

Oral GABA supplementation immediately improves standardized MOBA micro-performance and frontal EEG engagement in esports: a randomized, double-blind, crossover trial

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Abbreviations: ASIC, application-specific integrated circuit; BMI, body mass index; FFT, fast Fourier transform; FPS, first-person shooter(s); GABA, γ -aminobutyric acid (gamma-aminobutyric acid); LoL, League of Legends; MMR, matchmaking rating; MOBA, multiplayer online battle arena(s); MPG, Mobalytics Proving Ground; SMR, sensorimotor rhythm; TGAM, ThinkGear ASIC Module; Fp1, frontopolar site 1

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Abstract

Oral intake of gamma-aminobutyric acid (GABA) reduces stress and promotes relaxation, but its effect on esports performance is unclear. In a randomized, double-blind, placebo-controlled crossover trial, 21 MOBA-genre esports players were enrolled; 18 were analyzed after prespecified exclusions. Thirty minutes after ingesting 200 mg GABA or placebo, players completed the Mobalytics Proving Ground (MPG), a standardized MOBA micro-performance battery. Frontal EEG at Fp1 yielded an SMR-weighted, EEG-derived engagement index, a putative EEG marker of task engagement (flow). GABA increased total MPG score and the engagement index versus placebo ($p < 0.05$). Higher Δ SMR was associated with higher MPG scores ($r = 0.418$, $p = 0.011$), and the Δ SMR \times treatment interaction was not significant ($F(1,16) = 0.367$, $p = 0.553$). These findings indicate that oral GABA intake can enhance immediately micro-management performance under cognitive load accompanied by increasing EEG-indexed engagement in esports.

Keywords: Esports; MOBA; GABA; Electroencephalography (EEG); Micro-performance.

1. Introduction

Esports are defined as a form of sport in which competition occurs through electronic systems, where player inputs and system outputs are mediated via a human-computer interface (Hamari and Sjöblom, 2017). In recent years, esports has experienced rapid

growth, with the number of amateur players across PC, console, and mobile platforms reaching 3.42 billion worldwide. The global gaming market is projected to reach \$187.7 billion by 2024 (Newzoo, 2024). This growth highlights the increasing significance of esports as a research subject.

Enhancing esports performance requires interventions that sup-

port overall cognitive function. Nutritional supplementation has gained attention as a potential strategy for optimizing cognitive performance. Multiple studies have reported that caffeine reduces reaction times and enhances shooting accuracy (Sainz et al., 2020; Scott et al., 2017; Wu et al., 2024), although excessive caffeine intake carries potential risks (Juliano and Griffiths, 2004). Similarly, glucose consumption elevates blood sugar levels (Setoguchi et al., 2020) and temporarily enhances cognitive function (Furukado et al., 2022).

Because esports performance can be influenced by emotional and psychological states (Hung et al., 2019), many players attempt to manage their condition through commercially available products such as energy drinks, which may increase the risk of excessive intake of certain ingredients. More broadly, food-derived components with stress-reducing and cognitive-supporting properties are of interest in this field.

GABA has been recognized for its relaxation effects (Fujibayashi et al., 2008) and its role in reducing psychological stress (Abdou et al., 2006; Nakamura et al., 2009) with no reported adverse effects. Subchronic toxicity studies in rats have established a no-observed-adverse-effect-level (NOAEL) for GABA at 2,500 mg/kg body weight (Takeshima et al., 2014; Tashiro et al., 2017), and a 30-day human safety study confirmed that a daily oral intake of 250 mg of GABA resulted in no adverse effects (Horie et al., 2011). Studies on healthy adults have demonstrated that a single oral dose of 50 mg of GABA can temporarily enhance cognitive function (Kanehira et al., 2011). Additionally, daily intakes of 100 mg (Yamatsu et al., 2020a) and 200 mg (Yamatsu et al., 2020b) over a three-month period have also been shown to provide temporary cognitive benefits.

A comprehensive review provides detailed information on the human safety profile of orally ingested GABA (Oketch-Rabah et al., 2021). A systematic review of placebo-controlled trials in humans reported limited evidence for stress-related outcomes and limited evidence for sleep-improvement effects (Hepsomali et al., 2020). In addition, a recent review discussed the possibility that oral GABA intake may influence the brain, including potential neurophysiological effects such as changes in EEG responses and cognitive performance (Almutairi et al., 2024).

Despite this accumulating literature, evidence remains limited regarding acute effects and neurophysiological correlates of oral GABA during standardized MOBA performance tasks. A recent study by Hara et al. (2025) showed that a single oral dose of GABA not only improved objective game-performance indices but also reduced self-reported confusion, yet the physiological basis of these effects remains largely unexplored. To begin addressing this gap, the present study incorporates electroencephalography (EEG) as a non-invasive index of cortical activity during gameplay, providing an initial step toward linking GABA intake with objective neurophysiological correlates of performance. EEG is widely used to assess cognitive engagement and immersion during gameplay (Lim et al., 2019; Musha et al., 1997).

