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Neuro-signaling techniques in video gaming endorsements: a cognitive and neural dynamics approach

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Abstract

Background and objective: Technological advancements have significantly transformed the gaming industry, shifting from computer to mobile games. According to a global games market report, the gaming market was projected to reach \$180.1 billion by 2021. Consequently, time and money invested in mobile games have risen significantly. The gaming strategy plays a vital role in enhancing conceptual thinking, problem-solving abilities, and cognitive skills. However, comprehensive studies comparing neural dynamics and cognitive skills while playing different types of games using electroencephalography (EEG) signals are still lacking. This study investigates the cognitive and neural effects of action and puzzle video games on brain activity, focusing on memory processing, cognitive load, and alterations in brain rhythms.

Methods: Eighteen healthy adults, aged 17 to 36 years, participated in the experiment, engaging with two distinct games—Modern Warfare 2 (action genre) and Sudoku (puzzle genre). EEG data were recorded using a 14-channel Emotiv EPOC headset, capturing brain signals before, during, and after gameplay. Cognitive performance was assessed using PSYTASK software before and after gameplay to evaluate changes in attention, working memory, and cognitive flexibility. EEG signals underwent pre-processing, followed by wavelet transform decomposition to extract frequency band energy (delta, theta, alpha, beta, gamma) and EEG band ratios. Functional connectivity analysis mapped network-level brain dynamics during gameplay. Statistical analyses between gameplay conditions were performed using paired samples t-tests on EEG features, and a one-way repeated measures ANOVA assessed differences in these parameters across three gameplay conditions (before, during, and after) at 14 electrode locations, with significance set at $p < 0.05$.

Results: Modern Warfare 2 gameplay triggered elevated beta and gamma activity, indicating heightened attention, sensory-motor coordination, and real-time decision-making, while Sudoku gameplay increased theta and alpha activity, reflecting greater working memory load, logical reasoning, and cognitive processing. Functional connectivity patterns demonstrated broader network activation during action gameplay, contrasting with more localized activation during puzzle gameplay.

Conclusion: These findings suggest that action games enhance attention, motor coordination, and executive function, while puzzle games primarily strengthen working memory and cognitive flexibility. This indicates that video games can be effectively used as tools for improving thinking skills in therapy and education.

Keywords: EEG, Cognitive neuroscience, Action video games, Puzzle games, Brain rhythms, Functional connectivity, Cognitive load, Attention, Working memory

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Introduction

Video games have evolved far beyond mere entertainment to become a significant form of social interaction and engagement in the modern world. In 2022, the video game industry projected 3.2 billion players (Gaming Market Analysis APAC, 2025) and reached a market value of USD 196.8 billion, with expectations of increasing to USD 225.7 billion by 2025 as shown in Fig. 1 [1]. The Asia-Pacific region dominated the market with a 46.03% share in 2022. The global video game market is projected to reach approximately USD 664.96 billion by 2033, growing at a compound annual growth rate (CAGR) of 10.32% from 2024 to 2033. This rapid expansion is fuelled by the widespread adoption of augmented reality (AR) and virtual reality (VR) technologies, which offer more immersive and interactive gaming experiences [2].

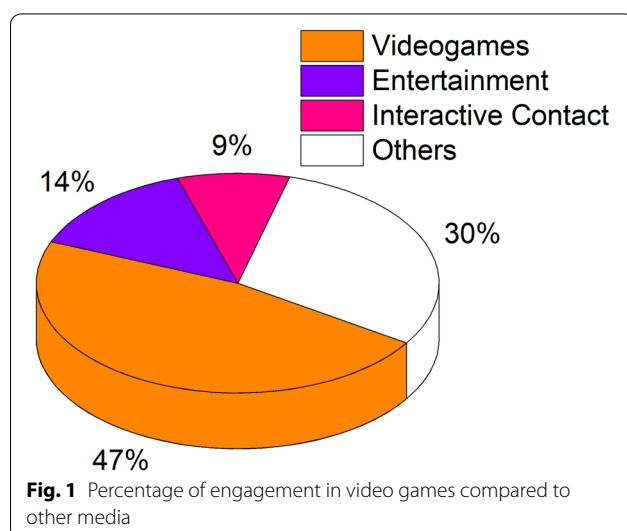
With these technological advancements, researchers have studied how video games impact brain functions, especially in areas like memory, attention, and executive function. One crucial cognitive ability influenced by gaming is working memory (WM), which helps in maintaining and processing active mental information [3]. Video games have been found to improve decision-making, memory, and cognitive flexibility, and they are also used in education to enhance learning, social interaction, and problem-solving skills. However, video games have also been linked to negative effects, particularly violent behaviour. For example, first-person shooter (FPS) games have been associated with aggression and school shootings, especially among middle and high school students, as reported in the media. On the other hand, strategic games improve decision-making, as seen in games like *Defense of the Ancients (DOTA)*, where players analyse different heroes' strengths and weaknesses to form

effective strategies. These games require quick decision-making in dynamic environments, engaging attentional and executive processes.

Studies have shown that action video game (AVG) players perform better than non-gamers (NG) in visuospatial attention [4], short-term memory capacity [5], information processing speed, and task-switching [6, 7]. Regular gamers also have better hand-eye coordination compared to non-video game players (NVGPs). Games such as *Call of Duty* and *Gears of War* demand high levels of attention and memory, requiring players to alternate between focused and distributed attention while reacting to rapidly changing stimuli. Puzzle games, in contrast, emphasize logic, reasoning, and problem-solving, stimulating brain regions associated with cognitive intelligence and attention [8]. Research suggests that playing puzzle games improves attention and executive function [9], while EEG studies indicate that puzzle-solving increases beta wave activity, reflecting improved cognitive performance [10].

Studies have also demonstrated that video game-based interventions can effectively reduce symptoms of depression [11]. Additionally, findings suggest that AVG players exhibit superior performance in short-term memory tasks, particularly in visuospatial memory [12]. While some research reports minimal changes in general memory functions among AVG players, improvements in visuospatial memory have been observed [13]. The cognitive effects of video games on WM accumulate over time, influencing attentional control and problem-solving abilities [14]. Further studies highlight that action games activate the frontal and parietal lobes more intensely than puzzle games, reinforcing the notion that different genres have distinct cognitive effects [15].

A study in [16] examined stress levels in three types of video games: strategic, puzzle, and combinational stimuli, using EEG. It analyzed the power spectral density (PSD) of the Alpha and Beta bands and the Beta-to-Alpha ratio (BAR). The findings indicate that non-gamers experience higher stress than gamers, with strategic games causing the most stress on the brain. During gameplay, the beta band in the frontal region is predominantly activated. Video games significantly contribute to education, skill enhancement, and cognitive development, fostering decision-making, cognitive abilities, and social interaction [5, 17, 18]. Different game genres impact cognition in unique ways. AVGs, such as FPS games, require rapid decision-making, fast visual processing, and strong attentional control [6, 7]. Electroencephalography (EEG) is widely used in research due to its high temporal resolution, non-invasiveness, and cost-effectiveness. It is applied in various domains, including neural engineering, neuroscience, and biomedical engineering, such as



brain-computer interface (BCI) applications [19], sleep analysis [20], stress analysis [16], and seizure detection [21]. EEG provides valuable insights into brain function across different cognitive processes, serving as a foundational tool for analyzing neural activity.

Gaurav et al. [22] employed EEG sensor-based topological dynamics analysis to capture fine-grained temporal fluctuations in cortical activity during gameplay, demonstrating how network-level changes in brain dynamics align with varying levels of engagement and task complexity. Coronel-Oliveros et al. [23] advanced this line of inquiry by applying a semi-empirical whole-brain computational model to show that long-term gaming expertise promotes meso-scale neural plasticity, increasing connectivity strength and efficiency in regions critical for higher-order cognition such as attentional control, reasoning, and inference. Complementary neuroimaging evidence was provided by Fujimoto et al. [24], who used fMRI to examine cue-induced neural activation triggered by gaming-related content on social media. Their results revealed significant correlations between gaming desire and activity in the left orbitofrontal cortex and right superior temporal gyrus, implicating reward valuation and social processing circuits in gaming-related motivation. Similarly, Uijong Ju [25] demonstrated that subjective gameplay experiences are encoded across multiple distributed brain networks, with strong involvement of visual and attentional processing pathways, emphasising the multidimensional and experiential nature of gaming-induced neural dynamics.

In the context of computational methods, Bakkouri et al. [26] proposed the MLCA2F framework, which employs multi-level context attentional feature fusion for COVID-19 lesion segmentation from CT scans, and showed its usefulness in improving automated medical image analysis. Similarly, the BG-3DM2F method has been used for Alzheimer's disease diagnosis through hippocampal analysis, combining a 3D multi-scale chained network with a bidirectional gated recurrent fusion unit, thereby achieving higher accuracy than conventional approaches. In another line of work, Bakkouri and Afdel [27] demonstrated the potential of multi-layer feature fusion in a CAD system for skin lesion recognition, highlighting the effectiveness of integrating multiple feature levels in complex pattern recognition tasks. Multi-scale CNNs based on region proposals have also been successfully applied for breast abnormality detection, further showing the versatility of fusion strategies in improving diagnostic reliability.

The most common approach involves designing mono-user games for traditional computers or video consoles. These games act as distractions or motivators for primary school children undergoing stressful procedures

like venipuncture or those suffering from chronic, neurological, or traumatic conditions [28]. On the one hand, game technologies seem to present physical and psychological benefits to pediatric patients. Neuroscientific research suggests that video games can both enhance and inhibit brain activity. EEG has proven effective in capturing brain dynamics during gameplay. A study investigating the influence of video game genres on attention and distraction suppression under different perceptual loads revealed that AVG players demonstrated superior attentional control compared to strategy video game (STG) players. The findings suggest that AVGs require rapid transitions between distributed and focused attention [29, 30]. However, empirical studies present mixed results, with some highlighting cognitive benefits associated with AVGs [31].

While previous research has shown that different genres of video games, such as action and puzzle games, influence cognitive performance in several ways, there is still a lack of brain dynamic analysis on the impact of different types of video games. Additionally, limited research has examined how these games influence short-term memory cognitive processing and how EEG signals can track these changes in real-time. Most of the existing EEG-based video game studies mainly focus on action games such as first-person shooters (FPS), real-time strategy (RTS); only a few studies focus on other genres such as puzzle, VR, etc. Findings from one genre may not generalize to others. Many studies use frequency bands (theta, alpha, beta) features without exploring advanced features such as connectivity, coherence, entropy, etc. Surface-level analysis may miss deeper brain dynamics related to cognitive effort or memory load during gaming.

To bridge this research gap, the present study examines how video games influence brain activity by focusing on two distinct genres: action and puzzle games. It compares cognitive performance and neural dynamic responses among players of both genres using EEG signals to assess brain wave activity, functional connectivity, WM, and attention, with a particular focus on visual short-term memory tasks. In the present work, we used 13 cognitive indices as features along with EEG frequency band features. To our knowledge, this is the first attempt at analyzing brain dynamics using functional connectivity (graph theory) – FC analysis while playing two genres of video games.

This research evaluates two types of video games—one designed to enhance visual short-term memory and working memory storage, and another aimed at improving logical thinking and cognitive skills in students. EEG data is analysed using energy bands to identify how the brain responds to different cognitive tasks. As a pilot

study, this research seeks to determine whether action or puzzle games are more effective in improving cognitive functions, memory performance, and both short- and long-term memory changes. Brain activity is examined through time–frequency analysis while subjects play different games, and functional brain connectivity is assessed using a graph-theory-based approach to analyze changes in brain rhythms across different game genres. Additionally, the study investigates how video game design influences cognitive skills, particularly in relation to working memory.

The EEG data processing and analysis are conducted using MATLAB (ver. R2024a, MathWorks, Natick, MA, USA), applying advanced signal processing techniques such as wavelet analysis to study variations in brain wave activity [29, 30]. Previous studies suggest that EEG is a powerful tool for understanding neural activity during video gaming, providing insights into cognitive functions and brain processes during tasks [8, 10]

This study contributes to the growing research on video games and cognitive enhancement by utilizing EEG-based analysis to examine brain responses during gameplay, with a focus on band energy ratios as indicators of cognitive load, memory performance, and attention. It also investigates brain functional connectivity using a graph-theory approach to provide insights into how different brain regions coordinate during gameplay. By comparing action video games and puzzle games, this study aims to provide a better understanding of how these genres impact cognitive abilities such as memory, attention, and decision-making. Additionally, it offers potential longitudinal insights into how these games influence brain activity over time and their role in cognitive training.

The findings of this study could have significant implications for cognitive training, learning strategies, and the development of brain-enhancing games for educational and therapeutic applications [5–8, 10, 17, 18, 29–31]. Furthermore, understanding the neural and cognitive effects of different game genres could aid in designing targeted cognitive interventions and brain-enhancing games, benefiting areas such as education, rehabilitation, and skill development.

The remainder of this manuscript is structured as follows: “[Materials and methods](#)” section details the methods and materials, including the research design, participant selection, experimental setup, EEG data acquisition, and analytical techniques. “[Results](#)” section presents the results, while “[Discussion](#)” section discusses the findings in relation to existing literature. Finally, “[Conclusion](#)” section concludes the study, summarizing key insights and potential implications for cognitive training, learning strategies, and the development of

brain-enhancing games for educational and therapeutic applications.

Materials and methods

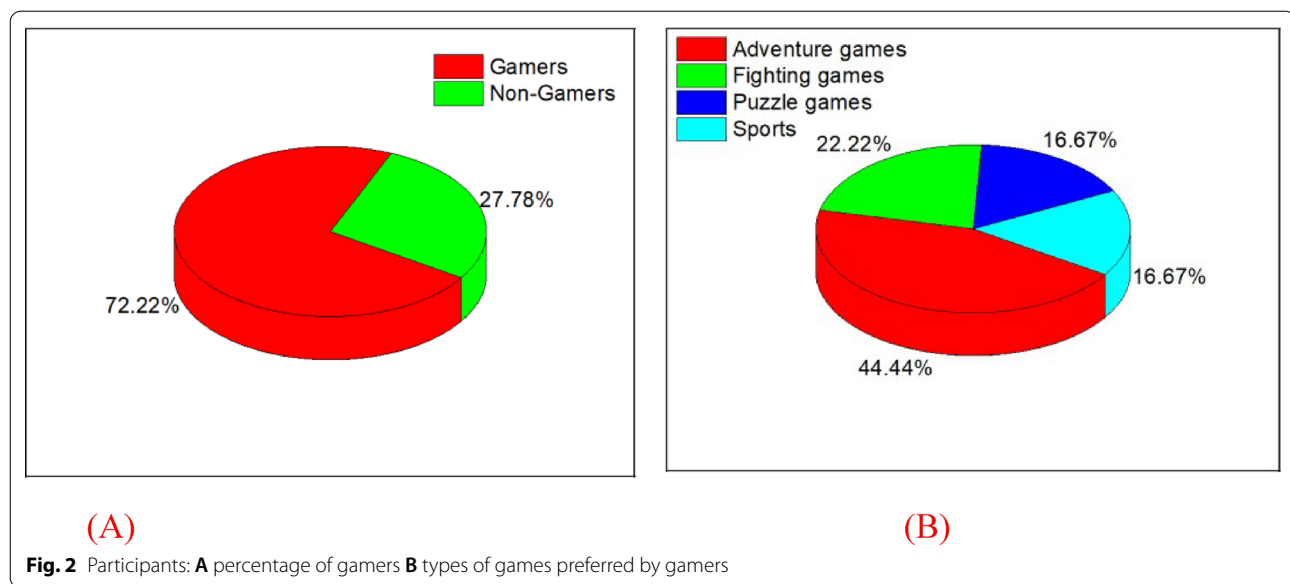
This section details the research design, participant selection, experimental setup, EEG data acquisition, and analytical techniques employed to investigate the cognitive and neural effects of video game engagement. The study was designed to compare brain activity and functional connectivity patterns between action and puzzle video games. EEG recordings were used to capture neural responses, and statistical analyses were performed to identify significant differences in cognitive load, arousal, and executive function. Data preprocessing, feature extraction, and statistical analyses were conducted to assess cognitive and neural responses during gameplay, providing insights into the differences between the two game types.

