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ABSTRACT

Electroencephalography (EEG) provides the temporal resolution required to map the neural activations for studying motor movements and control. This study aims to compare the power amplitude of electrodes covering the central and frontal regions of a 32-channel scalp EEG. The activations from a standard index finger-tapping and a game paradigm are analyzed. Twenty-five right-handed and five left-handed healthy subjects (range = 18–30 years; mean = 24.25 years; SD = 3.96 years) participated in this study. A novel single-frequency filter (SFF) bank was applied to identify the peak amplitude from the power spectral density plots. The results show that the gaming paradigm yields lower or comparable power amplitudes than the standard finger tapping. We observed that the right-hand finger tapping by the left-handed subjects shows lower between-subject dispersion in amplitude. Nonparametric Spearman correlation showed no association between game scores and power amplitude for the right-handed participants. However, for left-handers, both positive and negative associations were observed. This study demonstrates the efficacy of SFF for extracting power amplitudes with a better signal-to-noise ratio, which has implications in BCI and motor rehabilitation applications. The findings support the role of game paradigms for motor movement research and in understanding bilateral hemispheric activations in cognitive tasks.

1. Introduction

Understanding the brain activity in motor movement and control is critical for therapy, building assistive systems, and brain-controlled interfaces. The series of complex motor actions performed routinely, such as climbing stairs, playing games, typing on a keyboard, riding a bicycle, etc., are derived from basic movements classified as either discrete or rhythmic [23]. Discrete movements are acquired based on learning capacity, while rhythmic movements are inbuilt structurally in our brain. In previous works, it has also been shown that rhythmic movement engages lower-order cortical planning at the neural level than discrete movements [42]. Hence, the disruption in rhythmic movements due to the ischemic stroke (subsequent paralysis), injury or age-related motor degeneration are detrimental to quality life and require extensive neurorehabilitation. Though studies have established the relation between motor action and brain activity by using functional magnetic resonance imaging (fMRI), EEG, or MEG [16,22], the differences in the ipsilateral and contralateral cortical activations for simple motor actions and associated functional connectivity are not fully understood. The focus of the current study is to map the neural activations supporting simple index finger tapping action. Towards this, we performed a comparative analysis of the activations in electrodes covering the central and frontal part of a 32-channel scalp EEG. The participants engaged in finger tapping triggered by a visual cue and a digital game (designed and developed for this experiment). The game interface displays scores as a reward or motivation. Further, we compare the differences in right and left-handed participants in the right-hand index tapping tasks. The findings from the study add to the understanding of brain control of hand movements and application to (re)learning of a motor action.

1.1. Background

Functional neuroimaging techniques like electroencephalogram (EEG) have shown that actual and observed actions stimulate an extensive network of perceptual and motor areas [15,34]. EEG and Magnetoencephalography (MEG) are non-invasive methods to understand how movements are encoded or decoded in the primary motor area of the brain, essential for therapy and neurodegenerative disorders interventions. In addition to the neuroscience and clinical understanding of learning networks, EEG as a technique has been widely tested for

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Brain-computer interface (BCI) assistive systems due to the higher temporal resolution [6,31]. For BCI applications, the steady-state movement-related cortical potentials (SSMRCPs) characterized by repetitive finger movements [16] are highly accurate. This event-related potential in the sensorimotor region were also observed for motor imagery and applicable as the control signals in BCI applications. The sensorimotor system is essential for basic motor learning tasks [30]. Understanding the activations in these brain regions is imperative to model neurodevelopmental changes, a well-learned motor action [44], or re-learning in therapy.

The ability of the human system for (re)learning is attributed to the plasticity of the brain [43], commonly referred to as neuroplasticity; an ability of neurons and their connected networks in the brain to alter their associations and behavior response to new concepts, sensory inputs, developments, injury, or dysfunction. These changes range from an individual neuron making new connections to systemic improvements like cortical remapping [39,49]. The brain’s plasticity is essential for cognitive and motor learning [26,50] supported by feedback from the higher-level cortical areas to sensory regions [40]. Thus, learning induces neuroplasticity in the brain, and newly gained information modifies the neural maps, pathways, or circuits that include billions of neurons and synapses [54,10]. The brain activations measured by neuroimaging techniques while performing the upper limb’s motor actions are analyzed to understand motor actions subservient to neuroplasticity. Specifically, the EEG signals captured while performing limb movements like finger tapping, arm movement, flexion, extension, clenching, and natural gestures have shown consistent changes in the 8–12 Hz (alpha band) and 13–28 Hz (beta) frequency bands [55] have been of interest to estimate neuroplasticity. The most studied movement is the simple finger tapping, especially index finger [32,35,38,47,52] and the activation mapped to the motor cortex region of the brain. Extending the research on motor action and underlying inter and intra hemispheric responses, this paper reports findings from an EEG experiment with two paradigms using an index finger tapping action.