Unlike in traditional sports, esports performance is primarily dependent on cognitive rather than physical skills (Fanfarelli, 2018). Furthermore, the cognitive demands for performance vary across esports genres, such as first-person shooters (FPS), multiplayer online battle arenas (MOBA), fighting games, puzzle games, and sports games. For example, League of Legends (LoL), the most renowned MOBA game, involves teams of five competing to destroy an opponent's base.

MOBA performance can be broadly categorized into micro (micro-management) and macro (macro-management) components based on the relative importance of this variable across games and platforms (Kim, 2013). In this study, micro-management refers to

the set of fine motor and perceptual-motor control skills required for rapid in-game actions, whereas micro-performance denotes the measurable outcome of these skills, such as task scores in standardized assessments. According to Fanfarelli (2018), micro-performance refers to the precise and rapid control of input devices (e.g., mouse and keyboard), individual movements, and positioning. In team-based games such as Overwatch, it can also encompass mechanically synchronized actions with teammates, known as “team-based mechanical synergies.” This concept is distinct from strategic team coordination, which is typically categorized as macro-performance. Macro encompasses situational awareness, resource management, and overall game strategy. Macro-performance encompasses strategic decision-making and team coordination, making it inherently more difficult to quantify and evaluate objectively than micro-performance.

Micro-management is closely related to perceptual-motor skills, which involve the processing of sensory information and the execution of appropriate motor responses. In MOBA games, micro-controls include precise mouse and keyboard control, visual information processing, and reaction speed. In real-time strategy games such as StarCraft II, micro-management refers to fine-tuned control over unit actions, including resource gathering, combat, and movement (Zong et al., 2023). Perceptual-motor skills are essential for high-level performance (Pluss et al., 2023), and their improvement can be objectively evaluated. Therefore, when designing research on esports, it is important to determine the specific genre and performance components to be assessed using standardized evaluation methods. To address this issue, the present study employed the Mobalytics Proving Ground (MPG), a standardized assessment task specifically developed for LoL players by Pluss et al. (2023), to focus on micro-performance in the MOBA genre.

In the present study, we focus on the MOBA genre and objectively assess micro-performance using a standardized task. This study aimed to examine the effects of GABA intake on the esports performance and physiological indicators of MOBA players. Specifically, a randomized controlled trial (RCT) with a crossover design was conducted to compare micro-performance in MPG tasks under GABA and placebo conditions. EEG data were analyzed to investigate changes in cognitive states, particularly immersion, following GABA supplementation.

2. Materials and methods

2.1. Experimental design

The study design and experimental protocol used in this research are shown in Figure 1. This study employed a double-blind, repeated-measures, crossover trial design in which participants were randomly assigned to consume either GABA (encapsulated in an edible film) or dextrin as a placebo (also encapsulated in an edible film). A 7-day washout period was implemented between conditions before participants performed an esports task. The order in which the participants received the test compounds was determined using stratified block randomization (block size = 2). Specifically, participants were first stratified based on whether they were assigned to the GABA or placebo group, and allocation was conducted using a random number generator in Microsoft Excel for Microsoft 365 to ensure balance and randomness across conditions. To maintain blinding, the principal investigator, study coordinator, operators, and participants remained unaware of the assignment until the analysis phase was complete. The study commenced on March 25, 2024, and concluded on July 5, 2024.