Ethical approval and participant recruitment

The study was approved by the our university’s Ethical Review Board, and participation was voluntary. Each participant’s guardian signed a written informed consent, and the participants provided oral informed consent before participation. The study was conducted in accordance with the declaration of the University.

Eighteen healthy volunteers, consisting of 16 males and 2 females, aged between 17 and 35 years, were recruited for the study. The sample comprised 88.9% males ($n=16$) and 11.1% females ($n=2$). Among the participants, 72.2% reported prior gaming experience, whereas 27.8% identified themselves as non-gamers. The genre distribution among gamers revealed that 44.4% preferred adventure games, 22.2% favoured fighting games, 16.7% enjoyed puzzle games, and another 16.7% reported a preference for sports games. These details are presented in Fig. 2: (A) Gamer versus non-gamer classification; (B) Distribution of preferred game genres.

All participants were right-handed to minimise the confounding effects of hemispheric lateralisation. Individuals with any history of neurological disorder, hearing impairment, or ongoing medication were excluded. Screening ensured that none of the participants had received formal video game training. All had normal hearing ability and normal dietary intake before the experiment. The experimental sessions were carried out in the morning in a soundproof room, with participants seated comfortably to minimise muscular artefacts. One subject with signs of cognitive impairment and hearing difficulty was excluded from the dataset. The cognitive health of the participants was assessed using the Mini-Mental State Examination (MMSE), which evaluates various cognitive functions such as



language, orientation, memory, responsiveness, and visuospatial abilities, with scores ranging from 0 to 30. A score above 25 indicates normal cognitive status, ensuring that all participants were fit for the experimental recording.

Video game selection and experimental design

Two video games were selected for the study: *Modern Warfare 2* and *Sudoku*, as shown in Fig. 2. *Modern Warfare 2*, developed by Infinity Ward and released by Activision in 2009, is an action video game that involves fast-paced decision-making, attention, and emotional responses as depicted in Fig. 3A. Player performance was tracked based on metrics such as enemies eliminated, mission completion times, and civilian casualties. In contrast, *Sudoku*, a puzzle game, focuses on problem-solving, memory, and pattern recognition as shown in Fig. 3B. Performance was evaluated based on the number of moves taken, elapsed time, best completion time, and percentage of the grid filled. These metrics incentivized strategic decision-making and cognitive efficiency.

Before each gameplay, participants completed a two-minute cognitive task using PSYTASK® both pre- and post-gameplay to assess cognitive changes. Each 15-min gameplay session was spaced one day apart, with randomized order to mitigate order effects. PSYTASK®, a psychophysics and psychophysiology research tool, required participants to respond to or ignore visual and auditory stimuli. A mental arithmetic task was also included, with omission and commission errors recorded in an integrated database to evaluate cognitive performance. Throughout the experiment, EEG data were continuously recorded using scalp-mounted equipment to

analyse neural responses. The experimental protocol is summarized in Fig. 4.

After each gameplay session, participants completed a self-assessment questionnaire consisting of ten questions adapted from [32]. These questions evaluated various aspects of player engagement, including effort, time perception, immersion, enjoyment, perceived challenge, performance, emotional attachment, appreciation of graphics, overall satisfaction, and willingness to play again. The responses provided insights into player experience and informed potential improvements in game design.

EEG data acquisition and preprocessing

The hippocampus plays a crucial role in memory consolidation, learning, spatial navigation, and perception. While short-term memory processes are primarily associated with the prefrontal cortex, long-term memory functions involve the hippocampus (located in the temporal lobe), the neocortex, and the amygdala. The study employed the Emotiv EPOC X wireless EEG headset with 14 saline-based electrodes and 2 reference electrodes (P3–CMS and P4–DRL), positioned according to the 10–20 international system (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4). Data were sampled at 256 Hz with a 14-bit ADC, and connectivity was maintained via bluetooth low energy (BLE). The device consists of strategically positioned saline-based electrodes placed according to the international 10–20 electrode placement system, as illustrated in the Fig. 5, ensuring comprehensive scalp coverage. Additionally, reference electrodes were positioned behind the ears to enhance signal quality. The design enables balanced

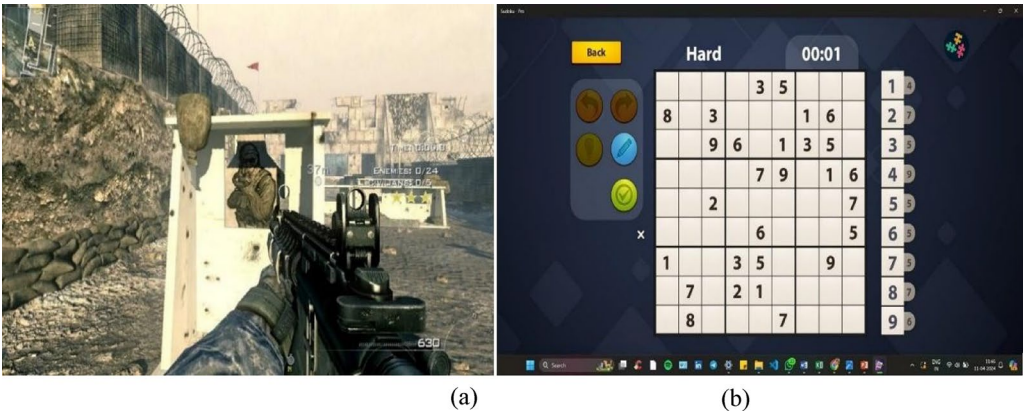


Fig. 3 Gameplay stimuli screenshots **a** Sudoku—a puzzle game focused on logic and memory. **b** Modern Warfare 2—an action game requiring fast decision-making

spatial coverage of cortical sites implicated in attention, memory, motor control, and visual processing during gameplay. The electrode contact quality was monitored throughout the recording and visually represented in real time on the acquisition interface. The status was coded by colour: green indicated good conduction and impedance, black represented no contact, red denoted poor impedance, and orange indicated moderate contact quality. Figure 5 illustrates the electrode layout and corresponding contact status.

Before initiating the EEG data acquisition process, the device’s sensors were immersed in saline solution to ensure optimal conductivity and high-quality signal capture. The experiment was conducted in an acoustically controlled, noise-free laboratory to minimize external

interference. Proper synchronization between the headset and the Software Development Kit (SDK) was maintained throughout the experiment to eliminate the possibility of acquiring false signals. Participants engaged in two different gaming conditions—an action video game (Call of Duty—COD) and a puzzle-based game (Sudoku)—while EEG data were recorded. The experimental setup and participants wearing the EEG headset during gaming sessions are illustrated in Figs. 6a and b.

EEG data were sampled at 256 Hz per channel to ensure adequate temporal resolution. Raw EEG signals are inherently non-stationary and prone to artefacts from muscle activity, eye blinks, and environmental noise. To improve the signal-to-noise ratio, the data underwent a structured preprocessing pipeline. A 4th-order Butterworth band-pass filter with a frequency range of 0.4–64 Hz was applied to retain physiologically relevant EEG rhythms while attenuating slow drifts and high-frequency noise. Additionally, a notch filter set at 49–51 Hz was implemented to suppress line noise due to mains power interference. Artefacts arising from eye blinks, movement, or poor electrode contact were managed by

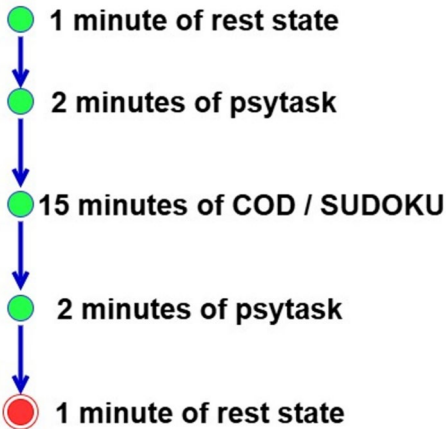


Fig. 4 Overview of the experimental protocol, including cognitive assessment, gameplay sessions, self-assessment, and EEG data recording

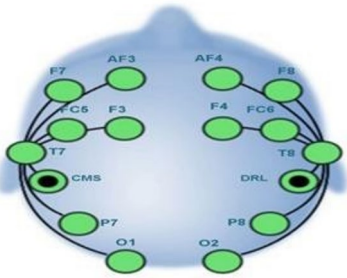


Fig. 5 Electrode positions and status of the EEG headset



A

B

Fig. 6 Experimental setup and EEG data acquisition with emotiv EPOC headset device, **A** action video game (COD), **B** puzzle game (Sudoku)

continuous impedance monitoring (green: good; orange: average; red: poor; black: no contact), and segments with poor contact quality were discarded before analysis. The preprocessing framework ensured that clean EEG signals were preserved for subsequent analysis of neural dynamics during gameplay. EEG signals from the left frontal lobe during two video game sessions were extracted and analysed. The theta, alpha, beta, and gamma signals from these recordings are depicted in Fig. 7A and B.

Feature extraction and functional connectivity analysis

The offline analysis of EEG signals acquired during different gaming conditions (Sudoku and Call of Duty—COD) was performed using Wavelet Transform Decomposition (WTD). The EEG signals in this study were decomposed into five levels using the Daubechies-4 (db4) wavelet [33] because db4 is widely adopted in EEG signal processing for its ability to provide smoothing while preserving signal morphology [34]. The db4 wavelet has a shape that closely resembles EEG waveforms, which improves denoising effectiveness [35]. The discrete wavelet transform with db4 offers variable time–frequency resolution—providing fine spectral details for low-frequency components (delta, theta) and good temporal localization for high-frequency components (gamma). Its coefficients concentrate signal energy, facilitating effective feature extraction and artifact removal [36]. Db4 has been successfully used in various EEG applications, including seizure detection, sleep staging, and brain–computer

interfaces [37–39]. Considering the EEG sampling frequency of 256 Hz in this study, decomposition into five levels using db4 effectively captures delta and theta band energies while retaining relevant high-frequency information, making it suitable for the current cognitive and neural analysis of video game play. Each recording lasted about 20 min, and to minimize adaptation and fatigue effects, the first and last 30 s of data were discarded. Less than 5% of epochs were rejected due to low-quality signals. Electrode impedance was maintained within recommended limits, and the in-built signal quality index confirmed that data quality remained above 80% across all electrodes for all participants.

In the present sample, the frequency of the EEG signal is 256 Hz. To the extraction, the delta, theta band energy Signal was decomposed into 5 levels as shown in Fig. 8

The EEG frequency bands and their corresponding wavelet packet decomposition (WPD) coefficients are summarized in Table 1.

In the proposed algorithm, the window function is applied as a mathematical tool that assigns zero values outside a selected interval, segmenting the original data into several consecutive sets. EEG signals are inherently non-stationary, meaning their properties can vary over time. To analyze them effectively, the signals are divided into short segments, or windows, where they can be considered quasi-stationary. Shorter windows (1–5 s) can capture rapid neuronal dynamics but are often noisy and unstable, whereas longer windows (>30 s) provide

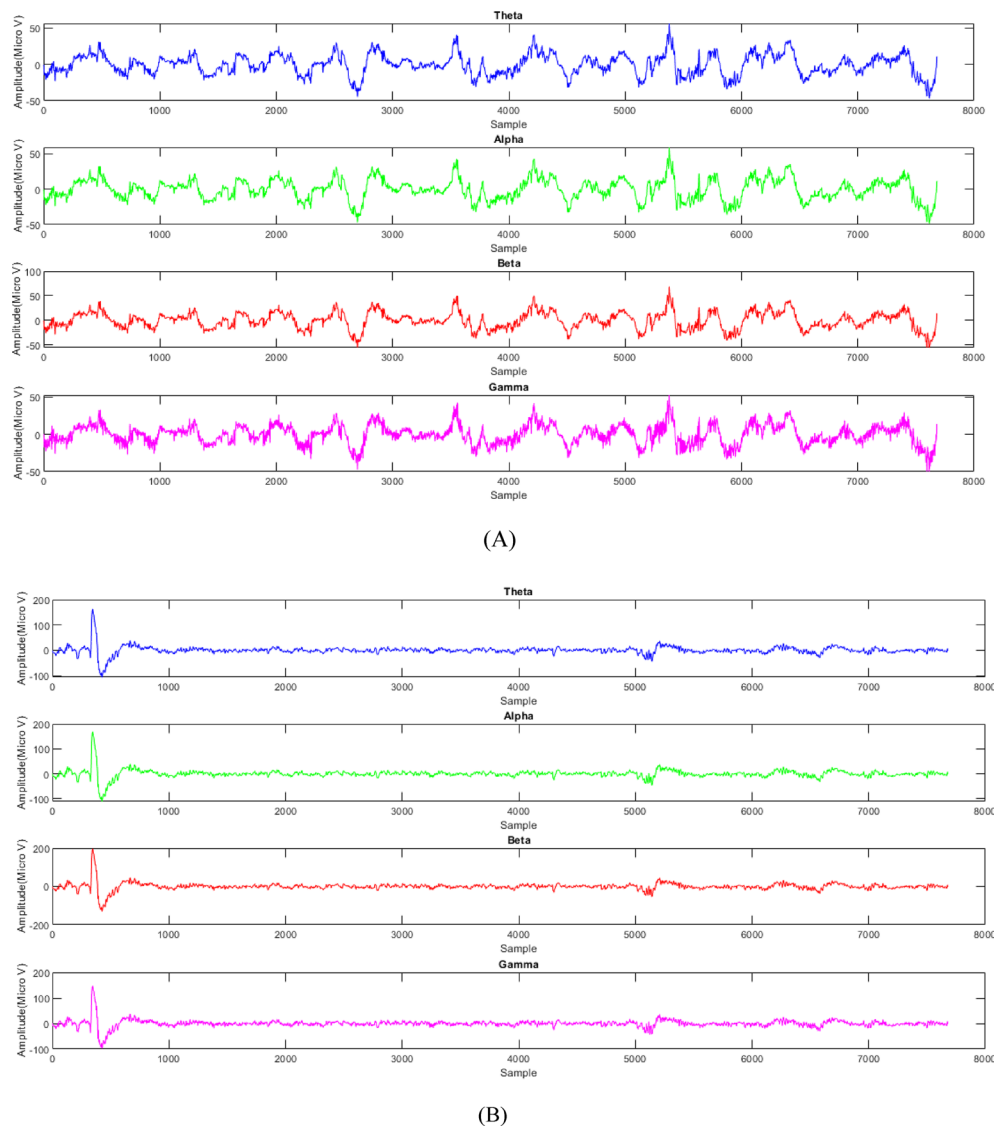


Fig. 7 EEG signals (theta, alpha, beta, and gamma) recorded from left frontal lobe electrode locations during **A** action video game (COD), **B** puzzle game (Sudoku)

smoother signals but may miss transient neuronal events. In the present study, a 20-s non-overlapping window was selected as a balance between temporal resolution and signal stability, yielding a frequency resolution of 0.05 Hz suitable for EEG band analysis. Non-overlapping windows also reduce temporal redundancy and simplify statistical analysis. Previous studies support this choice: Tzamourta et al. [40] found that 12-s non-overlapping windows provided the best classification accuracy for Alzheimer's detection, while Christou et al. [41] reported optimal EEG epilepsy detection performance using 20–21 s non-overlapping windows. These findings indicate that longer, non-overlapping epochs can enhance

analysis stability and classification accuracy without losing critical transient information. Specifically, a rectangular window function was used to divide the original 15-min signal into non-overlapping 20-s intervals, and each window signal. Wavelet packet decomposition (WPD) was performed to extract relevant features while preserving orthogonality, smoothness, and localization properties.

