of EEG synchronization and desynchronization when performing real and imagined hand reaching. *I P Pavlov J Higher Nerv Act*. 2024;74(2):210-22. doi:10.31857/s0044467724020069.
17. Galdo-Alvarez S, Bonilla FM, González-Villar AJ, Carrillo-De-La-Peña MT. Functional equivalence of imagined vs real performance of an inhibitory task: an EEG/ERP study. *Front Hum Neurosci*. 2016; 10:467. doi:10.3389/fnhum.2016.00467.
18. Bruno V, Ronga I, Fossataro C, Capozzi F, Garbarini F. Suppressing movements with phantom limbs and existing limbs evokes comparable electrophysiological inhibitory responses. *Cortex*. 2019; 117:64-76. doi: 10.1016/j.cortex.2019.02.024.

How to cite this article: Jitendra Kumawat, Anuradha Yadav, Preeti Sharma. Comparative analysis of P300 latency and amplitude during real and imaginary hand movements among healthy adult subjects. *Int J Health Sci Res*. 2026; 16(1):289-297. DOI: <https://doi.org/10.52403/ijhsr.20260134>