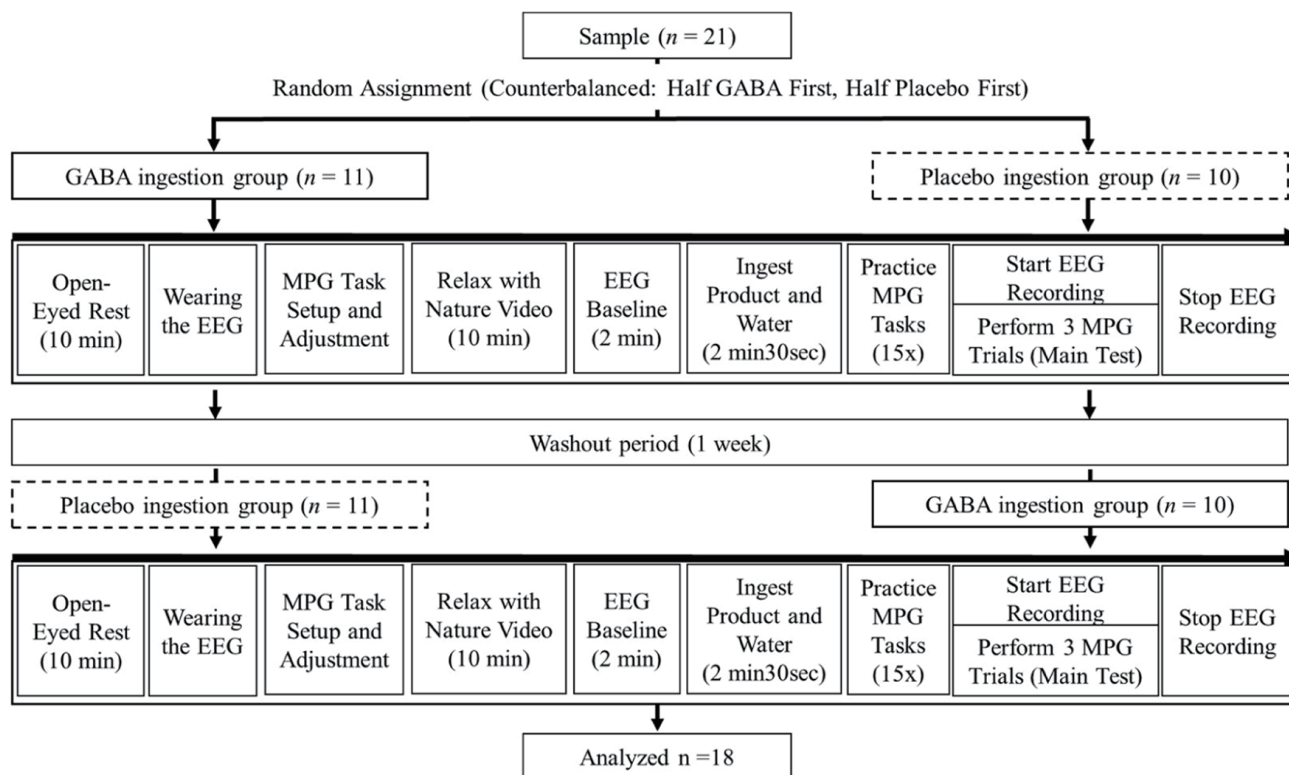


Figure 1. Study Design and Protocol. The order of test compound ingestion was designed with counterbalancing considerations. A one-week washout period was implemented between conditions. To maintain a quiet environment during the experiment, entry was restricted to only the operator.

All experiments were conducted in a dedicated esports laboratory equipped with gaming monitors with a refresh rate of at least 144 Hz while maintaining consistent room lighting and noise levels. The room temperature was controlled using an air-conditioning system set at $22 \pm 2^\circ\text{C}$, and the humidity was maintained at $55 \pm 10\%$. The participants used a familiar mouse and keyboard to ensure consistency in familiarity with the input device.

Upon entering the laboratory, participants sat in a chair and rested for 10 min before completing a demographic and gaming experience questionnaire. Next, a portable EEG device was fitted, and participants received instructions on the MPG esports task, including operational details. The participants were then allowed to adjust their mouse sensitivity settings to their preferences.

Following this preparation, participants were seated and instructed to watch a 10-minute nature video featuring a river stream with ambient sounds to induce relaxation. After this period, baseline EEG signals were recorded for 2 min while participants remained in an eyes-open state with minimal blinking. Next, participants were instructed to consume 30 mL of mineral water along with the assigned test compound (GABA or placebo). A 2-minute 30-second period was allocated for the test compound ingestion, followed by a 27-minute 30-second practice phase for the MPG task. During this phase, participants performed 15 practice trials with a 30-second interval between trials.

EEG recording was initiated 30 min after intake of the test compound. This timing was determined based on previous studies indicating that GABA blood concentration peaks around this time (Yamatsu et al., 2016), as well as findings that GABA increases parasympathetic nervous activity for up to 30 minutes post-intake (Nakamura et al., 2009). Additionally, LoL matches typically last

approximately 30 min, making this timeframe relevant for esports-related performance assessments (Demediuk et al., 2018; Novak et al., 2020). Based on previous research, the EEG recording lasted for 3 min (Furukado et al., 2022). During EEG data acquisition, the participants performed three official MPG trials, and their game performance scores were recorded.

2.2. Participants

We planned a 2×2 crossover powered for the within-subject treatment difference on the MPG Total Score. From an independent pilot (Hara et al., 2025), the within-subject *SD* of the paired difference (GABA–placebo) was $\sigma(d) = 59.08$ points ($n = 8$; per participant, mean of 18 trials per condition). Assuming Cohen's $d = 0.7$, the target mean difference was $\Delta = d \times \sigma(d) = 0.7 \times 59.08 \approx 41.4$ points. A two-sided paired-difference test ($\alpha = 0.05$, power = 0.80) indicated a required sample size of $n = 17$. To account for potential data exclusion or dropout, 21 healthy participants (19 males, 2 females) who were not undergoing pharmacological treatment for any medical condition and had no symptoms of memory impairment were initially recruited. The participants' demographic characteristics, including age, height, weight, and BMI, are summarized in Table 1.

Participants had prior experience with MOBA games and were recruited from university students and working professionals. The experiment was conducted between May and July 2024. Additionally, all participants had experience playing LoL, with an average weekly playtime of 4.93 ± 6.00 hours. According to the match-making rate (MMR) on the Japan server as of March 2024, 14

Table 1. Baseline characteristics participants

	Participant Characteristics (n = 21)
Age (Years)	26.24 ± 9.83
Sex (Male/Female)	19/2
Height (cm)	170.80 ± 4.16
Weight (kg)	71.65 ± 18.63
BMI (kg/m ²)	24.51 ± 6.17
Gameplay per week (h/week)	4.93 ± 6.00

Data are expressed as mean ± standard deviation. Sex data were presented as the number of male and female participants.

participants were unranked: 2 in the Bronze tier, 1 in Silver, 1 in Platinum, 2 in Emerald, and 1 in Diamond.