Time–frequency analysis was performed to capture dynamic spectral changes during gameplay. A representative scalogram was plotted for one typical subject using 30-s time windows at the frontal electrode (F3). Figure 9 A shows the time–frequency distribution for the action

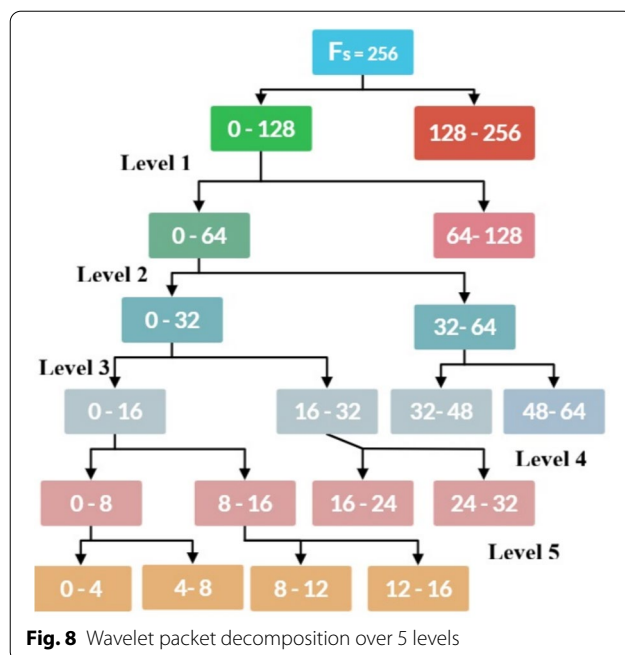


Table 1 Frequency ranges of EEG bands and corresponding wavelet packet decomposition coefficients

EEG band	Frequency range (Hz)	Wavelet packet decomposition coefficient
Gamma band	32–64	D (2,1)
Beta band	16–32	D (3,1)
Alpha band	8–12	D (4,2)
Theta band	4–8	D (5,1)
Delta band	0.1–4	A (5,1)

video game (COD), while Fig. 9 B shows the same for the puzzle game (Sudoku).

Further, the theta-band activity was extracted and analysed using 30-s epochs at the same electrode. The results (Fig. 10A—COD; Fig. 10B—Sudoku) clearly indicate that theta activity remained consistently elevated throughout all time windows during COD gameplay compared to Sudoku.

To perform this analysis, the wavelet transform, specifically wavelet packet decomposition, was applied to quantify the dynamic spectral changes between the two gaming conditions. These results support the observation that action video games impose higher cognitive load, reflected in stronger and sustained theta activity, while puzzle games induce comparatively weaker spectral dynamics.

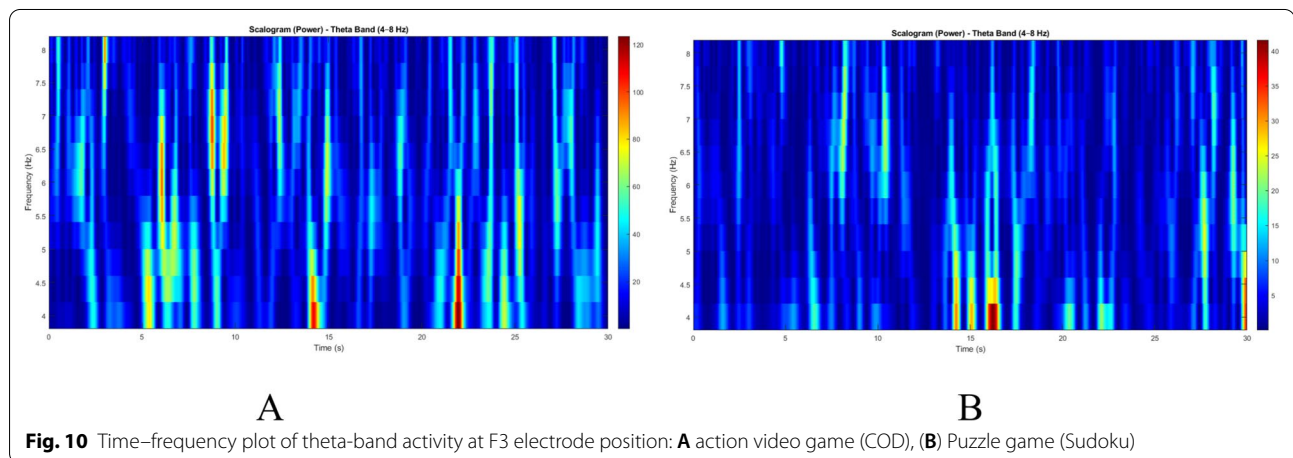
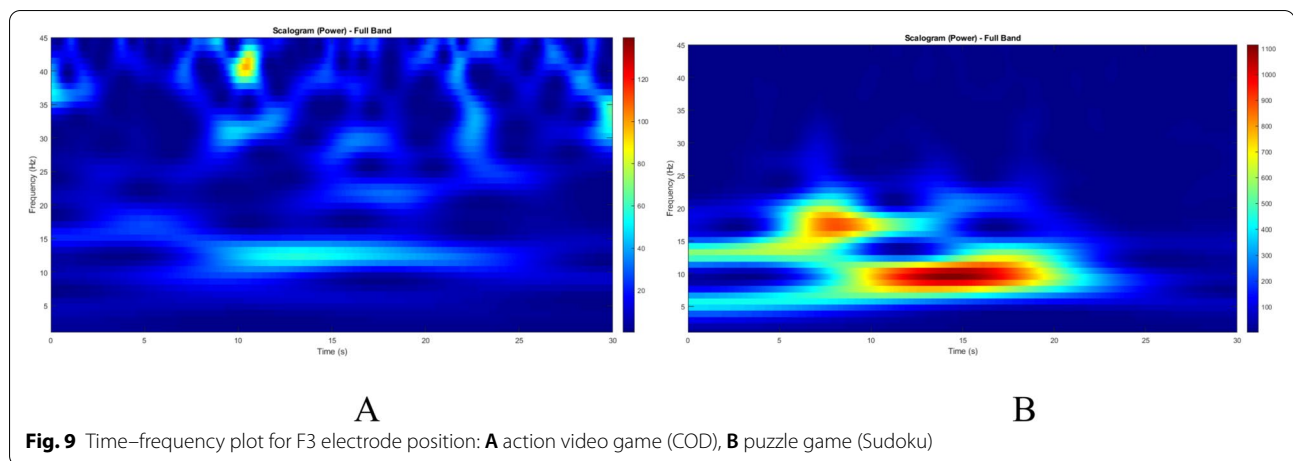
The decomposition provided relative energy measures for delta, theta, alpha, beta, and gamma bands, along with 13 cognitive indices including Heart Rate Index (HR), CNS Arousal (CNSA), Brain Perfusion (BP), Synchronization (Sync), LF/HF Ratio, Arousal Index (AI), Vigilance Index (VI), Cognitive Performance Index (CPI), Executive Load Index (ELI), Performance Enhancement Index (PEI), Alpha-Gamma Ratio (AGR), Neuronal Activity (NA), and Desynchronization (Desync). These features were extracted for all subjects during gameplay in both Sudoku and Call of Duty (COD), providing insights into cognitive and physiological responses as per the experimental protocol illustrated in Fig. 11.

Studying influential nodes (I-nodes) in brain networks holds substantial importance in the domain of brain imaging [42]. Brain functional connectivity examines the temporal dependencies of neural activation across various brain regions, providing insights into how these areas interact during different tasks and conditions. This approach is valuable for investigating specific brain functions and identifying alterations associated with pathological states. Functional brain networks are often modelled as graphs, where nodes represent EEG electrode positions and edges correspond to the strength of connectivity between these nodes, typically quantified by correlation coefficients between EEG signals.

In this study, EEG data from 14 electrodes were analysed during different video game conditions. Node values were calculated using one-sample t-tests, and edge values were determined through Spearman correlation tests, with all analyses conducted using IBM SPSS 20. To explore potential differences in brain network complexity between action and puzzle video games, connectivity graphs were generated focusing on beta and gamma energy parameters, as well as the Neuronal Activity (NA) ratio feature, during and after gameplay. These visualizations were created using BrainNet Viewer, a MATLAB-based tool designed for flexible and user-friendly brain network visualization.

Statistical analysis

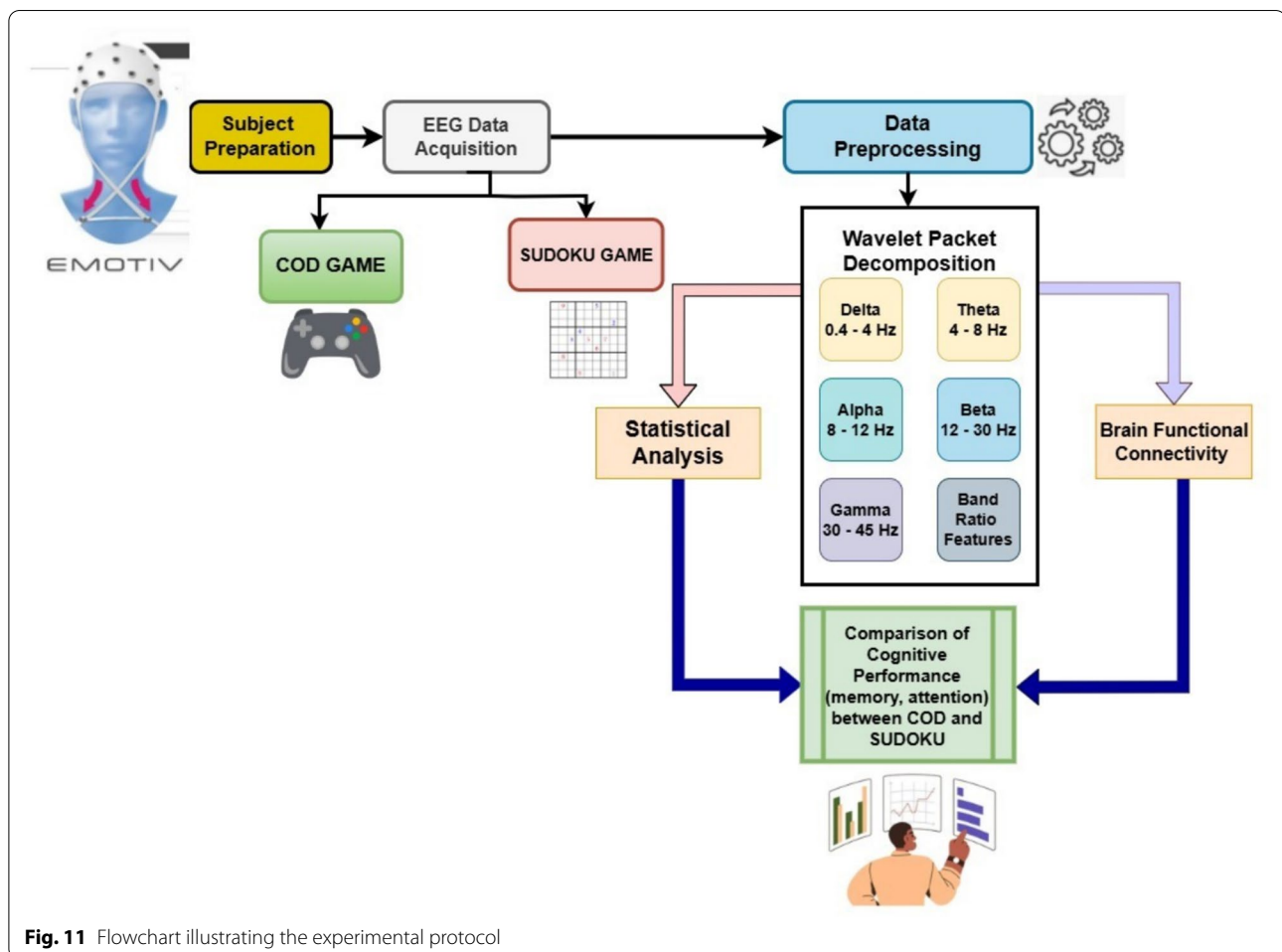
Statistical analysis plays a crucial role in this study by ensuring the reliability and validity of EEG-based findings while reducing the impact of random variations. It facilitates a structured assessment of differences in brain activity across various gameplay conditions, enabling the identification of significant cognitive and neural responses. Effect size calculations have now been included in the revised manuscript. Power analysis using G*Power was performed with 18 samples across three experimental groups, where power ($1-\beta$ error prob)=0.80 and significance level $p=0.05$ yielded an



effect size of 0.435. For comparisons between COD and Sudoku gameplay, Cohen's d was 1.05, indicating a large effect size (>0.8). For ANOVA tests across before, during, and after gameplay conditions, eta-squared (η^2) was calculated as 0.20, also reflecting a large effect size. Data were represented as the mean and standard error of the mean ($\text{Mean} \pm \text{SEM}$). EEG measurements focused on relative component energies across the delta, theta, alpha, beta, gamma, and ratio-frequency bands, which served as dependent variables. A one-way repeated measures ANOVA was conducted to assess overall differences in these parameters across three gameplay conditions (before, during, and after) at 14 electrode locations, with significance set at $p < 0.05$. The Posthoc Fisher's Least Significant Difference (LSD) was performed on different combinations of related groups, and a Bonferroni adjustment was calculated. The alpha value was divided by three conditions ($0.05/3 = 0.017$). So, the new significance level was set at $p = 0.017$. If the p value is larger than 0.017, it is not considered a statistically significant

result. So, the LSD test with Bonferroni adjustment was performed in different combinations of related groups. Participants engaged in both Sudoku and Call of Duty (COD) gameplay on separate days to prevent cross-game cognitive interference.

Comparative statistical analyses between gameplay conditions (Sudoku vs. COD) were performed using paired samples t -tests on EEG features, self-assessment questionnaire scores, and PSYTASK results, maintaining a significance level of $p < 0.05$. Significant node degrees in brain areas were identified using one-sample t -tests. Three features—beta, gamma, and neuronal activity (NA)—across all 14 electrodes were correlated using Pearson's approach to evaluate the alignment of key hubs with functional networks observed during various video games. For connectivity analysis, t -values for each electrode were calculated for the three features [43]. All statistical analyses were conducted using IBM SPSS Statistics for Windows, Version 20.0 (Armonk, NY: IBM Corp.)



Results

In this study, the mean relative energies for delta, theta, alpha, beta, gamma, and band ratio components were computed for electrode sites in both the left and right hemispheres during gameplay of Call of Duty (COD) and Sudoku. Research indicates that gamma waves are linked to the maintenance of visual representations, while alpha waves are associated with functional inhibition. Specifically, gamma activity correlates with the retention of facial orientation (dorsal stream), whereas alpha activity is observed during the retention of facial identities (ventral stream).

Self-assessment questionnaire

Self-assessment questionnaires revealed that participants reported significantly higher emotional scores ($p < 0.05$) during COD gameplay compared to Sudoku. Conversely, enjoyment scores were notably lower ($p < 0.05$) during Sudoku sessions than during COD play, as illustrated in Fig. 12. The rising popularity of gameplay videos suggests that engaging with COD, whether playing or observing,

offers positive emotional experiences and is widely regarded as enjoyable. These findings imply that COD induces heightened arousal and a positive emotional response in contrast to Sudoku. For COD players, this emotional state fosters an increased sense of enjoyment, enhancing motivation to continue playing and confront subsequent competitive gaming scenarios.

In contrast, Sudoku has been associated with mental health benefits, such as providing relief from daily stressors and enhancing cognitive functions. Engaging in Sudoku puzzles can offer a sense of satisfaction upon completion, potentially aiding in stress management and mental clarity. However, the emotional responses elicited by Sudoku differ from those induced by action-oriented games like COD, as Sudoku tends to promote relaxation and cognitive engagement rather than heightened arousal.