1.2. Ipsilateral and contralateral cerebral activation
 Neuroimaging studies suggest that the contralateral primary motor area, the ipsilateral frontal and parietal areas were activated even for a simple finger movement. Allison et al. [3] found that contralateral cerebral activation and ipsilateral cerebral deactivation are associated with unilateral hand movements. That is, for (non)dominant hand, the contralateral primary motor cortex and premotor cortices and the bilateral supplementary motor areas were all activated. Though in another study [37], for the non-dominant hand, the ipsilateral primary motor cortex was deactivated, and no ipsilateral deactivation was observed for the dominant hand. Irrespective of the laterality, Wu et al. [59] observed significant differences in the EEG activity recorded between the right-handed and left-handed groups. The authors also observed higher EEG activity in the right-handed subjects than the left-handed subjects. We extend the research on laterality in a right-hand index finger tapping action by right-handers and left-handers.

1.3. Game paradigm
 According to Ahissar & Hochstein [2] and Kramer & Colcombe [25], cognitive and motor activities should be intellectually stimulating to maximize the brain responses. EEG signals, when engaged in gameplay, provide insights into cognitive processing like attention [11,18], decision making [19], emotion identification [8], cognitive rehabilitation [7], motor-rehabilitation [5]. The argument for using games is motor learning being contingent on rewarding mechanisms [45,47]. In particular, reward and related motivated processes are considered critical factors in enhancing plasticity [12,56] and control plasticity [12]. Hence, interactive and immersive mediums such as games can provide insights into the role of motivation, attention, and skill (scores as measurement) on motor action.

2. Scope of the research
 Though EEG studies using finger-tapping paradigms are reported, few explore differences in activations by testing with multiple tasks (gaming). Second, there is a sparse understanding of the differences in the bilateral activations by left-handed and right-handed subjects in a finger-tapping task. Third, a novel single-frequency filter bank with a better signal-to-noise ratio compared to standard FFT or wavelet analysis methods is proposed to extract the power amplitudes.

As a premise or hypothesis, we expect higher power (amplitudes) in the frontal electrodes for the game paradigm. The right and left-handers are compared to examine for activation differences in the motor and frontal area electrode signals and correlate the same to performance (scores in the game). The findings from the control group (non-clinical) recruited for this study can be a reference model for designing interventions for stroke, spinal cord, or motor degeneration patients.

3. Methodology
 This study was conducted in two parts. First, participants were instructed to tap on a marked surface on the table with their right-hand index finger on a visual cue (+ sign) displayed on an LCD monitor. In the second part, the tap on a laptop’s touchpad was the interface to the game.

3.1. Participants
 The Ethics Committee of the International Institute of Information Technology, Hyderabad, India approved the study. Further, informed consent was obtained from each subject before recruitment into the study. The participants could exit the study at any time without explicitly citing a reason. An honorarium (INR 300) for each was credited. Twenty-five right-handed and five left-handed healthy male subjects (age = 18–30 years; mean = 24.25 years; SD = 3.96 years) volunteered for the study. The EEG data was collected independently for the two paradigms. All subjects had an unremarkable neurological condition and were not receiving any pharmacological treatment at the time of the recordings. BrainVision actiCHamp (32-channels) was used to record the EEG signals. Acticap offers much lower noise levels as it combines active electrodes based on Ag/AgCl sensors where impedance conversion occurs at the electrode level. Electrodes on the actiCAP were placed in accordance to the 10/20 international system.

