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# Long-term curling training reshapes region-specific patterns of prefrontal cortex resting-state activity: an expert–beginner comparison based on fNIRS

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# Abstract

Long-term athletic training shapes not only the body but also leaves measurable imprints on the brain. Yet previous research on athletic expertise has two gaps: most studies record brain activity during task performance rather than at rest, and they focus on high-contact, fast-reaction sports such as basketball and martial arts, while low-load sports demanding strategic planning, probability judgment, and self-control remain understudied. Curling typifies the latter, but whether and how long-term training reshapes resting-state prefrontal activity remains unclear. We recruited 21 trained curlers and 21 curling-naive controls and used brain imaging to record resting-state spontaneous prefrontal activity, comparing its intensity between groups and examining its relationship with training years and athletic level within the athlete group. The group differences were not a uniform increase or decrease but a regional shift reflecting functional specialization: activity decreased in regions linked to long-term planning, increased in those tied to immediate decision-making and control, and rose with training years in regions associated with inhibition. These findings suggest that curling training drives a directional redistribution of neural resources matching the sport's cognitive demands, offering new insight into brain adaptation in mentally demanding sports and a practical tool for athlete selection and evaluation.


# Introduction

The acquisition of athletic expertise relies on thousands of hours of specialized training. This process not only reshapes the musculoskeletal system and motor skills but also induces measurable structural and functional changes at the central nervous system level[1–4]. Understanding these training-related neural adaptations not only helps reveal the neural mechanisms of human skill learning but also provides potential objective indicators for athlete selection, training monitoring, and cognitive ability assessment[5]. However, among the many frameworks that describe the brain characteristics of experts, the neural efficiency hypothesis has gained widespread attention. Its core argument is that experts often exhibit lower or more selective brain activation when performing specialized tasks, reflecting an optimized allocation of neural resources[6–8]. Previous studies in shooting, golf, and martial arts using task-based fMRI and EEG have confirmed differences in activation patterns between experts in the prefrontal cortex and motor cortex[9–11]. However, the task-oriented paradigm captures transient activation induced by a specific task, making it difficult to reflect the relatively stable neural traits accumulated during training in a resting state[12–15]. Resting-state spontaneous neural activity provides a complementary perspective on this issue. The amplitude of low-frequency fluctuation (ALFF) and its normalized form (zALFF) can characterize the intensity of spontaneous activity in a region and have been widely used to identify experience-dependent markers of neural plasticity[16,17]. In recent years, functional near-infrared spectroscopy (fNIRS) has become a suitable tool for resting-state studies in athletes because of its good exercise tolerance, ecological validity, and effective coverage of the prefrontal cortex[18,19]. Using fNIRS, studies have identified training-related changes in prefrontal cortex resting-state spontaneous activity in athletes of some sports[20,21]. However, previous neurological research on sports has largely focused on open or highly physical sports, yet the resting-state neural

characteristics of cognitive-strategy-driven sports, which have relatively low physical loads but rely heavily on strategic planning, probabilistic reasoning, and inhibitory control, remain to be elucidated[22–26]. Curling is a typical example of such a sport: athletes need to make strategic plans across rounds, read the ice surface in real time and deduce the trajectory of their shots, suppress interference from opponents' shots, and evaluate the value of each shot's result[27–29]. These cognitive needs are highly compatible with the functions of various subregions of the prefrontal cortex—the frontal polar cortex (FPC) for prospective planning, the dorsolateral prefrontal cortex (DLPFC) for working memory and executive control, and the ventrolateral prefrontal cortex (VLPFC) for inhibitory control[30–35]. Therefore, whether and how long-term curling-specific training can reshape the resting-state spontaneous activity of the prefrontal cortex is a question with both theoretical and practical value; however, this question has not yet been systematically tested.

Therefore, this study used resting-state fNIRS to compare the low-frequency oscillation amplitudes (ALFF and zALFF) in channel 22 of the prefrontal cortex between curling experts and inexperienced beginners and further examined the correlation between these indicators and years of training and sport level within the expert group. We also formulated the following hypotheses: (H1) the expert group exhibits region-specific differences in prefrontal cortex amplitude indicators; and (H2) the degrees of change in the above amplitude indicators are related to the number of years of training.

## Methods

# Subject Information

This study employed a cross-sectional controlled design. All the participants were right-handed male university students and were divided into an expert curling group and a novice control group. The two groups were well matched in terms of demographic characteristics (see Table 1). The expert group was recruited from students specializing in ice and snow sports at Harbin Sport University, with inclusion requirements including continuous curling-specific training for ≥ 1 year and 2–3 specialized training sessions per week (approximately 1.5 hours per session, totaling approximately 3–4.5 hours/week). The novice control group was recruited from students on the same campus who were not involved in ice and snow sports and had never received systematic training in curling or similar skating sports. Owing to the limited number of curling-specific students, 23 participants were recruited to the expert group and 25 to the novice control group. After 2 participants from the expert group and 4 from the novice control group were removed using fNIRS signal quality control, the final effective sample for analysis consisted of 21 participants from each group, totaling 42 participants. Of the 21 participants in the expert panel, 14 held curling sport-level certificates issued by the General Administration of Sport of China, whereas the remaining 7 had completed at least one year of systematic specialized training but had not yet obtained a national-level assessment. Their training intensity and content were consistent with those who had already obtained levels, and they were included in the correlation analysis with training years as the variable based on their actual training years. All participants had no history of neurological or psychiatric

illness, no history of head trauma, and no visual or auditory impairments; they had not consumed caffeine or alcohol within 24 hours prior to the experiment, had slept 6–9 hours the previous night, and had not engaged in strenuous exercise within one hour prior to the experiment.