Analysis of EEG parameters during call of duty (COD) gameplay

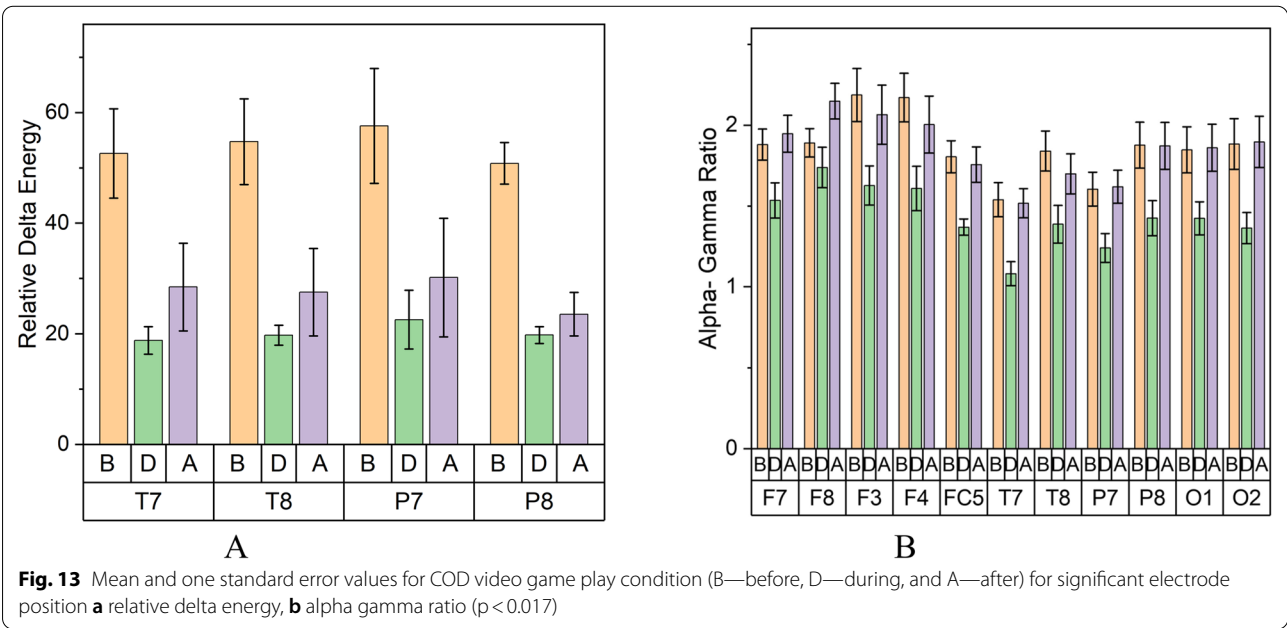
The delta frequency band is typically associated with attention regulation, inhibiting interferences during



cognitive tasks. The Posthoc Fisher’s Least Significant Difference (LSD) was performed on different combinations of related groups, and a Bonferroni adjustment was calculated. The alpha value was divided by three conditions ($0.05/3=0.017$). So, the new significance level was set at $p=0.017$. A significant difference in relative delta energy was observed across three experimental conditions at electrode sites T7, T8, P7, and P8 during COD gameplay, $F(2, 51)=4.601$, $p<0.05$, as depicted in Fig. 13A. Post hoc LSD tests revealed that delta energy

was significantly lower during gameplay (condition 2) compared to both before (condition 1, $p=0.005$) and after gameplay ($p=0.004$). This aligns with findings that high-skilled FPS players exhibit lower delta and theta power spectral density in frontal and temporal areas [44].

When analysing EEG in relation to short-term and long-term memory, researchers look at how the power or ratio of these bands may change during memory-related tasks. Alpha oscillations (8–12 Hz) play a critical role in selective attention by suppressing irrelevant information across sensory systems. Research indicates that alpha band activity reflects task-specific demands in parieto-occipital regions, with novices exhibiting more cortical activation than experts [45]. A significant difference ($p<0.017$) in the alpha-gamma ratio (AGR) was found across the three experimental conditions at bilateral frontal (F7, F8, F3, F4, FC5), temporal (T7, T8), parietal (P7, P8), and occipital (O1, O2) regions during COD gameplay, as shown in Fig. 13B. Post hoc analysis indicated that AGR was significantly lower during gameplay (condition 2) compared to before (condition 1) and after gameplay (condition 3) across all electrode locations, except AF3, AF4, and FC6. During and after, there is a significant ($p<0.002$) difference for F7, FC5, T7, P7, and O2 electrode position. No significant difference between before and during game play at P8 ($p=0.020$), O1 ($p=0.027$), F7 ($p=0.028$), P8 ($p=0.020$), O1 ($p=0.027$) brain regions. Similarly, there is a significant ($p<0.017$) variation between before and during game play conditions in F8 ($p=0.010$), F3 ($p=0.015$), F4 ($p=0.014$), electrode regions as shown in Fig. 13B. No significant variation was



observed between before and after gameplay conditions at any electrode position.

Increased arousal in humans is often manifested by faster responses to visual stimuli and is associated with higher EEG activation in beta bands. During COD gameplay, the vigilance index (VI)— $\frac{((\theta + \alpha)/\beta)}{((\theta + \alpha)/\beta)}$ —was significantly lower ($p < 0.05$) compared to before and after gameplay across most electrode locations, as illustrated in Fig. 14. At AF3 electrode position there is a significant ($p = 0.006$) variation of VI parameter between before and during action video game play condition. No significant variation of VI features between during and after game play ($p = 0.067$), before and after game play ($p = 0.321$) experimental condition. Similarly, all frontal region of the brain (F7, F8, F3, F4 and FC5) there is a significant ($p < 0.003$) difference between before and during game play, but VI parameter doesn't show any significant ($p > 0.018$) variation between before and after-action video game play conditions.

The Arousal Index (AI), defined as the beta/alpha ratio (BAR), was significantly higher ($p < 0.017$) during gameplay compared to before gameplay across eight electrode locations: frontal (AF4, F7, F8, F4) parietal (P7, P8), and occipital (O1, O2), except at AF3, F3, T7, T8, FC6, and F3, as detailed in Table 2. Similarly significant ($p < 0.011$) was observed for AI features between during and after-action game play condition at frontal (F7, F8, F4, FC5), temporal (T7, T8), parietal (P7, P8), and occipital (O1, O2) region of the brain. This suggests increased beta activity during COD gameplay, indicative of heightened attention and focus. Before gameplay, AI was lower, increasing by an

average of 17.56% during gameplay, as shown in Table 2. Simultaneously, desynchronization (alpha/beta ratio—ABR) significantly decreased ($p < 0.017$) during gameplay across all electrode positions except FC6, with a 17.12% reduction compared to the rest condition. Neuronal Activity (beta/theta ratio) also significantly increased ($p < 0.017$) in the left frontal, temporal, and parietal regions (F7, T7, P7) during COD gameplay compared to rest conditions. Also, NA was significant ($p < 0.017$) difference between during and after game in left frontal, temporal, and parietal regions (F7, FC5, T7, P7). Synchronization (delta/theta ratio), Desynchronization, LF to HF ratio, and executive load index (delta + theta/alpha) features significantly increased ($p < 0.017$) across most electrode positions during COD gameplay compared to rest conditions. Central Nervous System (CNS) Arousal, indicated by the theta/beta ratio, significantly decreased ($p < 0.017$) during gameplay in the left frontal region (F7), parietal (P7, P8), and right occipital regions, as shown in Table 2.

The Performance Enhancement Index (alpha/theta ratio—ATR) was significantly lower ($p < 0.017$) during gameplay compared to rest conditions in the frontal region (AF4, F3) but significantly increased ($p < 0.017$) in the left parietal region (P7) during gameplay. No significant differences were observed in other brain regions, as detailed in Table 2. EEG ratio features such as Synchronization, Executive Load Index, and LF to HF ratio exhibited higher values during rest conditions compared to COD gameplay. In contrast, CNS Arousal and Desynchronization were lower during rest conditions, as presented in Table 2. Table 2 summarizes the statistical significance of various EEG features measured across different electrodes before and during COD gameplay. The features analyzed include Arousal index, neuronal activity, synchronization, brain perfusion, central nervous system (CNS) Arousal, desynchronization, executive load index, performance enhancement index, and the low-frequency (LF) to high-frequency (HF) ratio. Changes in these parameters offer insights into the neural correlations of gaming experiences, such as increased arousal, cognitive load, and attentional shifts.

Analysis of EEG parameters during Sudoku gameplay

The delta band is primarily linked to attention regulation by minimizing external interferences during cognitive tasks [46]. During Sudoku gameplay, relative delta energy was significantly lower ($p < 0.05$) compared to the resting condition. This reduction was observed in the frontal region (AF3, F3, F4, F7, F8, FC5, and FC6), bilaterally in the parietal region (P7 and P8), the occipital lobe (O1 and O2), and the right temporal lobe. AF4 and T7 electrode position delta parameters doesn't

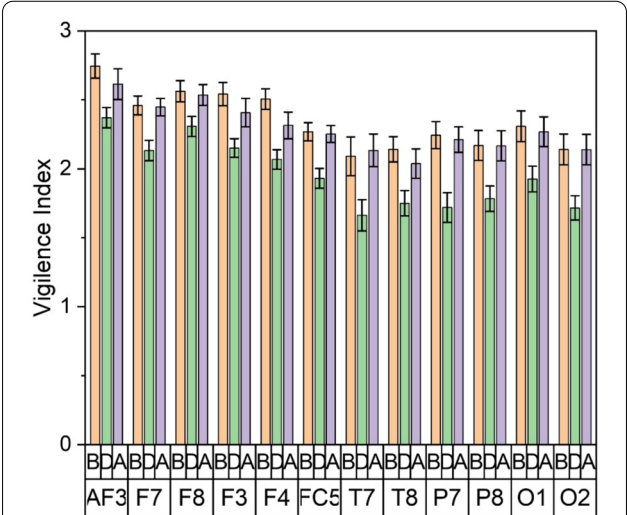


Fig. 14 Mean and one standard error values for COD video game play condition (B—before, D—during and A—after) for significant electrode position for vigilance index feature ($p < 0.017$)

Table 2 Statistical significance of EEG features before and during call of duty gameplay

Feature	Electrode	Before gameplay	During gameplay	Change (increase/decrease)
Arousal index	AF4	0.7998	0.8831	+0.0833
	F7	0.9234	1.1091	+0.1857
	F8	0.8264	0.9264	+0.1000
	F4	0.8488	0.9738	+0.1250
	FC5	0.9643	1.0652	+0.1009
	T7	1.0429	1.2494	+0.2065
	T8	0.9859	1.1202	+0.1343
	P7	0.9331	1.1928	+0.2597
	P8	0.8963	1.0892	+0.1929
	O1	0.8765	1.0472	+0.1707
Neuronal activity	O2	0.8928	1.0993	+0.2065
	F7	0.9018	1.1014	+0.1996
	FC5	1.0119	1.1565	+0.1446
	T7	1.1198	1.5390	+0.4192
	P7	1.0003	1.5447	+0.5444
Synchronization	O2	1.1522	1.5618	+0.4096
	AF4	9.8103	4.4861	−5.3242
	AF3	14.4533	5.0450	−9.4083
	F7	14.4238	6.8784	−7.5454
	F8	12.5575	6.6487	−5.9088
	F3	14.8215	5.2813	−9.5402
	F4	13.1032	5.1447	−7.9585
	FC5	15.0978	6.3136	−8.7842
	FC6	31.6223	7.6094	−24.0129
	T7	15.3919	6.3741	−9.0178
	T8	13.7003	5.5285	−8.1718
	P7	16.0687	6.6605	−9.4082
	P8	14.2593	6.1768	−8.0825
Brain perfusion	O1	15.3191	5.8445	−9.4746
	O2	14.2240	5.6636	−8.5604
CNS Arousal	FC6	0.2549	0.3918	+0.1369
	F7	1.2076	1.0776	−0.1300
	FC5	1.0963	0.8830	−0.2133
	T7	1.0778	0.7860	−0.2918
	T8	0.9708	0.6824	−0.2884
	P7	1.0975	0.8146	−0.2829
	P8	0.9969	0.8036	−0.1933
Desynchronization	O2	0.9444	0.6300	−0.3144
	AF4	1.2749	1.1939	−0.0810
	AF3	1.3472	1.1484	−0.1988
	F7	1.2520	1.0547	−0.1973
	F8	1.2899	1.1277	

show any significant ($p=0.0234$ and $p=0.168$) between three experimental condition. Remaining electrode's location shows significant ($p=0.00001$) difference between before and during game play; similarly, before and after game play condition also. These findings

suggest a shift in cognitive engagement, as shown in Fig. 15A.

A significant ($p < 0.05$) difference in the alpha-gamma ratio (AGR) was observed across the three experimental conditions (before, during, and after gameplay) at two specific electrode positions: the left frontal (AF3) and

parietal (P7) regions. Post hoc analysis using the LSD test further revealed that AGR was significantly lower ($0.05/3=0.017$) during Sudoku gameplay compared to the pre-gameplay state. In AF3 electrode location during game play condition AGR is significantly ($p=0.014$) low when compared to before game play, no significant ($p=0.048$) difference between during and after game play condition. Left parietal lobes (P7), there is a significant ($p=0.004$) difference between during and after game play, and the remaining experimental conditions don't show any significant ($p=0.077$ and $p=0.243$) difference between them. This reduction may indicate an increased cognitive load and attention modulation while solving puzzles, as illustrated in Fig. 15B.

The Arousal Index, represented by the beta/alpha ratio, was significantly higher ($p<0.017$) during gameplay compared to the pre-gameplay condition at four electrode locations: the left frontal region (AF3 and F3), the left parietal region (P7), and the right occipital lobe (O2). AF3, F3, P7, and O2 electrode position arousal index value is significantly ($p=0.002$) different between during and after game play, except O1 position ($p=0.098$). In all, electrode position there is no significant ($p=0.124$) difference between before and during, before and after game play conditions. This increase in beta activity suggests a heightened cognitive demand, particularly in the left frontal region, which is associated with problem-solving and logical reasoning (Fig. 16A).

The Heart Rate Index (HR), represented by the theta/alpha ratio, typically decreases during a relaxed state.

However, during Sudoku gameplay, it was significantly higher ($p<0.05$) compared to the resting condition at multiple brain regions, including the frontal (AF3, F8, F3, FC5, FC6), right parietal (P8), right temporal (T8), and left occipital (O1) regions. There is a significant ($p<0.016$) difference between during and after game play in frontal electrodes (AF3, F8, F3, FC5), right parietal (P8) and temporal (T8) lobes, left occipital (O1) Heart rate index was significantly ($p=0.016$) high during SUDOKO game play compared to before game play condition at AF3 electrode position. There is no significant ($p>0.017$) difference between before and after game-play conditions for all the electrodes except F8. This increase in the HR Index suggests that Sudoku gameplay places higher demands on working memory (WM) storage, as players actively engage in information processing and problem-solving (Fig. 16B).

The Synchronization Index (delta/theta ratio), Executive Load Index (delta+theta/alpha ratio), and LF/HF ratio were significantly lower ($p<0.017$) during Sudoku gameplay compared to the resting condition across all electrode locations, as shown in Table 3. These reductions indicate an overall shift in neural processing patterns when engaged in cognitively demanding tasks.