Eligibility criteria: The inclusion criteria were as follows: (i) healthy adults without pain, mental disorders, insomnia, or any injuries and who had not used any medication in the past two months; and (ii) individuals who had been playing LoL, a MOBA game, for at least two years. The exclusion criteria were as follows: (i) female participants during their menstrual period, (ii) individuals under 18 years old, (iii) individuals without sufficient competitive experience in MOBA games, and (iv) individuals with cardiovascular disease or any condition that could cause physical discomfort. Eligibility was assessed at enrollment using a brief health questionnaire and a short interview. Medication use within the prior two months and relevant health conditions were confirmed by self-report. For female participants, sessions were scheduled outside the menstrual period based on self-report.

All participants received a thorough explanation of the experimental procedures and associated risks and provided written informed consent. This study was approved by the Little Software Ethics Committee (Approval No. 2024-0010, March 25, 2024) and conducted in accordance with the Declaration of Helsinki. Three participants were excluded from the EEG analysis due to missing or invalid EEG recordings (data-quality-based exclusion), resulting in a final EEG sample of 18 participants (see Section 2.6).

2.3. Test product

The participants were instructed to ensure they had adequate sleep (at least 7 h) the night before the experiment and were prohibited from engaging in intense physical activity or consuming alcoholic beverages the night before. On the day of the experiment, the participants were required to refrain from smoking, chewing gum, or consuming food and beverages (including coffee, energy drinks, chocolate, phosphate-based drinks, and caffeinated tea) for at least two hours before the experiment. Only water consumption was permitted. Furthermore, participants verbally confirmed on the day of testing that they had not consumed any caffeine-containing substances since waking up.

Pharma GABA® (with more than 95% pure naturally fermented GABA, Pharma Foods International Co., Ltd, Kyoto, Japan) was used in this study. 200 mg GABA was wrapped in wafer paper (oblate) for test group, whereas the placebo used dextrin (Sandec® #100, Dextrose Equivalent 10-13, Sanwa Starch Co., Ltd., Nara, Japan) instead of GABA. The GABA and placebo samples were identical in size, shape, and color when observed through the oblate film. All participants completed the protocol without any adverse effects related to gameplay or ingestion of the test compounds.

2.4. Esports task (Mobalytics Proving Ground)

MPG (<https://pg.mobalytics.gg/>) is a task developed by Gamers Net, Inc., which simulates gameplay in LoL, a leading title in the MOBA genre, and evaluates micro-management, including Aim, Background Processing, and Map Awareness (Figure 2). The exact scoring system of the MPG is undisclosed; however, empirical observations suggest a 2,000-point scale, with the aim task contributing 1,000 points, Background Processing 500 points, and Map Awareness 500 points. Each MPG session lasted 60 s, during which players accumulated points by executing the three tasks simultaneously with optimal efficiency.

In the Aim task, circular targets appeared randomly on the screen at brief intervals, requiring players to quickly move the mouse cursor to the target and destroy it. In total, 117 targets appeared within 60 s (1.95 occurrences per s). Regardless of whether the target was destroyed, it automatically disappeared after one second. Owing to minor timing variations in target generation, a maximum of three targets may be displayed on the screen at any given moment. More points are awarded for clicking closer to the center of the target, whereas inaccurate clicks or failure to click before the target disappears results in a point deduction. The aim of the task was to evaluate the speed and accuracy of the mouse-based approach.

In the Background Processing task, four bars appeared on the upper left of the screen and gradually decreased at varying speeds. Players must press the corresponding keys (Q, W, E, and R, which are the default ability keys in LoL) at the correct time when the bars change from red (default) to green. Points were granted only when the correct key was pressed while the bar was green, causing the bar to be reset to its full level. Pressing the wrong key or missing the color change turns the bar gray, locks it for five seconds, and prevents further point acquisition. The bars decrease at a random speed in each attempt, allowing for 42 to 46 input opportunities within 60 s (0.7 to 0.77 times per s).

In the Map Awareness task, players used a minimap in the lower right corner of the screen to navigate an airplane object to the left or right, avoiding obstacles (right movement = F, left movement = D, which are the default summoner spell keys in LoL). If the airplane collides with an obstacle, its movement is restricted, thereby limiting the player's opportunity to gain points. There are 8 to 10 input opportunities within 60 s (0.13 to 0.17 times per s).