3.2. Experimental paradigm
 Before the finger-tapping cue, the participants were requested to execute relaxation procedures like deep breathing followed by 2-min resting-state. Participants were asked to perform a finger tapping on a motor paradigm designed on the OpenSesame software [27]. The paradigm requires ten trails of recurring taps (Fig. 1) on a visual cue (+ sign) presented for 2 s with the right-hand index finger. A gap of 6 s interspersed each trial.

An interactive game (Fig. 2(A)) was designed on the Unity3D game engine for the next part. The gameplay and mechanics is based on an outdoor game called ‘seven stones’. An ancient game traced to the Indian subcontinent involving a ball and a pile of flat stones, generally played in a large area by two teams. The aim is to knock the pile of stones with the ball thrown from a distance of 10–12 feet and re-stack it while being attacked by the opponent team. For the experiment, it was re-designed as a single-player game. The pile of stones is fixed, and a ball hovers on a track (the blue/yellow strip shown in Fig. 2(A)). The player must align the ball (manoeuvre onto the yellow ribbon) with the pile of stones and release it (finger tap on the touchpad) to knock off the maximum number of stones. The corresponding timestamp is stored on
the CPU. Scores calculated as per hit accuracy are displayed to increase the engagement. For a perfect hit (when the pile collapses), the maximum score was awarded. In the gameplay, the participants’ scores act as a motivation and increase attention to the task. Hence, it provides challenges at various multisensory inputs and skill levels. The user interface and gameplay was designed for stroke/injury patients and, therefore, very simple.

3.3. Pre-processing and artefact removal

EEG signal processing and statistical analysis were performed in MATLAB, 2020b software. The EEGLAB toolbox was used to process time-series EEG data [14]. A flow chart representation of the pre-processing is provided in Fig. 3(A). As shown in Fig. 3(B), electrodes corresponding to the prefrontal, frontal, and motor cortical scalp area were considered in this study.

To cancel the outward positive currents with the inward negative currents, EEG signals were referenced to the common average. Further, baseline noise was removed by subtracting the mean from the raw signal [53]. To remove the low-frequency and high-frequency components, a bandpass filter with a cut-off frequency of 1 Hz and 50 Hz, respectively, was applied to the EEG signals and the signals were sampled at a frequency of 500 Hz (Fig. 3(A)).

Sinusoidal artefacts, a prominent noise component in recorded electrophysiological data was removed to reduce the effects of alternating current (AC) power line fluctuations and from other power sources. Subsequently, Independent Component Analysis (ICA) was performed to remove the artefacts.
applied to remove the artefacts from eye blinks and physiological activity (pulse rate mainly). The Independent Components (ICs), with high artefact probability, were identified by visual inspection and removed using the Multiple Artifact Rejection Algorithm (MARA). MARA is a supervised machine learning algorithm trained from the expert rating of 1290 components [58]. Hence, it can handle eye artefacts, muscular artefacts, and artefacts generated due to noisy electrodes.

3.4. Data analysis

For the standard rhythmic paradigm & the game paradigm, time-locked trials of length 4sec were obtained by extracting 2 sec before and 2 sec (−2 to +2) after the onset of a finger tap. The data from all the participants were concatenated, leading to 300 (10 trails × 30 participants) data points (peak amplitude) for the standard finger tapping and 840 (28 trails × 30 participants) taps for the game paradigm. Finally, outliers were detected using the interquartile range (IQR) method, and the detected outliers were removed from the dataset. The game paradigm had 504 trials, while the standard tapping had 169 trials. Using the Single frequency filtering (SFF) algorithm on the epoched EEG data, time–frequency analysis was carried out. The peak value corresponding to the maximum amplitude was extracted from the epoched segment. The novel SFF method was introduced for voice detection [4] and applied for the first time on EEG signals. A sample run of the standard Hilbert-Huang method and the SFF on one participant data is presented in the Fig. A1 for comparison. As the spectrograms indicate, the SFF method seems to show higher temporal resolution at lower frequencies. The comparative analysis between left-handed and right-handed subjects was conducted with data from five randomly selected right-handed participants set (from the twenty-five) and five left-handed subjects. The left-handed subjects played the game with their right hand.