However, specific EEG features exhibited localized effects. Desynchronization (alpha/beta ratio) was significantly lower ($p<0.017$) only in left-brain regions, including the frontal (AF3, F7, F3, FC5), parietal (P7), and occipital (O1) regions. In contrast, the Performance Enhancement Index (alpha/theta ratio—ATR) showed

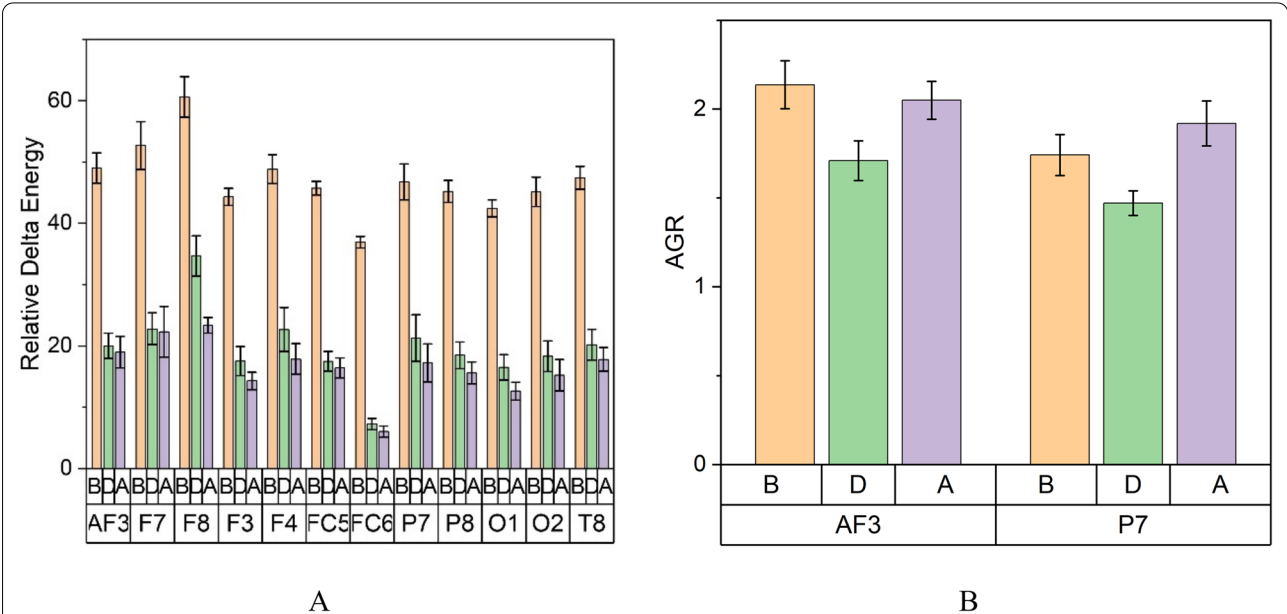
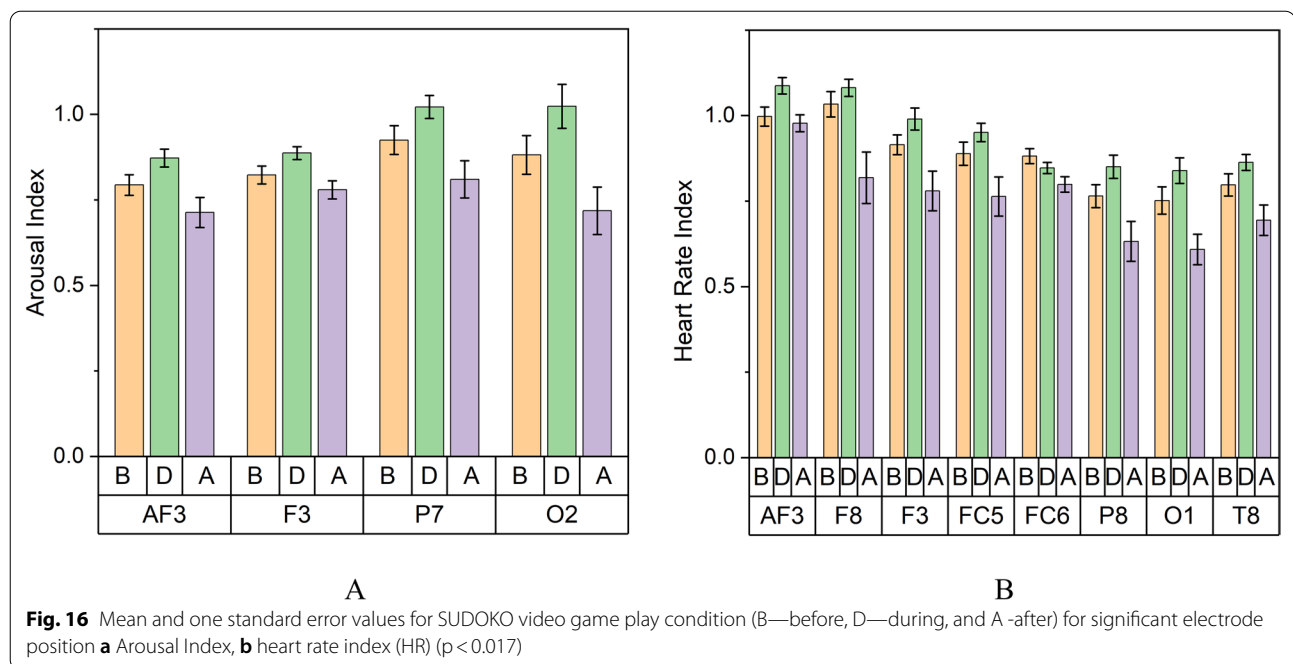


Fig. 15 Mean and one standard error values for SUDOKO video game play condition (B—before, D—during, and A—after) for significant electrode position **a** relative delta energy, **b** alpha gamma ratio ($p<0.05$)



significant variations ($p < 0.017$) predominantly in right-sided electrode locations (F8, F4, FC6, T8, P8). These findings highlight the lateralization of cognitive processing, with different hemispheres of the brain playing distinct roles in problem-solving and working memory functions during Sudoku gameplay.

Analysis of EEG features between COD and SUDOKU gameplay

Beta waves are generally associated with active attention and concentration. An increased magnitude of beta waves indicates participants' efforts to focus on the game environment while minimizing attention to external disturbances [47, 48]. The relative beta energy was significantly higher ($p < 0.05$) during action video game (call of duty—COD) play compared to puzzle-based gameplay (Sudoku) in the left frontal (AF3; $p = 0.015$, F3; $p = 0.003$) and parietal (P7; $p = 0.020$) brain regions, as illustrated in Fig. 17A. No significant ($p > 0.231$) differences were observed at other electrode locations between the two gameplay conditions.

Neural signals in the gamma frequency range (approximately 30–100 Hz) have received significant attention in neuroscience over the past 15 years. The relative gamma energy exhibited a significant difference ($p < 0.05$) between the two gaming conditions, showing higher values during action gameplay. This increase was more pronounced in the left hemisphere, particularly in the frontal (AF3; $p = 0.040$, F3; $p = 0.003$), temporal (T7; $p = 0.010$), and parietal (P7; $p = 0.013$) regions, as shown in Fig. 17B.

The gamma band energy was especially high in the parietal and temporal regions during COD gameplay compared to the frontal region. The Arousal index (beta/alpha ratio) serves as an indicator of attention levels. During attentive states, beta power increases while alpha power decreases relative to resting states [49, 50]. The Arousal index (BAR) was significantly lower ($p < 0.05$) while playing Sudoku in the frontal (F3; $p = 0.046$, F8; $p = 0.010$) and parietal (P7; $p = 0.009$, P8; $p = 0.007$) regions, as illustrated in Fig. 17C.

CNS arousal, measured as the theta/beta ratio, reflects autonomic nervous system (ANS) balance and is associated with trait attentional control [51]. A significant difference ($p < 0.05$) was observed in CNS Arousal between action and puzzle-based games, with an increased theta/beta ratio for Sudoku at F3 ($p = 0.004$), F8 ($p = 0.011$), and P8 ($p = 0.018$) electrode positions compared to COD.

This suggests reduced attentional control during Sudoku gameplay, as depicted in Fig. 18A. The Alpha-Gamma Ratio (AGR) showed a significant difference ($p < 0.05$) between the two gaming conditions, with higher values observed in the left frontal (F3; $p = 0.020$) and bilateral parietal (P7; $p = 0.001$, P8; $p = 0.009$) regions. Similarly, the Cognitive Performance Index (CPI) significantly differed ($p < 0.05$) between COD and Sudoku gameplay, with notable differences in the right frontal (F8; $p = 0.007$) and bilateral parietal (P7; $p = 0.023$, P8; $p = 0.001$) regions, as presented in Fig. 18B. The Vigilance Index (VI), calculated as $((\text{theta} + \alpha)/\text{beta})$, is considered the inverse of the engagement index. While playing

Table 3 Statistical significance for EEG features during SUDOKU gameplay

Sl. No	Features	Electrode	Before	During*	Increase/decrease
1	Synchronisation	AF3	12.7962	5.6211	− 7.1751
		AF4	8.4733	4.2413	− 4.232
		F7	13.9039	6.2996	− 7.6043
		F8	11.7962	5.8708	− 5.9254
		F3	14.6754	5.9786	− 8.6968
		F4	13.3630	5.7091	− 7.6539
		FC5	14.2539	5.9259	− 8.328
		FC6	31.5614	7.7623	− 23.7991
		T7	16.7074	7.3873	− 9.3201
		T8	13.7046	5.9633	− 7.7413
		P7	17.6535	7.8039	− 9.8496
		P8	14.8088	6.1573	− 8.6515
2	Desynchronisation	AF3	1.3604	1.1863	− 0.1741
		F7	1.1578	1.0133	− 0.1445
		F3	1.3077	1.1020	− 0.2057
		FC5	1.1071	0.9511	− 0.156
		P7	1.1883	0.9087	− 0.2796
		O1	1.3097	1.0954	− 0.2143
		O2	1.2719	1.0718	− 0.2001
3	Executive load index	AF3	15.8902	7.2287	− 8.6615
		AF4	11.0914	6.0615	− 5.0299
		F7	16.7514	7.8818	− 8.8696
		F8	14.7126	7.6649	− 7.0477
		F3	16.8987	7.1299	− 9.7688
		F4	14.3942	6.3103	− 8.0839
		FC5	15.6866	6.7456	− 8.941
		FC6	40.1551	8.0180	− 32.1371
		T7	16.0566	7.4713	− 8.5853
		T8	13.9823	6.2229	− 7.7594
		P7	17.9888	8.1904	− 9.7984
		P8	14.8015	6.4251	− 8.3764
4	Performance enhancement index	O1	14.6370	6.0626	− 8.5744
		O2	11.1412	4.8742	− 6.267
		AF3	1.0946	0.9522	− 0.1424
		F8	1.0522	0.9327	− 0.1195
		F3	1.1763	0.9516	− 0.2247
		F4	1.2217	1.1311	− 0.0906
		FC6	1.2083	1.2113	0.003
		T7	1.4470	1.1987	− 0.2483
		T8	1.3298	1.1498	− 0.18
		P8	1.4171	1.1677	− 0.2494
		O1	1.5816	1.2888	− 0.2928
5	LF to HF ratio	AF3	8.4451	3.8508	− 4.5943
		AF4	5.9465	3.2960	− 2.6505
		F7	8.3937	4.0122	− 4.3815
		F8	7.8209	4.1466	− 3.6743
		F3	8.7520	3.7448	− 5.0072
		F4	7.4537	3.3466	− 4.1071
		FC5	7.5109	3.2988	− 4.2121

Table 3 (continued)

Sl. No	Features	Electrode	Before	During*	Increase/decrease
		FC6	18.5996	3.6921	− 14.9075
		T7	7.2458	3.4462	− 3.7996
		T8	6.7651	3.0775	− 3.6876
		P7	9.0801	4.0960	− 4.9841
		P8	7.4972	3.2933	− 4.2039
		O1	7.4550	3.0463	− 4.4087
		O2	5.7898	2.4431	− 3.3467

COD, VI was significantly lower ($p < 0.05$) in the left frontal (F3; $p = 0.003$) and bilateral parietal (P7; $p = 0.007$, P8; $p = 0.015$) regions, suggesting higher engagement during action gameplay, as shown in Fig. 18C.

Analysis of brain signals after COD and Sudoku gameplay

Increased theta spectral power is known to correlate with enhanced cognitive resource utilization [52], task difficulty [53], and working memory activation [54]. Relative theta energy exhibited a significant difference ($p < 0.05$) between COD and Sudoku after gameplay. Specifically, theta activity was significantly higher in the left hemisphere at electrode positions AF3, F7, P7, and O1 following COD gameplay compared to Sudoku, as shown in Fig. 19A. This indicates that after playing the action game, cognitive resource engagement and working memory activity remained elevated. In contrast, these cognitive processes showed a reduction after playing Sudoku, indicating lower cognitive demand.

The gamma band is closely linked to perceptual processing and the retention of information over short periods, making it a critical marker for working memory [55]. Post-game relative gamma energy also showed a significant difference ($p < 0.05$) between COD and Sudoku, with higher gamma activity in the left prefrontal and parietal regions after COD play, as shown in Fig. 19B. This suggests that working memory processing and memory load were better sustained after action gameplay compared to the puzzle game. CNS arousal, assessed via the theta/beta ratio (TBR), is associated with attentional control. Post-game, CNS arousal (theta energy) was significantly higher ($p < 0.05$) following COD play in the left frontal, temporal, and occipital lobes when compared to Sudoku, as shown in Fig. 19C. This indicates that memory, attention, and cognitive control were enhanced after action gameplay, leading to improved post-game performance.

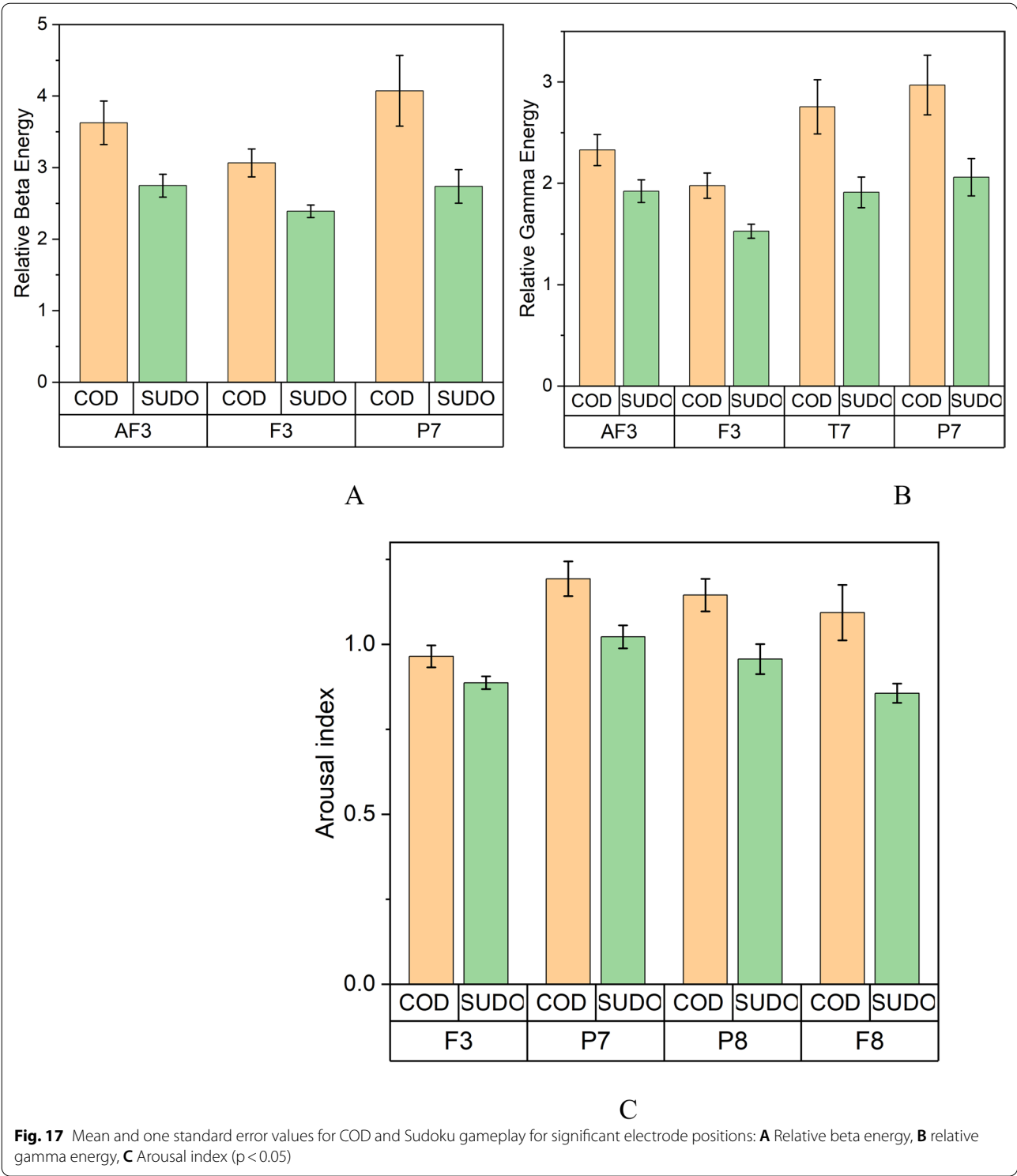
Neuronal Activity (NA), calculated as beta/theta, is inversely related to CNS arousal (TBR) [56]. Post-game analysis showed significantly lower NA ($p < 0.05$) after COD gameplay in the left frontal and temporal regions,

as shown in Fig. 19D. The Vigilance Index (VI), computed as $((\text{theta} + \alpha)/\text{beta})$, also significantly differed ($p < 0.05$) between COD and Sudoku post-game, as shown in Fig. 19E. After COD, theta activity increased, while alpha and beta activity decreased in the left frontal and temporal regions (F7, FC5, and T7). This pattern reflects increased task difficulty and higher cognitive effort following the action game. In contrast, after Sudoku, beta increased and theta decreased, indicating lower task difficulty, reduced working memory engagement, and lower cognitive load post-game. The detailed inferences derived from the EEG features across COD and SUDOKU gameplay are summarized in Table 4.