2.5. Outcome measures: evaluation of effect during gameplay using EEG data

Standard EEG systems can sample multiple cortical sites, yet their lengthy setup and tight headgear may burden participants. Prior work shows that the left-frontal region, which is less obstructed by hair, is suitable for psychological recordings (Sakamoto et al., 2006). Within this area, Fp1 is effective for tracking cognitive engagement and interest (Negishi et al., 2011). Because esports players wear large headsets and rely heavily on auditory cues, a frontal montage avoids interference; therefore, the active electrode was placed at Fp1 in accordance with the international 10-20 system (Jasper, 1958). EEG signals, which reflect neural activity, yield information about cognitive states through frequency-band categorization (Karlik and Hayta, 2014).

This study adopted the effective frequency bands of sensorimotor rhythm (SMR) waves (12–13.25 Hz). SMR waves constitute a frequency range of brain activity linked to psychological states of relaxation and concentration (Heinrich et al., 2007). In this study, the flow state was defined as a psychological state in which a play-



Figure 2. Explanation of the MPG task and task execution screen (Gamers Net, Inc.©). The image illustrates the three tasks in the MPG environment. (1) Aim Task: Circular targets appear at random with slight time variations near the center of the screen. Participants must quickly align the mouse cursor with the target and destroy it. (2) Background Processing (BP) Task: Four bars displayed in the top-left corner of the screen decrease at random speeds. Participants must press the correct key (Q, W, E, or R) at the right moment when the bar changes from red (default) to green. Points are only awarded when the bar is green. Incorrect key presses turn the bar gray, locking it for five seconds. (3) Map Awareness (MAP) Task: In the bottom-right area, participants use the F and D keys to maneuver an airplane object left and right to avoid obstacles falling from above. If the airplane collides with an obstacle, movement is restricted, limiting the opportunity to earn points. Each session lasts 60 seconds.

er is fully immersed in a task while maintaining an optimal balance between the challenge and skill (Csikszentmihalyi, 1990). Flow is often associated with enhanced cognitive performance, sustained attention, and an altered perception of time. Given that SMR waves are linked to cognitive engagement and focus, we adopted the SMR wave activity as a physiological marker of cognitive involvement in this study.

The EEG data analysis followed the general procedures of previous studies (Furukado et al., 2022; Hagiwara et al., 2020) with minor adaptations for the present experiment. Signals were recorded with a consumer-grade, single-channel MindWave headset containing the ThinkGear™ ASIC Module (TGAM; NeuroSky Inc., San Jose, USA); reference and ground electrodes were clipped to the left earlobe. According to the TGAM datasheet, the analog front-end incorporates a hardware high-pass filter with a cut-off close to 3 Hz and a low-pass cut-off near 100 Hz, together with a 50/60 Hz notch filter for mains-noise suppression (NeuroSky, 2011). Independent bench tests have shown that frequencies below about 3 Hz are markedly attenuated, confirming the intended suppression of sub-delta activity (Rieiro et al., 2019). The module's on-chip artefact routine detects eye blinks and outputs a proprietary blink-detection flag (NeuroSky, 2011). After digitization at 512 Hz, data were streamed via Bluetooth to Sports KANSEI (LittleSoftware Inc., Tokyo, Japan) for offline processing. Continuous traces were segmented into 4-s epochs (2,048 samples, 50 % overlap), tapered with a Hanning window, and converted to power spectra by fast Fourier transform (FFT) with a 0.25 Hz resolution. Because blink artifacts concentrate in the delta band (0.5–4 Hz) (Bonfiglio et al., 2013; Rieiro et al., 2019), delta-band power was excluded from all subsequent analyses. Relative SMR power was

then computed with Equations (1)–(3) and expressed as a percentage change from baseline; these values were then compared between supplementation conditions. According to Equation (1), the average power of the SMR waves P_x was calculated based on V_f EEG power at a given frequency f Hz. Subsequently, the total power sum (P_{sum}) was derived from the alpha and beta frequency bands using Equation (2). Finally, the proportion of SMR power relative to the total power (R_x) was computed using Equation (3). Specifically, the change was calculated by subtracting the baseline value from the gameplay value.

$$P_x = \sum_{f=f_{min}^x}^{f_{max}^x} \frac{V_f}{F_{max}^x - F_{min}^x + 1} \quad (1)$$

$$P_{sum} = P_\alpha + P_\beta \quad (2)$$

$$R_x = \frac{P_x}{P_{sum}} \quad (3)$$

2.6. Statistical analysis

A total of 21 participants were enrolled in the study. Due to missing or invalid EEG data, three participants (IDs 9, 16, and 17) were excluded, leaving 18 participants for the final analysis. The effects of the test supplement versus placebo on both MPG game performance and the flow index were assessed with a two-period, two-sequence crossover general linear mixed-effects model that included intervention and sequence as fixed factors and participant

Table 2. Comparison of MPG scores between the GABA and placebo conditions

MPG task score	Unit	Placebo			GABA			Intervention Effect				
		N	Mean	SD	N	Mean	SD	Δ	SE	95% CI-	95% CI+	P
Total Score	Points	18	1,055	200	18	1,173	175	123	33	52	193	0.002
Aim	%	18	64.6	9.8	18	68.7	8.3	4.3	1.1	2.0	6.5	0.001
Background processing	%	18	20.3	6.0	18	26.4	13.5	6.2	2.7	0.6	11.9	0.032
Map awareness	%	18	47.3	18.5	18	56.4	13.6	9.2	3.5	1.8	16.6	0.018