3.5. Statistical analysis

Spearman’s rank correlation coefficient examined the relationship between the activation energies for the peak amplitude of the electrodes in the bilateral pairs covering the frontal, prefrontal, and motor areas (FC1, FC2, F3, F4, FP1, FP2, C3, C4, CP1, CP2, C6, and CP5) for both the paradigms. The scores were also included for the game paradigm to check for correlations between performance and peak amplitude. The non-parametric Mann-Whitney U test was used to test the group differences in the activation energies of gaming and the standard paradigm. The Friedman’s two-way ANOVA test with factors: Group (Game finger tapping, Standard finger tapping) and Channels (FC1, FC2, F3, F4, FP1, FP2, C3, C4, CP1, CP2, C6, and CP5) was applied to check for significance in the contralateral and ipsilateral electrodes pairs. The statistical significance threshold for both tests was set at \( p < 0.05 \).

3.6. Single frequency filtering: analysis of EEG data

The spectral EEG helps to reveal the hidden asymmetries of the brain [13]. In our analysis, we applied a novel Single Frequency Filtering (SFF) algorithm to analyze the non-stationary EEG signals in the time–frequency domain. In the case of non-stationary EEG signals, power is non-uniformly distributed across frequencies. Hence, the signal-to-noise ratio is higher in some frequencies and lower for others. The high-resolution property of SFF results in a higher value of the signal-to-noise ratio in time and frequency domains [4].

Single-frequency filter bank (SFFB) is an extension of the SFF and was used to decompose the EEG signal into different frequency bands. The filter bank [20] is a signal processing technique that uses a bank of complex band-pass filters to decompose the input signal into different components at high spectro-temporal resolution and outputs the power spectral density of the time-series EEG data. In our analysis the amplitude envelope was extracted at each frequency.

The transfer function of Single frequency filtering was given by:

\[
H(z) = \frac{1}{(1 - az^{-1})}
\]

where \( a \) indicates the location of the pole and determines the bandwidth of the single-frequency filter. In this study, we picked \( a = 0.995 \) so that filter bandwidth is equivalent to 0.001 Hz. Equally spaced frequency-modulated single-frequency filters form the core of the single-frequency filter banks, and the transfer function for the frequency modulated SFF was given by:

\[
H(z) = \frac{1}{(1 - a \omega^{-1})}
\]

where, \( a_0 = a^{\exp(-j\omega_0)}, \omega_k = (2\pi f_\omega k)/f_s \), \( \omega_k \) : kth frequency component of the signal

\( f_s : \) Sampling rate

Thus, the EEG signal was divided into M frequency components, and a single frequency filter bank was given by:

\[
S_{\text{filterbank}} = [H_1(w)H_2(w)\ldots H_M(w)]^T
\]

where \( k = 1, 2, 3, \ldots M \)

The frequency components from 1 Hz to 50 Hz were decomposed with a frequency resolution of 1 Hz. The kth filter response \( y[k] \), and the corresponding envelope of each filtered component \( m[k] \) were given by:

\[
y[k] = \sum_{n=0}^{N} h[k]
\]

\[
m[k] = (y_{\text{re}}[k] + y_{\text{im}}[k])^{1/2}
\]

\( Y_{\text{re}}[n] \) and \( Y_{\text{im}}[n] \) are the real and imaginary parts of the filtered component \( y[k] \). EEG signal is represented by \( x[n] \) and \( n \) is the discrete-time variable.

The amplitudes of the power spectral density plots were extracted for each trail from the above method. The spectro-temporal resolution is essential to extract the changes in the signal due to the tapping action and not so much the particular frequencies indicating the change. Hence, we applied the single-frequency filter bank to achieve higher resolution than the traditional bandpass filtering, short-time FFT, or continuous wavelet transform analysis using the sliding window method.

To illustrate the spectro-temporal resolution, a sample spectrogram of a single participant’s data from the standard Hilbert-Huang method and the SFF is provided in the Fig. A1.

4. Results

We first present the activation strength estimated from the power amplitude of electrodes covering the scalp’s central and frontal regions, followed by comparing the standard finger-tapping and the game paradigm for the right-handed participants. Next, the analysis for the right and left-handed participants in the right-hand one-finger tapping exercise is presented.

4.1. Finger tapping in Right-handed participants

The differences in activation energy for hemispheric lateralization, comparative analysis, and seed-based Spearman correlation analysis were conducted for the standard finger tapping and gaming paradigm. Additionally, we estimated the correlation values for activation energy and game scores in the game paradigm.