Relationship between Game parameters and the EEG signal

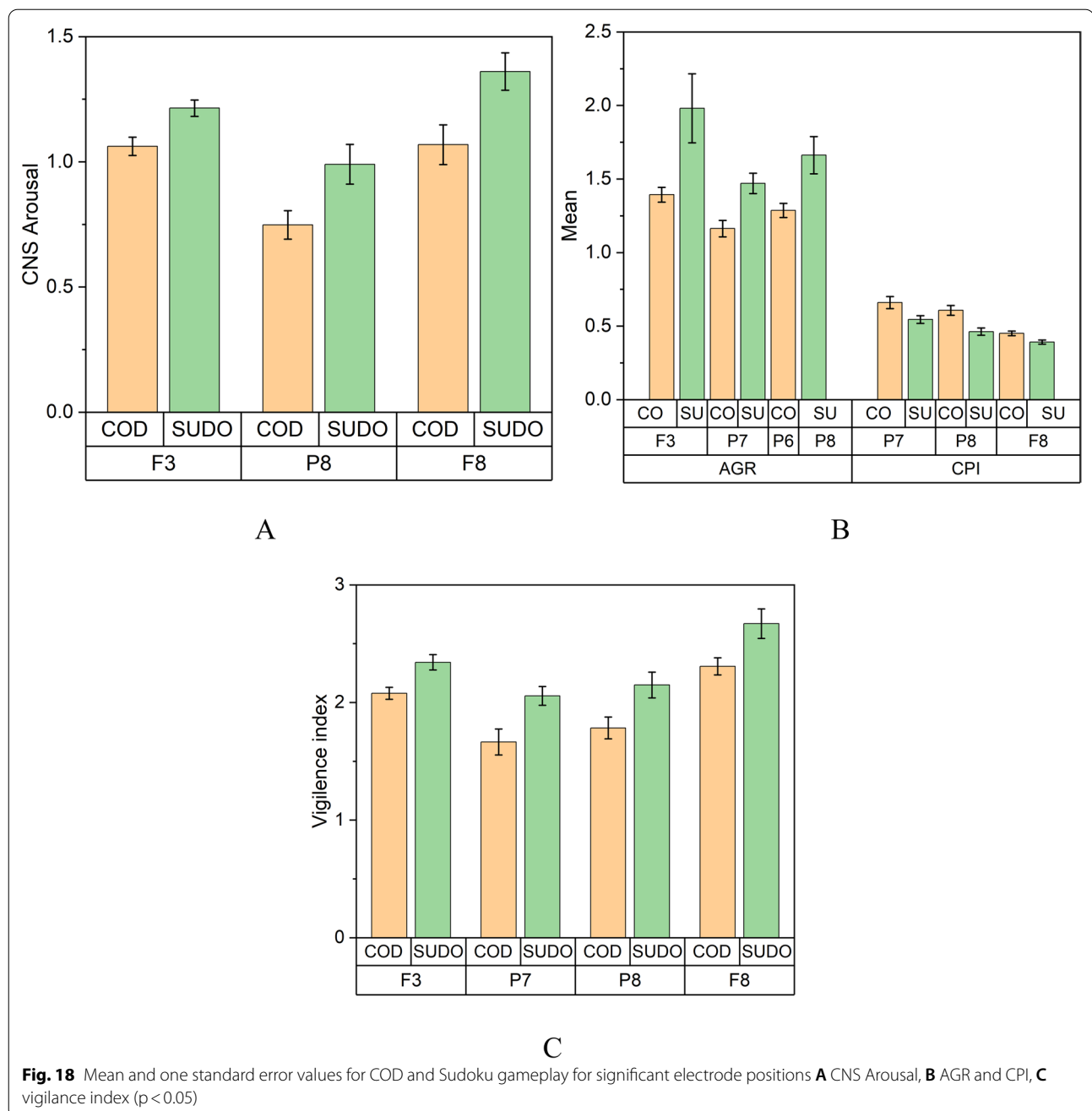
Correlation analysis was performed between game performance parameters (number of kills and respawn counts) and EEG features during COD gameplay. The results, as shown in Table 5, indicate that kill scores exhibited a moderate positive correlation with the Arousal Index at AF4 ($r = 0.537$) and the Cognitive Performance Index at P8 ($r = 0.469$). Respawn scores were strongly correlated with EEG features at occipital electrodes. Specifically, Synchronisation ($r = 0.630$), Executive Load Index ($r = 0.685$), and LF to HF ratio ($r = 0.845$) at O1 showed high positive correlations with respawn counts. Moderate positive correlations were also observed for the Alpha–Gamma ratio at O2 ($r = 0.487$ and $r = 0.517$).

These results indicate that performance in COD is strongly linked with neural indices of arousal, executive load, and spectral balance, particularly in the occipital and frontal regions, as reported in Table 5. The positive correlations between respawn counts and EEG features such as executive load and LF/HF ratio suggest that higher cognitive effort may be associated with task performance. Similarly, the moderate positive correlations between kill scores and arousal/cognitive indices highlight the role of heightened alertness and cognitive resource engagement in successful performance.



In contrast, no significant correlations were observed between game performance metrics and EEG features during Sudoku gameplay ($r < 0.321$ across all electrodes), suggesting that task complexity and cognitive demands in action games drive stronger performance–neural activity coupling compared to puzzle games.

In COD gameplay, the behavioural measure of commission errors (responding to a non-target stimulus)



showed significant negative correlations with EEG features before and after gameplay. The executive load index (delta+theta/alpha), LF to HF ratio, and synchronisation (delta/theta ratio) demonstrated moderate to high negative correlation coefficients, ranging from -0.50 to -0.67 . After gameplay, stronger negative correlations were observed at AF4 and AF3, showing that lower commission errors were associated with more efficient neural processing. The detailed results are provided in Table 6.

Similarly, omission errors (failing to respond to a target stimulus) showed positive correlations with the same EEG features. Before and after gameplay, correlation coefficients ranged between 0.60 and 0.70 , with particularly strong effects observed at AF4 and P8. This indicates that lapses in target detection were linked with higher executive load and synchronisation. The detailed results are presented in Table 7.

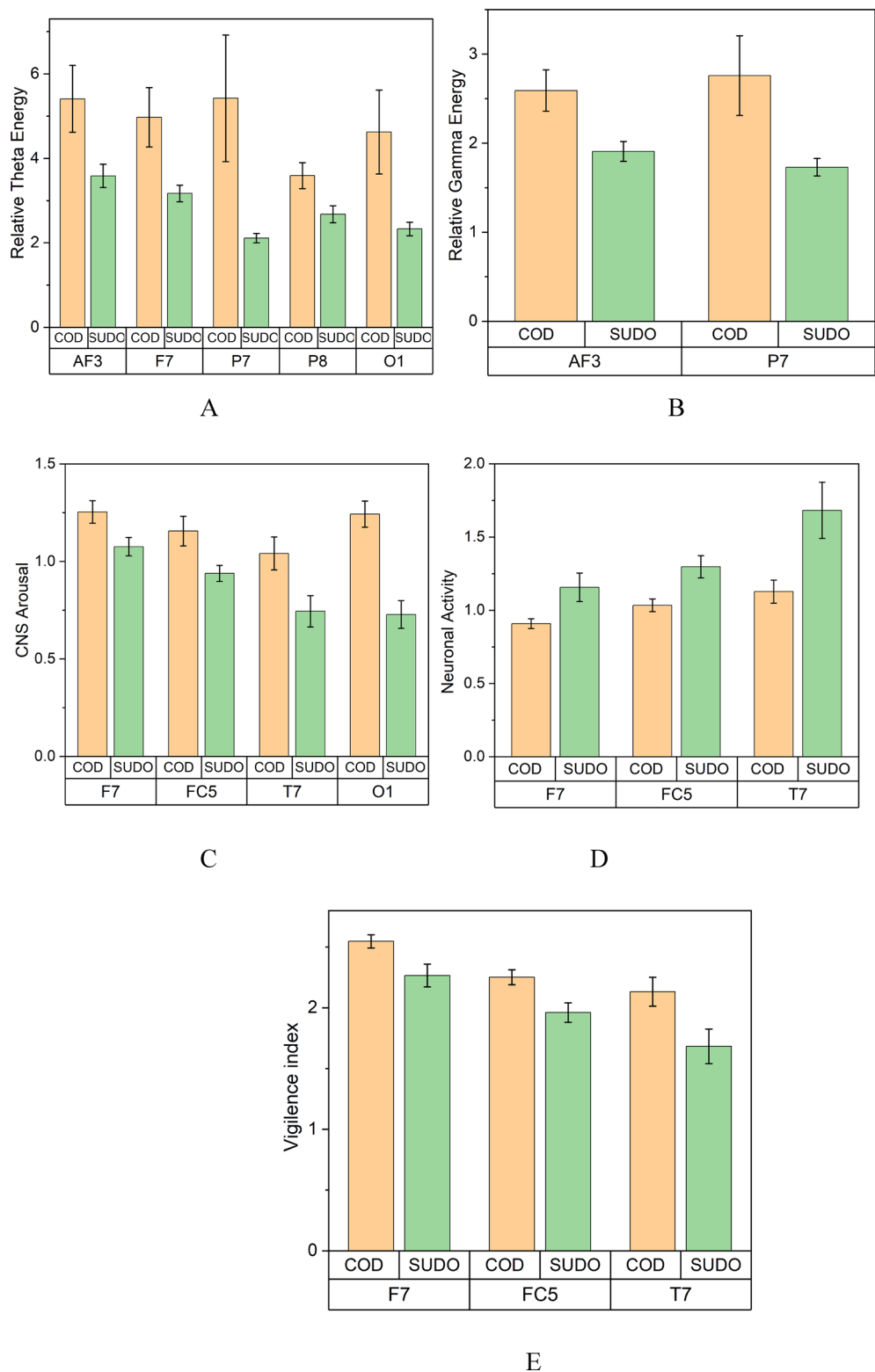


Fig. 19 Mean and one standard error values for COD and SUDOKU after video game play for the significantly different electrode positions: **A** relative theta energy, **B** Relative gamma energy, **C** CNS Arousal (theta/beta ratio), **D** neuronal activity (beta/theta ratio), and **E** Vigilance Index (VI) ($p < 0.05$)

Table 4 Inferences from EEG Features During COD and Sudoku Gameplay

EEG Feature	Key Electrode Positions	Dominant Hemisphere	COD (Action Game)	Sudoku (Puzzle Game)	Inference
Beta	AF3, F3, P7	Left Frontal	Increase	Decrease	Higher alertness and goal-directed attentiveness in COD
Gamma	AF3, F3, T7, P7	Left Frontal	Increase	Decrease	Enhanced working memory processing and perception post-COD
Arousal Index (AI) (Beta/Alpha Ratio—BAR)	F3, F8, P7, P8	Bilateral Frontal & Parietal	Increase	Decrease	Higher vigilance and cognitive processing in COD
Cognitive Performance Index (CPI) (Beta/(Theta + Alpha)) [57]	P7, P8, F8	Bilateral Parietal	Increase	Decrease	Higher attentional engagement in COD; Sudoku reduced alertness
Vigilance Index (VI) ((Theta + Alpha)/Beta)	F3, F8, P7, P8	Bilateral Frontal & Parietal	Decrease	Increase	Lower VI in COD reflects better attention control
CNS Arousal (TBR) (Theta/Beta) [58]	F3, F8, P8	Right Frontal	Decrease	Increase	Sudoku induced more mind wandering (MW) than COD
Alpha-Gamma Ratio (AGR)	F3, P7, P8	Left Parietal	Decrease	Increase	COD gameplay activated cognitive functions like attention targeting, while Sudoku showed reduced cognitive focus

Table 5 Correlation between COD gameplay performance measures and EEG features

Sl. No	Score type	Electrode	EEG feature	Correlation coefficient (r)	Interpretation
1	Kill	AF4	Arousal index	0.537	Moderate positive correlation
2	Kill	P8	Cognitive performance index	0.469	Moderate positive correlation
3	Respawn	O1	Synchronisation	0.630	High positive correlation
4	Respawn	O1	Executive load index	0.685	High positive correlation
5	Respawn	O1	LF to HF ratio	0.845	High positive correlation
6	Respawn	O2	Alpha–gamma ratio	0.487	Moderate positive correlation
7	Respawn	O2	Alpha–gamma ratio	0.517	Moderate positive correlation

In contrast, Sudoku gameplay did not show any meaningful correlation between behavioural errors and EEG features before or after gameplay, as all values were below $r=0.321$. These findings suggest that COD gameplay strongly modulates the relationship between behavioural errors and EEG markers of cognitive processing, while Sudoku does not. Negative correlations between commission errors and EEG features observed from Table 6 indicate that participants with more efficient neural functioning committed fewer false responses, whereas positive correlations between omission errors and EEG features presented in Table 7 suggest that lapses in target detection were linked with higher executive load and cognitive stress. Together, these results demonstrate that action video games enhance attentional control and error monitoring more effectively than puzzle games.

Brain functional connectivity network between COD and SUDOKU games

A brain functional connectivity network (FCN) graph is a representation of how different regions of the brain interact with each other based on functional correlations. In neuroscience, functional connectivity (FC) refers to the degree of co-variation between spatially distributed brain signals recorded using various functional neuroimaging techniques, including functional magnetic resonance imaging (fMRI) [59] electroencephalography (EEG) [60], magnetoencephalography (MEG) [61], functional near-infrared spectroscopy (fNIRS) [62] and electrocorticography (ECoG) [63]. A functional connectome refers to a comprehensive map of functional connections across the brain.

To facilitate comparison, the functional connectivity network is plotted for two video gameplay conditions

Table 6 Correlation between commission errors and EEG features during COD gameplay

Sl. No	Electrode	Feature	Correlation coefficient (r)	Interpretation
Before gameplay				
1	O1	Executive load index	− 0.620	Moderate negative correlation
2	P8	LF to HF ratio	− 0.529	Moderate negative correlation
		Synchronisation	− 0.609	Moderate negative correlation
3	F4	Executive load index	− 0.657	High negative correlation
		LF to HF ratio	− 0.666	High negative correlation
4	F8	Synchronisation	− 0.631	Moderate negative correlation
		Executive load index	− 0.529	Moderate negative correlation
5	AF4	LF to HF ratio	− 0.565	Moderate negative correlation
		Synchronisation	− 0.548	Moderate negative correlation
After gameplay				
6	AF3	Synchronisation	− 0.749	High negative correlation
7	AF4	Executive load index	− 0.611	Moderate negative correlation
		LF to HF ratio	− 0.612	Moderate negative correlation
8	AF3	Synchronisation	− 0.526	Moderate negative correlation

Table 7 Correlation between omission errors and EEG features during COD gameplay

Sl. No	Electrode	Feature	Correlation coefficient (r)	Interpretation
Before gameplay				
1	O1	Executive load index	0.620	Moderate positive correlation
		LF to HF ratio	0.529	Moderate positive correlation
2	P8	Synchronisation	0.609	Moderate positive correlation
		Executive load index	0.657	High positive correlation
		LF to HF ratio	0.669	High positive correlation
3	F4	Synchronisation	0.631	Moderate positive correlation
		Executive load index	0.529	Moderate positive correlation
		LF to HF ratio	0.565	Moderate positive correlation
4	F8	Synchronisation	0.548	Moderate positive correlation
After gameplay				
5	AF4	Synchronisation	0.749	High positive correlation
		Executive load index	0.611	Moderate positive correlation
		LF to HF ratio	0.621	Moderate positive correlation
6	AF3	Synchronisation	0.526	Moderate positive correlation

(COD and SUDOKU), considering three EEG features: Beta energy, Gamma energy, and Neuronal Activity (NA). In the Beta band connectivity, the red-to-blue gradient indicates activity intensity, with red showing higher activity and blue indicating lower activity. During COD gameplay, the beta band shows higher activation in the bilateral frontal and prefrontal regions. Conversely, during SUDOKU gameplay, beta energy exhibits higher activation in the left hemisphere of the frontal lobe, as well as in the bilateral parietal and occipital regions, as shown in Fig. 20A and B.