M = mean, SD = standard deviation, Δ = difference in estimated marginal means, SE = standard error, 95% CI- = 95% confidence interval (lower bound), 95% CI+ = 95% confidence interval (upper bound). Aim, Background Processing, and Map Awareness represent score percentages (%). Each MPG task score indicates the mean of three official MPG trials completed during the 3-min EEG recording (30 min post-intake).

as a random intercept. Specifically, the model treated GROUP (i.e., sequence: Placebo \rightarrow GABA or GABA \rightarrow Placebo), VISIT (i.e., period: first or second measurement), and FOOD (i.e., treatment: Placebo or GABA) as fixed factors, and participant ID as a random factor. Pairwise contrasts were evaluated with the least-significant-difference (LSD) procedure.

A within-participant (subject-centered) Pearson correlation was computed between the condition-level change in Fp1 SMR (gameplay minus baseline; averaged across official trials within each condition) and concurrent MPG performance. To formally test whether this EEG-performance coupling differed by treatment, a linear mixed-effects model was additionally fitted with participant as a random intercept and fixed effects for treatment, the condition-level EEG measure, and their interaction. Models were estimated with restricted maximum likelihood and Satterthwaite degrees of freedom; the significance threshold remained at $p < 0.05$. All analyses were performed with IBM SPSS Statistics version 28 (IBM Corp., Chicago, IL, USA).

3. Results

The total score was significantly higher in the GABA condition than in the placebo condition, with a difference in estimated marginal means ($\Delta = 122.8$ points, SE = 33.2, 95% CI: 52.4 to 193.2, $p = 0.002$, $F(1,16) = 13.7$). The Aim score also showed a significant increase under the GABA condition ($\Delta = 4.3\%$, SE = 1.1, 95% CI: 2.0 to 6.5, $p = 0.001$, $F(1,16) = 13.6$). Background processing was significantly improved ($\Delta = 6.2\%$, SE = 2.7, 95% CI: 0.6 to 11.9, $p = 0.032$, $F(1,16) = 5.5$). For Map awareness, the GABA condition outperformed the placebo condition ($\Delta = 9.2\%$, SE = 3.5, 95% CI: 1.8 to 16.6, $p = 0.018$, $F(1,16) = 7.0$). No significant period or carry-over effects were observed for MPG outcomes, as indicated by non-significant effects of sequence and visit ($p > 0.05$).

Further statistical details, including differences in estimated marginal means and confidence intervals for each condition, are summarized in Table 2.

The percentage of SMR wave power 30 min after consumption of the test product was compared between the GABA and placebo groups, which represented the target measurement time in this study. In addition, the change from the baseline (at rest) was calculated for both reagent conditions. A significant increase in SMR power was observed in the GABA condition (5.40%, SE = 1.11) compared to the placebo condition (1.78%, SE = 1.11), with an estimated mean difference of 3.62% (SE = 1.57, 95% CI: 0.3 to 6.95, $p = 0.034$, $F(1, 16) = 5.34$) (Figure 3). These values represent changes from the resting state, adjusted using a general linear mixed model. For EEG outcomes, a significant order effect was observed based on the sequence of intervention groups ($p = 0.037$), whereas no significant period effect was found across visits ($p = 0.806$).

A positive within-participant association was observed between Fp1 Δ SMR and MPG performance ($r = 0.418$, $p = 0.011$; 36 observations from 18 participants), where MPG performance was defined as the mean of three official MPG trials completed during the 3-min EEG recording at 30 min post-intake. In the linear mixed-effects model, the Δ SMR \times treatment interaction was not significant ($F(1,16) = 0.367$, $p = 0.553$), indicating no evidence that the EEG-performance coupling differed between GABA and placebo. The main effect of Δ SMR was not significant ($F(1,16) = 0.302$, $p = 0.590$). In addition, the main effect of treatment was significant ($F(1,16) = 7.309$, $p = 0.016$); the estimated marginal mean was higher in GABA than in placebo by 107.26 points (95% CI 23.15–191.36).

4. Discussion

The aim of this study was to investigate the immediate effects of ingesting 200 mg of GABA on micro-performance and flow state (task immersion and focused state) in MOBA esports players, as evaluated using task scores and EEG indicators, respectively.

The GABA intake amount was set at 200 mg based on previous research findings. Studies have reported that GABA 28 mg alleviates psychological stress (Nakamura et al., 2009), GABA 50 mg reduces mental and physical fatigue while enhancing problem-solving ability (Kanehira et al., 2011), and GABA 100 and 200 mg result in more pronounced improvements in cognitive function (Yamatsu et al., 2020a, 2020b).