4.2. Variation in activation energy - Game and standard paradigm

Twelve electrodes on the ipsilateral and contralateral hemispheres covering the central and frontal part of the scalp were considered. Quantified EEG had a significantly higher amplitude during the motor exercise.
movements as reflected in the signal’s power spectrum (Fig. A2). The median power for the frontal electrodes was comparable for the two paradigms (Fig. 4(A, B)), while central electrodes show relative differences (Fig. 4(C, D)). The data was also symmetrical, relatively tightly grouped and skewed towards the upper quartile.

4.3. Laterality analysis - game and standard finger tapping

Independent of the paradigm, right finger tapping EEG data shows higher contralaterality at the FP1 electrode (see Fig. 4(A)), than the FP2 (ipsilateral) (Friedman test, gameplay: \(\chi^2(1) = 40.654\) and p-value < 0.001 and std. Template: \(\chi^2(1) = 4.667\) and p-value = 0.031). Similarly, the activation energy at FC1 was significantly higher than the FC2 electrode (Friedman test, gameplay: \(\chi^2(1) = 30.078\) and p-value < 0.001 and std. Template: \(\chi^2(1) = 22.881\) and p-value < 0.001). The gaming paradigm shows significantly higher activation energy at F3 than F4 (Friedman test, gameplay: \(\chi^2(1) = 8.400\) and p-value = 0.004), whereas no significant difference was seen in the case of the standard template paradigm. Among frontal electrodes, FP2 shows the lowest activation energy, while F3 and F4 have the highest (see Fig. 4(A) & (B)).

The activation energy in the central or motor cortical surface electrodes show no clear laterality trend. The gaming paradigm shows significantly higher activation energy at C4 than C3 (Friedman test, gameplay: \(\chi^2(1) = 21.918\) and p-value < 0.001), whereas no significant difference was seen in the case of the standard template paradigm. In both the paradigms, the activation energy at CP1 was significantly higher than the CP2 electrode (Friedman test, gameplay: \(\chi^2(1) = 177.736\) and p-value < 0.001 and std. Template: \(\chi^2(1) = 34.381\) and p-value < 0.001). Irrespective of the paradigm, the activation energy at the CP5 electrode was significantly lower than that of CP6. (Friedman test, gameplay: \(\chi^2(1) = 264.861\) and p-value < 0.001 and std. Template: \(\chi^2(1) = 36.214\) and p-value < 0.001). Among central electrodes, C3 and C4 show the lowest activation energy, while CP5 and CP6 have the highest (see Fig. 4(C) & (D)).

4.4. Comparative analysis between paradigms

Activation energy at FP2 electrode was significantly higher in the standard finger tapping than the gaming paradigm (Mann–Whitney U = 34572.00; n1 = 503, n2 = 168; p-value < 0.001 two-tailed).

Among the central electrodes, activation energy at CP1, CP2 and CP5 were significantly higher in the standard finger tapping than the gaming paradigm (CP1 :: Mann–Whitney U = 35572.00; n1 = 503, n2 = 168; p-value = 0.002 two-tailed; CP2 :: Mann–Whitney U = 31264.00; n1 = 503, n2 = 168; p-value < 0.001 two-tailed; CP5 :: Mann–Whitney U = 33496.00; n1 = 503, n2 = 168; p-value < 0.001 two-tailed).

The electrodes F3, F4, and C3, C4 show no significant difference among the two paradigms.

4.5. Seed-based correlation analysis of the frontal and central electrodes

The full Spearman Correlation matrix across all electrodes and conditions is provided in Fig. A4. In this section, the coefficients with C3 and C4 as seed is discussed and represented in a plot (Fig. 5). For the contralateral electrode, C3 considered as seed, the standard finger tapping reflects higher correlation values for the frontal and central electrodes, especially for Fp1, F4, FC2, CP5, and CP6 (Fig. 5(A, C)). Independent of the paradigm, ipsilateral frontal electrodes show higher correlation than their respective contralateral electrodes. In comparison, the contralateral central electrodes show higher correlation than the corresponding ipsilateral electrodes.