Gamma band activity, associated with high concentration and problem-solving, shows stronger connectivity

between prefrontal and frontal cortices during COD gameplay, particularly between AF3-F3, AF4-F4, and other frontal edges, as shown in Fig. 21. This pattern reflects the cognitive and motor demands of action gameplay. For SUDOKU, gamma activity is concentrated in the parietal and occipital cortices across both hemispheres, supporting its dependence on visuospatial processing and logical reasoning. Strong edges during COD involve frontal nodes like F3, FC5, and F4, while SUDOKU shows enhanced connectivity between parietal-occipital edges such as P7-O1 and P8-O2, reinforcing the game's visual and cognitive demands.

Analysing functional connectivity for neuronal activity (NA) helps to identify cognitive functions such as memory and learning [63]. In this analysis, correlations between regions of interest (ROIs) define the edge strengths between nodes. During COD gameplay, NA connectivity is stronger in the right hemisphere, particularly between FC5 and temporal, parietal, and occipital cortices. During SUDOKU gameplay, stronger NA connectivity is observed in the right frontal lobe and across the bilateral parietal and occipital cortices (e.g., F4-P7, P8, O1, and O2). Higher connectivity is evident in the right hemisphere for SUDOKU, while COD exhibits stronger connectivity within the left central hemisphere, as shown in Fig. 22A and B.

The strong nodes and edges detected during the connectivity analysis for both games across the three EEG features (beta, gamma, and NA) are summarized in Table 8. In this study, a node is considered strong if its t-value exceeds 10, and an edge is considered strong if the correlation coefficient exceeds 0.6. Nodes and edges below these thresholds were excluded from further analysis.

The overall functional connectivity findings for both games are summarized in Table 9, highlighting the key cognitive inferences drawn from the connectivity patterns.

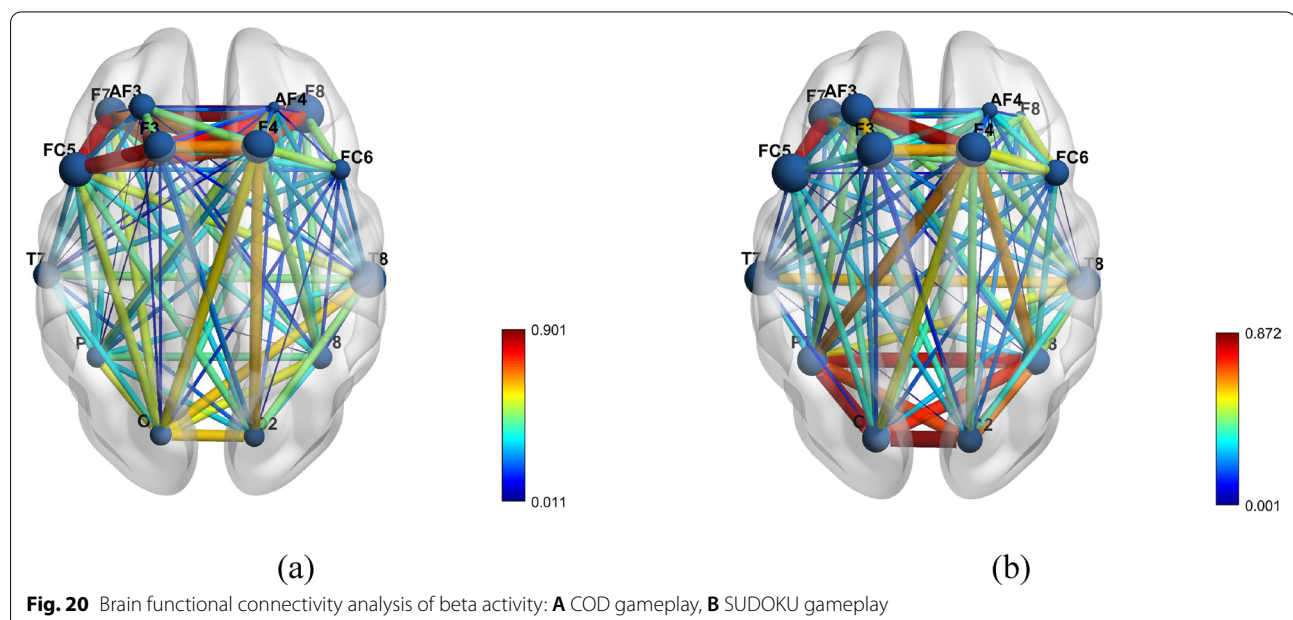
Network topology metrics such as Clustering Coefficient, Path Length, and Small-World Index (SWI) were calculated for EEG features in both COD (Action Video Game) and Sudoku (Puzzle Game) conditions. The results are summarized in Tables 10, 11, and 12. The

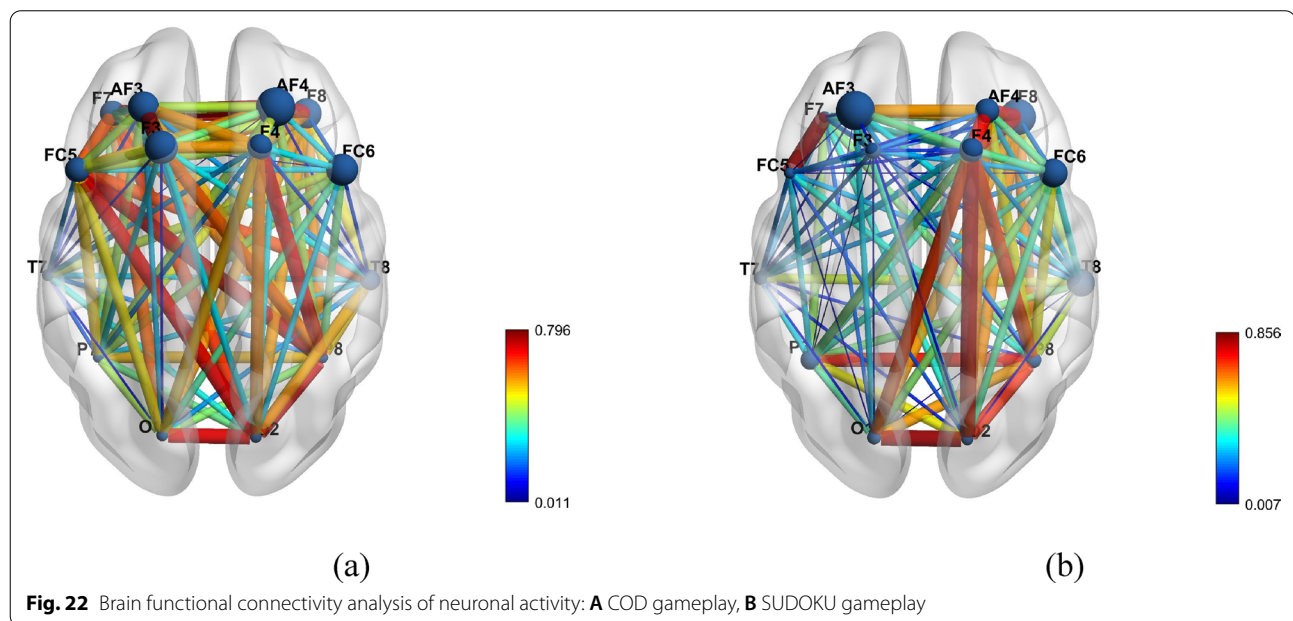
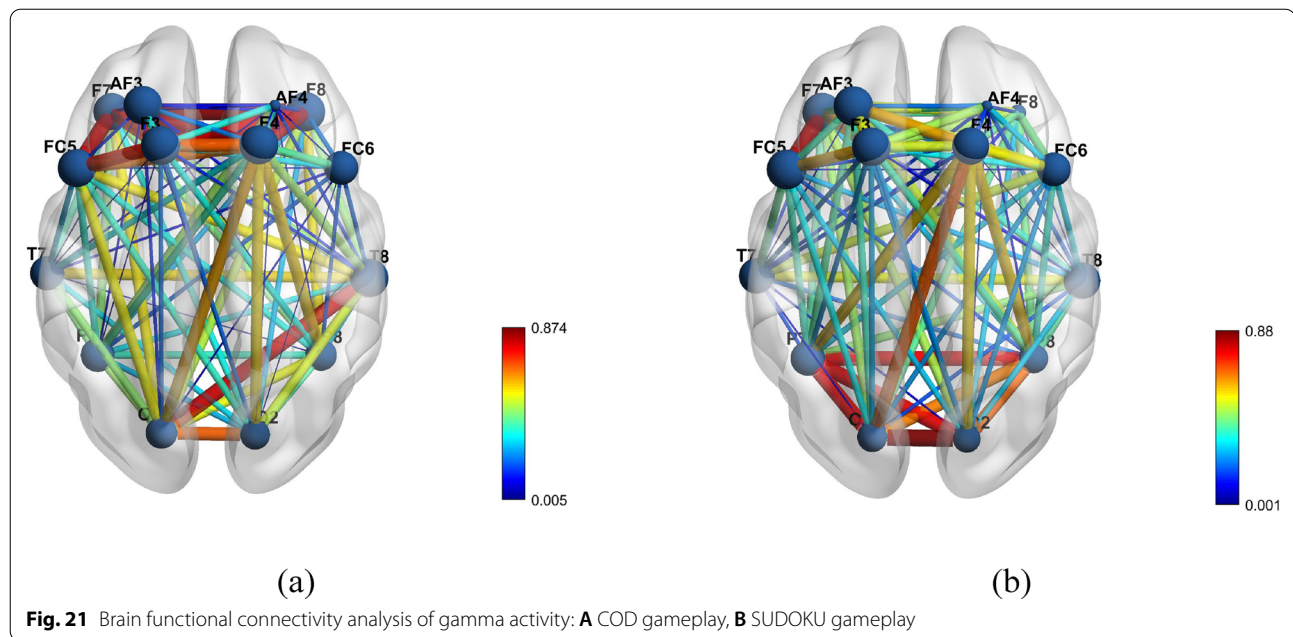
clustering coefficient reflects the tendency of nodes to form local clusters, supporting modular and task-specific processing. Higher clustering in fronto-parietal and prefrontal regions indicates better working memory capacity and efficient sensory information processing. In our data, COD gameplay showed higher clustering coefficients compared to Sudoku, indicating enhanced modular connectivity during fast-paced action gaming, as shown in Table 10.

Path length measures the efficiency of information transfer across the network. Shorter path length indicates higher global efficiency, allowing rapid integration of information across distant brain regions. Interestingly, Sudoku showed slightly shorter path lengths than COD, as shown in Table 11, reflecting distributed connectivity supporting logical reasoning and problem-solving.

Small-worldness (Sigma) combines high clustering and short path length to indicate an optimal balance between local specialization and global integration. COD gameplay showed higher Sigma values as shown in Table 12, indicating that action games enhance efficient information processing, faster reaction times, and improved memory encoding.

These results indicate that action video game play promotes modular, efficient, and high-performance brain network topology, while puzzle gameplay emphasizes distributed, global connectivity supporting analytical and logical reasoning. Inclusion of these metrics strengthens the manuscript by providing a quantitative network-level perspective of cognitive engagement across gaming conditions.





Advanced functional connectivity—mutual information (MI), and phase locking value (PLV)

The functional connectivity analysis has been extended beyond Pearson correlation by incorporating Mutual Information (MI) and Phase Locking Value (PLV), as suggested. Mutual Information, originally proposed in information theory [64], quantifies the statistical dependence between two signals without assuming linearity. When applied to EEG, MI provides a robust measure of

dynamical coupling between regions and is particularly effective for identifying both linear and non-linear interactions across spectral bands [65].

In the present study, Fig. 23 illustrates MI analysis of beta activity. During Call of Duty gameplay, information flow was concentrated in the frontal regions, indicating stronger executive and attentional processing. In contrast, during Sudoku gameplay, lower frontal flow was observed, accompanied by increased coupling across

Table 8 Connectivity analysis across different brain regions for COD and SUDOKU gameplay

Sl. No	EEG feature	Strong node details (COD)	Strong node details (SUDOKU)	Strong edge details (COD)	Strong edge details (SUDOKU)
1	Beta energy	F8, T8, FC5, F4, F7, F3, T7, AF3	FC5, F3, F7, T7, F4, T8, AF3, P7	F7-F3, FC5, F4, F8; F3-FC5, F4, F8; FC5-F4, F8; F4-F8; O1-O2	AF3-F4; F7-FC5; F3-F4; P7-O1, O2, P8, F4; O1-O2, P8; O2-P8; P8-F4
2	Gamma energy	AF3, F7, F3, FC5, T7, P7, T8, F4, F8	AF3, FC5, F7, F3, F4, T8, T7, P7, FC6	F7-F3, FC5, F4, F8; F3-FC5, F4, F8; FC5-F4, F8; O1-O2, T8, F4; F4-F8	AF3-F4; F7-F3, FC5; F3-FC5; P7-O1, O2, P8; O1-O2, P8, F4; O2-P8; P8-F4
3	Neuronal activity	AF4, F3, FC6, AF3, F8, F7, FC5, F4, T8, P8, O1, O2, T7, P7	AF3, F8, FC6, T8, AF4, F4, P7, P8, F3	AF3-F3; F7-FC5, O1, O2, F8, AF4; F3-P8; FC5-O2, P8, T8, F8; O1-O2; O2-P8, F4; P8-F4; F8-AF4	AF3-F8, AF4; F7-FC5; P7-P8; O1-O2, P8, F4, F8; O2-P8, F4, F8, AF4; P8-F4, F8; F4-F8, AF4; F8-AF4

occipital and temporal lobes, highlighting the involvement of visual and associative networks.

In parallel, Phase Locking Value (PLV) was used as an additional connectivity metric. PLV evaluates the degree of phase synchronisation between signals, which is well suited to the nonlinear and nonstationary characteristics of EEG [66, 67]. Figure 24 shows PLV analysis results: action gameplay produced tightly clustered synchronisation within frontal regions, consistent with heightened executive control and sustained attention. Puzzle gameplay, in comparison, exhibited more distributed connectivity spanning frontal-parietal, temporal-frontal, and occipital-parietal interactions. This broader pattern corresponds to cognitive functions such as visual attention, working memory, and memory retrieval.

The inclusion of MI and PLV thus provides a more comprehensive picture of EEG functional connectivity and addresses the reviewer's concern by demonstrating how distinct gameplay conditions are underpinned by different neural coupling patterns.

Discussion

The analysis of EEG signals during gameplay provided valuable insights into the cognitive and neural processes associated with several types of video games, specifically Action Video Games (AVGs) like Call of Duty: Modern Warfare 2 (COD) and Puzzle Games like Sudoku. Compared to the baseline rest condition, both games triggered distinct neural signatures, highlighting variations in cognitive load, attentional demands, working memory utilization, and emotional arousal. During COD gameplay, Delta energy and Synchronization Ratio (Delta/Theta) were significantly reduced, indicating increased cognitive engagement and sustained attentional focus. This aligns with previous findings [68, 69], which reported similar reductions in low-frequency oscillations during fast-paced, stimulus-driven gaming. Alpha desynchronization, a reliable marker of attentional engagement,

was particularly pronounced in COD, reinforcing the heightened visual scanning and sensorimotor integration required in action gaming environments.