Additionally, the esports task used in this study (MPG) required complex cognitive skills such as visual search involving various user interface elements in the LoL, rapid decision-making, and attentional distribution. The task also involves asynchronous move-

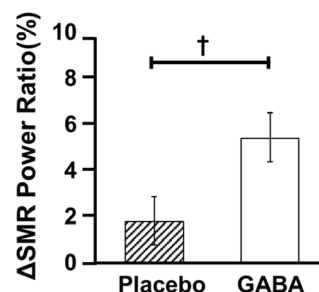


Figure 3. Estimated marginal means of relative SMR power (%) during gameplay, adjusted for baseline values using a general linear mixed-effects model. Bars indicate the change from the resting state to 30 minutes after intake for the placebo and GABA conditions. Error bars represent the standard error of the mean. † $p < 0.05$, significantly different from placebo.

ments of both hands, making it cognitively demanding. Given these factors, GABA 200 mg was considered the most appropriate dosage.

This study employed a double-blind crossover design with MOBA-experienced players, and their MPG task scores were evaluated. The main finding of this study was that the micro-performance of amateur esports players who play MOBA games (LoL) for an average of 4.93 hours per week significantly improved temporarily after GABA intake. The extent to which the present findings generalize beyond the MOBA genre should be interpreted with caution. Robust conclusions about GABA's effects in first-person shooter (FPS) games will require dedicated experimental paradigms; for example, the target-aiming software Aim Lab (Statespace Labs Inc., 2018) could be employed to verify such effects.

Secondary analyses indicated a concurrent within-participant association between Fp1 Δ SMR and MPG performance—higher Δ SMR tended to coincide with higher scores. At the condition level (means across official trials within each condition), this correspondence did not appear to change with GABA ingestion, suggesting that the treatment primarily raised the mean level of execution rather than altering the correspondence between EEG measures and performance.

In LoL, players must distribute their attentional resources across multiple simultaneous tasks that require parallel processing (Pluss et al., 2023). During MPG execution, attentional resources are primarily allocated to Aim and Background Processing tasks, which operate at a higher frequency (Aim: 1.95 times/sec, Background Processing: 0.7–0.77 times/sec) than Map Awareness (0.13–0.17 times/sec). Furthermore, in the GABA-intake condition, significant performance score differences were observed for all three elements, including Map Awareness, which had the lowest operation frequency. This suggests that GABA intake may reduce the cognitive load during MPG execution, a task composed of three subtasks requiring attentional distribution, shifting, maintenance, and selection, ultimately contributing to improved task performance and EEG data.

In this study, we used EEG, a physiological indicator, to clarify how GABA intake affects the physiological state of players under high cognitive load conditions rather than simply evaluating changes in game scores. In esports EEG research focusing on the fighting game genre, pre-match beta wave activity in the parietal region has been identified as a key predictor of competition outcomes (Minami et al., 2024). However, these studies primarily assess pre-game conditions rather than directly measuring cognitive processes during gameplay. This study investigated the effects of GABA intake on cognitive engagement under high cognitive load by analyzing EEG data recorded during task execution, which is a defining characteristic of the MOBA genre that demands parallel processing.

The left prefrontal cortex has been shown to be involved in emotional regulation (Davidson, 2004). Furthermore, Fp1, which was the focus of this study, is considered to partially reflect prefrontal cortex activity and has been used to assess cognitive engagement and interest (Negishi et al., 2011). The results of the EEG analysis of the Fp1 region of the left frontal lobe showed that the SMR wave power ratio 30 minutes post-intake was significantly higher than that in the placebo condition. This result is comparable to findings from a previous study on racing games (Furukado et al., 2022), in which glucose intake was found to maintain SMR waves after approximately 25 min of play. This suggests that GABA may have contributed to the maintenance of the flow state 30 min after intake in the MPG, a task with a high cognitive load.

In another study (Furukado and Hagiwara, 2023), eye movement data from experienced LoL players were analyzed, and it was reported that skilled players mainly focused their gaze on the center of the game screen and frequently shifted their gaze to the minimap and neutral object areas. Additionally, immersion in LoL gameplay was associated with a local increase in beta band

(13–30 Hz) activity, particularly in the frontal region, suggesting that game-related visual processing may contribute to a decrease in alpha band power (Lim et al., 2019).

Thus, during MPG task execution, frequent gaze shifts between screen areas associated with the three tasks likely contributed to a decrease in the alpha-band power ratio and an increase in the beta-band power ratio in the Fp1 region. Stress triggers increased excitation in the limbic system (McEwen, 2007). However, GABA is believed to counteract stress by inhibiting neuronal excitation as part of the body's defense mechanism (Abdou et al., 2006). Studies on the autonomic nervous system indicate that GABA-induced parasympathetic activation may alleviate stress (Nakamura et al., 2009; Okita et al., 2009). Additionally, a study in mice reported that oral administration of GABA activates or enhances the activity of vagal afferent nerves, influencing brain function (Nakamura et al., 2022).