The standard finger tapping shows higher values for the ipsilateral electrode (i.e., C4) (Fig. 5(B, D)) for frontal and central electrodes. Similarly, for the gaming paradigm, high correlation values were observed. Independent of the paradigm, ipsilateral central electrodes show higher correlation values than the contralateral central electrodes (Fig. 5).

4.6. Activation energy and correlation to the game scores

In the gaming paradigm, frontal and central electrodes negatively correlate with the scores (Fig. 6), i.e., activation energy decreases as the score increases. Correlation values of the prefrontal electrodes (i.e., FP1, FP2) were almost zero, whereas other frontal electrodes showed marginally negative values (Fig. 6(A)), though only FC1 and FC2 were significant (Fig. A4). The electrodes C3, CP1 & CP2, showed a small but
negative correlation, while only C3 and CP1 were significant.

4.7. Comparative analysis between left-handed and right-handed participants

The activation energy for the electrodes and the Spearman correlation analysis across the standard finger tapping and the gaming paradigm are presented in the following sections.

4.8. Variation in activation energy

The left-handed participants’ box-whisker plots of the activation energy in the selected electrodes show minimal dispersion, i.e., fewer outliers (Fig. 7(B, D)). The right-handed participants’ activation energy distribution in quartiles was higher (see Fig. 7(A, C)). Interestingly, the median values for the ipsilateral electrodes (C4, CP2, and CP6) are slightly lower than mirror contralateral electrodes in the left-handers. In contrast, an opposite trend was observed for the right-handers (except for CP2 (<CP1)). In the frontal electrodes, the median value for Fp2, F4 was higher in the left-handers while it was lower for Fp2, while only F4 was higher in the right-handers.

4.9. Spearman correlation analysis w.r.t. contralateral and ipsilateral electrodes

The correlations values of the contralateral (C3) with same-side (intra-hemispheric) frontal and central were positive and high for both left–right handers in the game paradigm (Fig. 8). In contrast, C3’s correlation with ipsilateral central electrodes was not significant for left-handers. The values suggest stronger inter-hemispheric central connectivity for right-handers. The connectivity to frontal electrodes of both hemispheres is similar (montage EEG representation in Fig. A6). The correlation matrix for all electrodes pairs is included in Fig. A5.

With the ipsilateral (C4) central electrode, the right-handers intra-hemispheric correlations were positive and significant except with CP6, while in the left-handers, except for CP2 no significant correlations was observed for frontal or central electrodes. The inter-hemispheric connectivity with C4 was stronger across the electrodes for right-handers while it was low or not significant for the left-handers. Taken in conjunction, the right-handers seem to definitely recruit both ipsi and contralateral hemispheres, while a similar trend is not observed in the left-handers.

4.10. Correlation with game scores

Only F4, FC1, C3 and CP2 for the left-handers and no electrode among the right-handers cross significance (Fig. 9, correlation matrix Fig. A5). Hence, the correlation analysis indicates the gaming scores and the activations in the right-handed participants show a lower association. In contrast, for left-handers, both positive and negative correlation values were observed.
5. Discussion

We investigated the neural activations supporting simple movements like finger tapping in a visual cue modulated tap and in the game paradigm. A novel time–frequency method, single-frequency filter bank, was applied to reduce the spectral leakage observed in standard FFT. The amplitude (peak power) from the signal analysis was extracted for each trial in a four-second window (2 sec before and 2 sec after the tap). We compared the differences in peak amplitude for the right/left-handed participants. The self-motivated finger tapping for the game was examined by running a correlation analysis of the game scores and the peak amplitude of the power (activation energy) in the selected electrodes. Using seed-based correlation analysis, the functional connectivity between ipsilateral and contralateral central electrodes was estimated to make inferences about inter & intra hemispheric connectivity as a possible model of neuroplasticity.