Theta power is linked to memory encoding and retrieval in some cognitive tasks, particularly in short-term memory. Sudoku gameplay elicited a significant increase in Theta power, particularly over frontal electrodes, indicating higher short-term memory load associated with logical reasoning and problem-solving. This pattern aligns with previous findings[70], which demonstrated a clear link between frontal theta and working memory processing. While both games increased Beta power, the spatial distribution differed: COD produced stronger bilateral beta activation over frontal and parietal regions, indicative of motor preparation and executive control, whereas Sudoku resulted in a more localized increase over parietal and occipital lobes, reflecting visuospatial reasoning and mathematical cognition. This observation is consistent with prior research[71], which linked these regions to motor and attentional control in action games, and logical reasoning in puzzle solving, respectively. Gamma activity was high in while playing action video game when compared to sudoku, gamma band was associated with higher cognitive functions like attention, learning, and memory processes, particularly in long-term memory encoding and retrieval. It shows for COD game play long term memory was activated more.

A comparison of Cognitive Performance Index (CPI) and Engagement Index showed that players were significantly more engaged during COD than Sudoku, consistent with previous findings[72], which reported higher engagement during dynamic, visually immersive tasks. However, CNS Arousal Index (Theta/Beta Ratio) was higher in Sudoku than in COD, increased theta relative to beta is often seen in situations involving memory encoding and working memory (short-term memory) for sudoku. Also, it indicates higher

Table 9 Inferences from brain connectivity analysis for COD and SUDOKU gameplay

Energy bands	Brain connectivity edges (COD)	Brain connectivity edges (SUDOKU)	Inferences
Beta	More neuronal activity in Brodmann area 4 (Primary Motor Cortex), Brodmann area 9 (Dorsolateral Prefrontal Cortex), Brodmann area 35 & 36 (Dorsal Entorhinal Cortex)	More neuronal activity in Brodmann area 39 (Angular Gyrus), Brodmann area 20 (Inferior Temporal Gyrus)	• High cognitive functions such as working memory, attention, and executive function during COD • Complex visual processing and enhanced working memory are required during COD • SUDOKU involves visual information processing, number processing, spatial cognition, and memory retrieval
Gamma	Brodmann area 4 (Primary Motor Cortex), Brodmann area 9 (Dorsolateral Prefrontal Cortex), Brodmann area 35 & 36 (Dorsal Entorhinal Cortex), Brodmann area 19 (Associative Visual Cortex: V3, V4 & V5)	Brodmann area 39 (Angular Gyrus), Brodmann area 20 (Inferior Temporal Gyrus)	Similar patterns to the beta band but with greater emphasis on attention and sensory integration for COD and visuospatial reasoning for SUDOKU
Neuronal activity (NA)	Brodmann area 4 (Primary Motor Cortex), Brodmann area 9 (Dorsolateral Prefrontal Cortex), Brodmann area 35 & 36 (Dorsal Entorhinal Cortex), Brodmann area 19 (Associative Visual Cortex: V3, V4 & V5)	Absence of neuronal activity in Brodmann area 19 (Associative Visual Cortex)	COD gameplay requires continuous visual processing and sensory-motor coordination, while SUDOKU relies more on logical reasoning and working memory, with reduced motion-based visual processing

Table 10 Clustering coefficient of EEG features during COD and Sudoku gameplay

Sl. No	EEG features	Network topology metrics Features		Inferences
		COD	Sudoku	
1	Beta	0.9038	0.8986	Clustering Coefficient are high while subject playing COD game when compared to Clustering Coefficient. It shows that High clustering in frontoparietal and prefrontal regions supports modular, task-specific processing and better working memory capacity. Also, subject have fast filtering and processing of sensory information
2	Gamma	0.9086	0.8991	
3	NA	0.9890	0.9331	

Table 11 Path length of EEG networks during COD and Sudoku gameplay

Sl. No	EEG features	Network topology metrics: features		Inferences
		COD	Sudoku	
1	Beta	1.2198	1.1429	In the Sudoku game, subjects have shorter path length, which shows global efficiency, enabling rapid integration of information across distant brain regions. It is associated with improved executive function and problem-solving
2	Gamma	1.1538	1.1429	
3	NA	1.0110	1.0769	

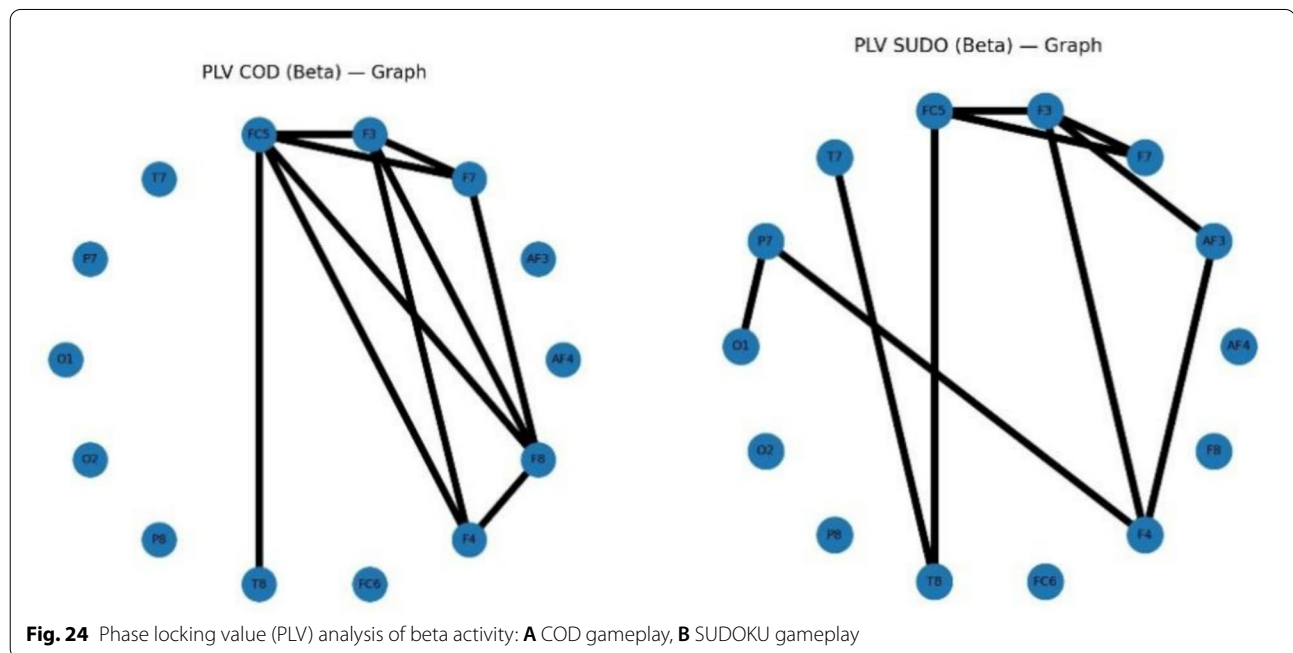
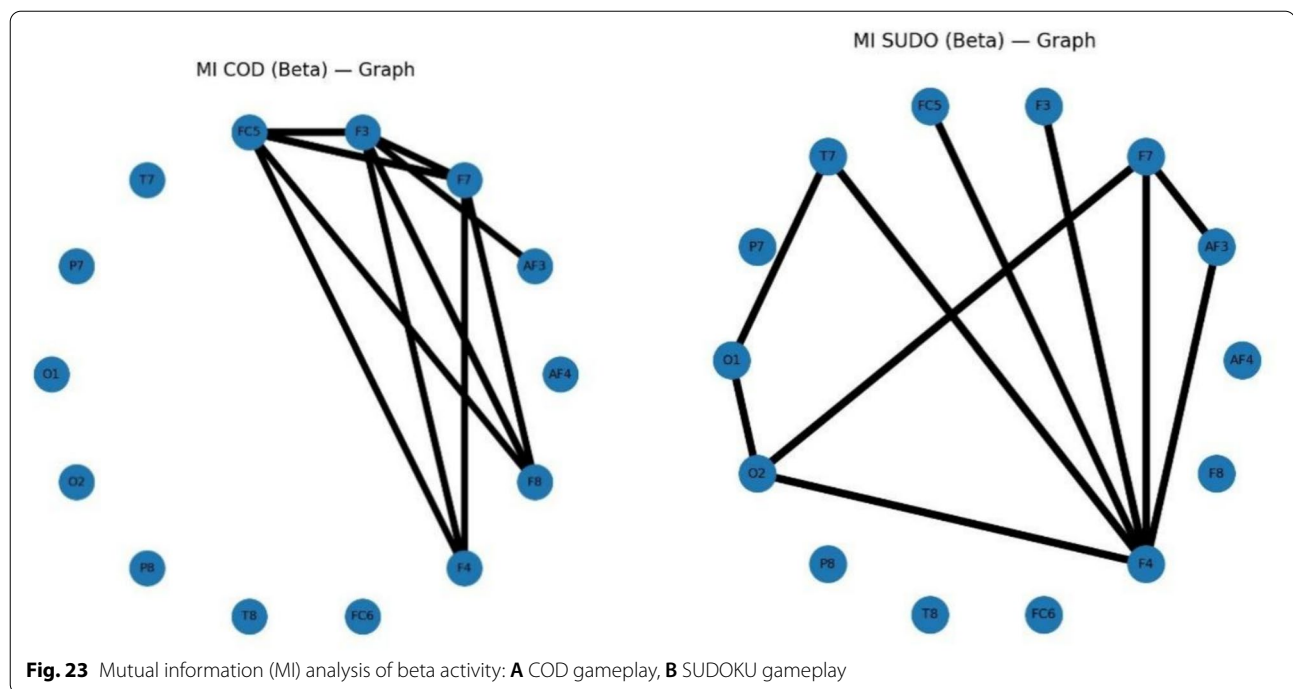
Table 12 Small-world index of EEG features during COD and Sudoku gameplay

Sl. No	EEG Features	Gamma		Lambda		Sigma (SWI)		Inferences
		COD	Sudoku	COD	Sudoku	COD	Sudoku	
1	Beta	1.1276	1.0607	1.0174	0.9914	1.1082	1.0699	COD game players have an increasingly pronounced small-world characteristic as compared to Sudoku; it shows that action video game play induces a better cognitive performance, faster reaction times, and more efficient memory encoding
2	Gamma	1.0861	1.0396	0.9915	1.0052	1.0954	1.0343	
3	NA	1.0025	1.0092	0.9978	1.0003	1.0047	1.0089	

cognitive stress associated with analytical reasoning under time pressure, aligning with cognitive stress patterns reported in [73]. Functional connectivity analysis further highlighted that COD gameplay activated bilateral fronto-parietal networks, supporting the real-time integration of sensory, motor, and executive functions, while Sudoku produced stronger right-lateralized connectivity between frontal and parietal cortices, emphasizing the right hemisphere's role in logical and spatial reasoning.

When benchmarking these findings against established cognitive neuroscience literature, as illustrated in Table 13, COD gameplay appears to promote attentional focus, motor coordination, and aspects of cognitive flexibility, supported by bilateral fronto-parietal coupling and strong alpha suppression. In contrast, Sudoku gameplay seems to engage working memory processes, logical reasoning, and problem-solving efficiency, reflected in theta enhancement and right parietal activation. Both game types impose cognitive load, but the nature of this load differs — sensory-motor and attention-driven in COD versus cognitive-analytical

in Sudoku. These distinctions provide preliminary evidence that different video game genres may engage distinct neural mechanisms, which in turn could be leveraged for targeted cognitive training strategies. However, given the modest sample size and the use of a consumer-grade EEG system, the present findings should be interpreted cautiously. Future studies with larger and more diverse cohorts, combined with multimodal neuroimaging approaches, are needed to validate these results and explore their generalisability. Overall, this study contributes to the growing body of work on game-based cognitive neuroscience by highlighting genre-specific neural and cognitive engagement patterns. While our findings are in line with prior literature, they remain exploratory and warrant replication before strong conclusions can be drawn about their translational potential for cognitive training or rehabilitation.



Conclusion

This study examined neurophysiological responses to two gaming genres: Action Video Games (AVG), represented by Call of Duty (COD), and Puzzle Games, represented by Sudoku. EEG data were analyzed across delta, theta, alpha, beta, and gamma bands, alongside cognitive

markers including attention, working memory, engagement, and CNS arousal, as well as functional connectivity patterns. COD gameplay was associated with enhanced visual attention, motor coordination, executive control, and bilateral fronto-parietal connectivity. Lower Theta/Beta ratios, higher Beta power, and alpha suppression

Table 13 Comparative benchmarking of neurophysiological responses during gameplay in Action Video Games (Call of Duty) and Puzzle Games (Sudoku) highlighting preliminary cognitive and neural correlates observed in this study, with reference to key benchmarking studies

Parameter	COD (AVG)	Sudoku (puzzle)	Benchmark studies
Attention (Theta/Beta)	↓ (More focus)	↑ (More cognitive stress)	Markus Bauer et al. [73]; Enda Tan et al. [68]
Working Memory (Theta Power)	Moderate ↑	High ↑	Fingelkurts et al. [70]
Alpha Suppression	Strong (Alertness)	Moderate (Logical Reasoning)	Klimesch [50]
Beta Power	High (Motor prep)	Moderate (Problem Solving)	Baker et al. [71]
Engagement Index	High	Moderate	Berka et al. [72]
Functional Connectivity	Bilateral (Fronto-parietal)	Right-dominant (Fronto-parietal)	Corbetta and Shulman [74]
CNS Arousal	Low (Focused)	High (Stressful)	van Son et al. [69]

indicated greater attentional focus, sensory-motor readiness, and alertness, while engagement was high, albeit with moderate cognitive stress due to fast-paced, time-sensitive tasks.

Sudoku gameplay elicited higher working memory demands, right-dominant fronto-parietal connectivity, and increased parietal activation, reflecting logical reasoning, stepwise problem-solving, and visuospatial processing. Elevated theta activity indicated memory retrieval and cognitive processing, with moderate engagement and higher analytical stress. These patterns are consistent with prior findings that action games enhance perceptual-motor and attentional networks, whereas puzzle games strengthen reasoning and memory systems.

Behavioral measures, including commission and omission errors and performance scores, correlated with EEG features such as executive load index, LF/HF ratio, synchronization, arousal index, and cognitive performance index. However, these correlations do not imply causality, and the direction of influence between neural activity and behavioral performance remains to be investigated. Practical challenges with the EMOTIV EEG headset contributed to the gender imbalance. For accurate readings, the sensors require direct scalp contact, which can be difficult with long hair, more commonly seen in female participants. Ensuring proper sensor placement and high-quality EEG data was a priority. Future studies will aim for a larger and more gender-balanced sample to allow robust analyses of potential gender-related differences.

While this study provides valuable insights into the neural dynamics of action and puzzle video games, its findings should be interpreted with caution. The relatively modest and gender-imbalanced sample size limits its statistical power and generalisability, and the use of the Emotiv EPOC X headset, although convenient and non-invasive, offers lower spatial resolution than

clinical-grade EEG or MEG systems. In addition, the focus on a narrow age range of healthy young adults restricts applicability to other populations such as children, older adults, or clinical groups. In light of these limitations, these factors indicate that the present results should be regarded as exploratory. Future work should therefore employ larger and more diverse cohorts, incorporate multimodal neuroimaging techniques (e.g., EEG–fMRI or MEG), and adopt longitudinal designs to test the stability of the observed effects. Such directions will be essential to validate and extend these preliminary findings, and to establish the broader potential of video games as tools in cognitive neuroscience, education, and rehabilitation.

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Author contributions

Kuppan Chetty Ramanathan: conceptualization, methodology, investigation, supervision, writing—review & editing. Adalarasu Kanagasabai: conceptualization, methodology, analysis, investigation, validation, project administration, supervision, writing—original draft. Arunkumar Pinagapani: data curation, validation, software. Thevarayan Iyappan: experimentation, data curation. G. Sivani: experimentation, data curation.

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Data availability

The data that support the findings of this study are available from the first author and the corresponding author upon reasonable request.

Declarations

Conflict of 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.

Ethical approval

This study was conducted in full compliance with the ethical guidelines and institutional policies. All necessary precautions were taken to ensure the

welfare and rights of the participants. Informed consent was obtained from all participants before their involvement in the study, ensuring they were fully aware of the study's purpose, procedures, and potential risks. The confidentiality and privacy of all participants were strictly maintained throughout the research process.

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