Therefore, the reduction in stress associated with MPG task execution, along with the increase in blood GABA concentration approximately 30 minutes post-ingestion, may have contributed to the observed rise in the power ratio of the SMR band, including the High α band (10–12.5 Hz) and the Low β band (13–20 Hz) (Kakee et al., 2001), during task execution. Supporting this interpretation, previous studies have reported that GABA intake leads to an increase in α wave activity and a decrease in β wave activity (Abdou et al., 2006).

These findings suggest that GABA intake not only induces relaxation effects but also plays a role in maintaining attention and cognitive processing during cognitively demanding gaming tasks. Importantly, caffeine, which is commonly used to enhance cognitive function, has been associated with potential side effects such as increased heart rate and insomnia, particularly at higher doses (Guest et al., 2021). In contrast, GABA is a naturally occurring compound that may serve as a safer alternative for esports players. GABA supplementation can be integrated into training blocks that prioritize high-load micro-performance. Ingesting a single 200 mg dose about 30 min before practice may sustain the flow state and preserve the quality of repeated precision drills. This timing could enable amateur and semi-professional players to maintain attentional focus during target-tracking, last-hit, and multi-task exercises, thereby accelerating the consolidation of fine motor routines. By stabilizing micro-performance execution under prolonged cognitive load, regular GABA use may also provide a more reliable foundation for subsequent macro-strategic training without compromising mechanical accuracy. Indeed, a 12-week double-blind study, daily GABA supplementation (100–200 mg) significantly enhanced working memory, sustained attention, visuospatial memory, and delayed memory in healthy adults (Yamatsu et al., 2020a; 2020b). These longitudinal findings strengthen the rationale for integrating scheduled GABA dosing into esports training cycles, where sustained attention and rapid decision-making are essential.

The findings of this study contribute to the understanding of the potential benefits of nutritional interventions using GABA to enhance esports performance and EEG-indexed engagement related to task immersion (flow state). Furthermore, this research will aid in standardizing micro-performance evaluations in the MOBA genre and advance the use of physiological indicators in esports studies. By deepening the scientific understanding of esports, this study is expected to make both academic and practical contributions to the field.

5. Research Limitations

Future studies should enhance the reliability and validity of the present single-channel EEG protocol by examining its correlation with multichannel recordings. Leveraging the ability to record EEG

while participants wear a headset during gameplay would also permit more ecologically valid and truly real-time assessments of performance. Moreover, the study did not administer any self-report flow measures (e.g., Flow State Scale-2; Jackson and Eklund, 2002), adding such subjective data in future work could clarify the convergent validity between SMR indices and experiential flow.

The sample size was determined from earlier literature, yet a larger cohort is needed to improve reproducibility. Testing professional esports athletes, whose micro-performance tends to fluctuate less, and tracking the duration of any GABA-induced flow state, could inform the design of more efficient training programs. Future work should also determine whether different ingestion formats (e.g., chewing gum or tablets taken without water) alter esports performance.

From a task-design perspective, the present MPG protocol isolates micro-performance but lacks opponent pressure and voice communication typical of ranked LoL matches. Replicating the experiment in full 5-v-5 scrimmages would therefore strengthen ecological validity. Finally, the influence of GABA intake on macro-performance (situation-judgement or movement decisions) remains to be explored.

6. Conclusion

This study aimed to clarify the physiological effects of GABA on micro-performance and frontal EEG engagement in esports such as MOBA genre. The results showed that a 200 mg intake of GABA maintained and enhanced SMR activity, and SMR changes were positively associated with concurrent micro-performance. These findings suggest that GABA may support SMR-related engagement and thereby improve micro-performance in MOBA tasks that require parallel processing under high cognitive load. Taken together, GABA may represent a promising food-derived component that could contribute to addressing performance demands in competitive esports contexts.

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Data availability

The datasets generated and analyzed in this study are available from the corresponding author upon reasonable request.

Institutional review board statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Little Software (protocol code 2024-0010, date of approval: March 25, 2024). Prior to the start of the study, the contents were registered with UMIN-CTR, which is managed by the University Hospital Medical Information Network Center (UMIN) (UMIN000054264).

Informed consent statement

Informed consent was obtained from all participants involved in the study.

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Conflict of interest

The datasets generated and analyzed in the current study are available from the corresponding author upon reasonable request. The five authors (YH, UN, KK, YY, and KY) have financial conflicts of interest. Funding: Research support (consumables) from Pharma Foods may have potential financial benefits from the publication of this paper. In addition, the author (KY) is the director of Pharma Foods and holds shares in a company that may have potential financial benefits or losses from the publication of this paper.

Author contributions

Ryousuke Furukado: Writing-review and editing, writing-original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, formal analysis, data curation, and conceptualization. Yoshihiro Hara: Writing-review and editing, Methodology, Investigation, Formal analysis, data curation. Utano Nakamura: Writing-review and editing, Methodology, Investigation, Formal analysis, data curation. Keita Koga: Project administration, Methodology, Investigation. Yusuke Yamashita: Project administration, Methodology, Investigation. Youngil Kim: Project administration, Writing-review and editing, Validation, Supervision. Goichi Hagiwara: Methodology, Writing-review and editing, and supervision.

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