5.1. Game versus standard finger tapping

The gaming paradigm shows lower (especially in FP2, CP1, CP2, and CP5) or comparable amplitudes (F3, F4, C3, and C4) to the standard finger tapping. This is contrary to our initial premise of gameplay.
evoking higher activations in the central areas. A possible explanation for the lower peak power amplitude could be the cognitive and motor action processing sequences required for the game: planning, controlling, and executing a slower process than the event or impulse triggered tap as performed in the standard tapping exercise. Our findings support some of the previously reported studies where the specific frequency bands were analyzed. The role of the prefrontal cortex in decision-making and control of motor actions has shown a decrease during video gameplay [28]. Studies have found that the frontal midline, localized as the anterior cingulate cortex by dipole models, showed a theta rhythm increase for memory load while alpha signals decreased in high-load tasks [17]. Pellouchoud et al. [36] also reported suppression of alpha amplitude during play conditions, contrary to the expectation that a task like the game requires greater attention or concentration. They attribute it to the higher visual stimulation from the game suppressing the alpha frequency. However, a recent study [33] using various games involving higher cognitive skills found that the game shows higher activation in the frontal lobe electrodes. As a possible explanation, the game presented in our study requires minimal cognitive processing and primarily engages the visuomotor system, which might explain the lower activation. But, our finding needs to be explored further with more complex visuomotor control games to make more robust inferences.

5.2. Bilaterality – Game and standard finger tapping

Two contralateral hemispheric frontal electrodes (FP1 > FP2; FC1 > FC2) show higher activation for both the paradigms and F3 > F4 only for the game. The recruitment of the frontal lobe for cognitive tasks has been reported, while most motor action examinations like finger tapping EEG studies, only consider the activation of the central and parietal electrodes. Thus, our study hypothesizes cognitive processing due to the experiment setup – the visual cue for standard tapping and the gameplay reasoning, hence the activation of the frontal electrodes. The comparable higher activation on the contralateral side requires more experiments to understand the cognitive processing and laterality. The ipsilateral electrode power amplitude was marginally higher in the central electrodes, with CP6 significant for both paradigms. From the pair-wise significance (CP1 & CP2; C3 & C4 etc.), only CP1 (>CP2) was significant for both the paradigms. The findings from only one electrode corroborate the delta band frequency analysis [35] and the study with unilateral hand movements [3]. The electrode-wise differences require further experiments, though a study on encoding of speed information bilateral involvement was observed [60]. While specific electrodes on the same hemispheric side show higher activations, it could be due to the activity of the adjoining sensor, which is highly correlated due to the volume conduction of electrical activity across the scalp surface.

In the seed (C3 & C4) correlation analysis, the calculated coefficients were high and significant for the ipsi and contralateral frontal and central electrodes. This implies the engagement of a more extensive network in task execution, as observed from resting-state data [41]. Comparatively, the standard tapping shows higher positive correlation values for all the electrodes to the game data. We attribute this to the automatic and lower cognitive processing compared to the game. Interestingly, we observed higher correlation values for the contralateral C3 with the ipsilateral frontal electrodes and an opposite effect for the central electrodes in both paradigms. These findings could have a possible explanation of the right hemisphere (ipsilateral in our case), predominating frontoparietal networks [1], associated with goal-directed cognition and integration of information [46,51]. The contralaterality for central electrodes could indicate the motor control and the inter-hemispheric information processing as expected. For the ipsilateral electrode C4, similar to C3, the correlation values are high for both paradigms for the bilateral frontal and central electrodes. In the standard-finger tapping paradigm, the bilateral frontal electrodes show almost equal values. In contrast, for the gaming paradigm, we observe ipsilateral frontal electrodes having marginally higher values than the contralateral frontal lobe electrodes, indicating a differential engagement of the right hemisphere for a cognitive task. Independent of the paradigm, the ipsilateral central electrodes (Fig. 5(b) & (d)) show higher values of correlation than their respective contralateral electrodes. Though the role of ipsilateral activation for motor action is not understood completely, a theory posits inhibition of mirror motor areas controlling the steady hand [9]. This theory is supported by research on mirror neuron firing, particularly in the motor areas for action observed or in imagery (review article: [24]). Though it is premature to make inferences from the laterality differences, studies analyzing the alpha band power symmetry between the left and right frontal hemisphere (reflecting the dorsal prefrontal cortex) have attributed it to motivation [21], further classifying it as increased right frontal activation as an indicator of withdrawal and increased left frontal activation as an indicator of motivation.

Interestingly, game scores and power amplitudes for all electrodes show negative values, with significance levels achieved for FC1 & FC2 and C3 & CP1. The findings imply that as score increases, activation as measured by amplitude decreases. This seems to be counterintuitive and invalidates our hypothesis. A possible explanation is increased attention for a task, inhibiting ‘mind wandering’ [48], or distribution of activation across brain regions in response to the task performance, as supported by the power spectrum amplitude for the game paradigm, which consistently shows lower activation energy. Understanding this difference is essential for the application of games in neuro-rehab to decipher motor response and the cognitive processes engaging the frontal brain areas.

Fig. 9. Spearman Correlation coefficients of score with Motor and Frontal electrodes (A) Frontal electrodes. The frontal electrodes, FP1, F3, and FC2, show a positive correlation coefficients for the left-handers’, and negative values for F4 and FC1 electrodes. (B) Central electrodes. The electrodes, C4 and CP2, positively correlate with the left-handers game scores, while C3, CP5, and CP6 negatively correlate. The values for right-handers is low and nearly constant across the electrodes.
5.3. Left and right-handed

For both paradigms (Fig. 7), the inter-subject variance in the power amplitude for left-handers is lower. The findings suggest possible differential lateralization of finger movements’ neural representation in the right- and left-handed individuals. These results support Wu et al. [59] study, who observed significantly more EEG activity in the right-handed subjects than the left-handed subjects and in contrast with findings from a visually induced self-motion perception wherein both groups showed comparable activations [29]. The seed-based correlation of left-handers ipsilateral C4 shows fewer significant associations with bilateral electrodes than the contralateral C3. The right-handers display higher connections across hemispheres.

In the game task, an interesting difference in the correlation analysis with the scores was observed. The right-handers show no significant association between activation and scores, while left-handers had negative and positive correlations for frontal and central electrodes. The findings indicate lower cognitive or motor effort in right-handers playing with their dominant hand, as in automatic movement. The left-handers show association (+ve or –ve) in the frontal electrodes across hemispheres, implying possible higher visuomotor coordination effort and cognitive processing when using their non-dominant hand in games. The findings are contrary to studies of [37], who report that the ipsilateral primary motor cortex was deactivated in the non-dominant hand. In contrast, for the left-handers playing with their non-dominant hands, we observe high and positive correlation values for the electrodes C4 and C2. But a strong claim could have been made if the task required the right-handers to play the game with their left hand. However, the findings are new and add to the discussions on stimulating cortical changes through sensory-motor learning activities [39,49], especially when re-learning using the non-dominant hand.

The extensive testing of finger-tapping with standard and game tasks, analysis of the power amplitude extracted from a novel single-frequency filter bank method, and the comparative analysis present new insights on activation differences in left/right-handers while supporting existing theories on contra-laterality in motor response. We collected data from non-clinical healthy participants to generate baseline references for motor response impairments due to stroke, injury, or age-related degeneration. It will help us to understand the process of rewiring/neuroplasticity in stroke patients, in particular. Focusing on areas where activation energy is inhibited post-stroke will help us systematically study the brain’s ability to form new connections. The functional connectivity analysis from the power amplitude extracted from power spectral density plots for simple finger movement is particularly important for BCI applications.

6. Limitations and future scope

There are a few factors that limit this study and require further investigation. First, the data was collected from only healthy participants. Second, only the younger age group and all males were recruited in this study. Third, the testing on right-handers using the left hand for gameplay would have further strengthened the findings on gameplay with non-dominant hands by left-handers. In the future, it would be interesting to extend this work to post-stroke patients by using the current results as a classifier.

7. Conclusion

The present study investigated the differential activations in a finger-tapping exercise for two paradigms using EEG. Finger tapping tasks are used to test for motor system disorders, and games as test paradigms increase the motivation and attention to the task. Our study used a visual cue as priming for the standard finger tapping, while the findings can be extrapolated to other sensory cues, for example auditory. An analysis of left-right handers demonstrated the extent and differences in the areas engaged. The incorporation of peak amplitude analysis using a novel single-frequency filtering method provided significant insights into activations at each frequency. The technique is computationally efficient and can be applied for online analysis, BCI applications, and functional connectivity network analysis in clinical settings like surgery. The use of games highlighted the motivation for using a game interface for therapy.

CRediT authorship contribution statement

Arhart Jain: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. Krishna Gurugubelli: Software, Formal analysis, Data curation, Validation, Visualization. Anil Kumar Vuppala: Validation, Supervision. Kavita Venuri: Conceptualization, Validation, Formal analysis, Resources, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References