Table 1
Demographic and training characteristics of the two groups of participants

| Variable | Curling expert panel (n = 21) | Beginner control group (n = 21) | $t/\chi^2$ | p |
|---|---|---|---|---|
| Age (years) | 20.05 ± 1.63 | 20.86 ± 1.62 | -1.62 | .114 |
| Height (cm) | 177.71 ± 5.51 | 176.38 ± 6.75 | 0.70 | .487 |
| Weight (kg) | 71.29 ± 10.97 | 75.21 ± 10.22 | -1.20 | .237 |
| BMI (kg/m²) | 22.59 ± 3.53 | 24.13 ± 2.58 | -1.61 | .115 |
| Sex (male), n (%) | 21 (100) | 21 (100) | — | — |
| Dominant hand (right-handed), n (%) | 21 (100) | 21 (100) | — | — |
| Education level (undergraduate), n (%) | 21 (100) | 21 (100) | — | — |
| Training duration (years), M ± SD (range) | 4.24 ± 2.66 (1–10) | 0 | — | — |
| Athletic level (Master/Level 1/Level 2/None), n | 2/1/11/7 | — | — | — |

Note: M = mean; SD = standard deviation; BMI = body mass index. Independent samples t tests were used for intergroup comparisons of continuous variables (age, height, weight, and BMI); because age slightly deviated from the normal distribution in both groups, the Mann–Whitney U test was also used for verification, with consistent results (age p = .113). All the participants were right-handed males with a bachelor's degree; these three items were completely consistent between the two groups, and no statistical tests were performed. Years of training and athletic level were the defining characteristics of the two groups; the novice control group had zero years of training and no national athletic level; therefore, no intergroup tests were performed. The differences between groups for continuous demographic variables did not reach statistical significance (p > .05), indicating a good match between the two groups.

# Experimental Procedure

Data collection was conducted in a dedicated fNIRS testing room in the Psychology Laboratory of Harbin Sport University. The testing room maintained a constant temperature (22–24°C), constant lighting (curtains drawn and overhead lights on), and a quiet environment with no noise sources other than the subjects' breathing and slight body movements. To minimize fluctuations in physiological arousal levels upon entry, all the subjects waited quietly for approximately 10 minutes in the rest area outside the

laboratory before entering the testing room. Formal data collection employed a resting-state paradigm. The subjects sat with their heads in a natural, neutral position, hands placed on the table, and eyes focused on a white crosshair fixation point (black background) displayed on the computer screen directly in front of them. Upon entry, the experimenter donned the fNIRS probe cap, and an initial signal quality check was performed. The complete resting-state data collection lasted 10 minutes.

# fNIRS Data Acquisition

fNIRS data were acquired using a BS-7000 near-infrared brain imaging system (Wuhan Zilian Hongkang Technology Co., Ltd., Wuhan, China). This system employs dual-wavelength laser diodes (690 nm and 830 nm) with a sampling frequency of 20 Hz. The sampling frequency was reduced to 10 Hz for ease of use in the subsequent data analysis. In this study, a prefrontal cortex-specific probe template provided by the manufacturer was used. This template is configured with 8 sources and 8 detectors, with a 3 cm spacing between adjacent source–detector pairs, forming 22 effective measurement channels within the prefrontal cortex. The placement of the probe cap strictly followed the international 10–20 system standard, using the Fpz point corresponding to source S2 as the positioning anchor point and ensuring left–right symmetry and a consistent front–back position of the probe cap based on head circumference measurements.

The three-dimensional spatial coordinates of the light poles (including reference points such as Nz, Cz, AL, and RL) were measured and recorded point by point using a 3D digital locator (NirMap, Wuhan Zilian Hongkang Technology Co., Ltd., Wuhan, China). The 22 channels were subsequently projected onto the normalized cortical surface using the NIRS-SPM method, and the anatomical brain region corresponding to each channel was determined based on the Brodmann probabilistic brain atlas.

Based on channel–brain region mapping, in this study, 22 channels were assigned to four anatomical functional areas of the prefrontal cortex according to the Brodmann partitioning results: the dorsolateral prefrontal cortex (DLPFC), the ventrolateral prefrontal cortex (VLPFC), the frontal pole cortex (FPC), and the orbitofrontal cortex (OFC). To facilitate the summarization of the amplitude distribution of each functional area according to the anatomical hemisphere and to support subsequent hemispheric differentiation analysis, the above four regions were further divided into left and right hemispheres, resulting in eight symmetrical regions of interest (ROIs): DLPFC_L, DLPFC_R, VLPFC_L, VLPFC_R, FPC_L, FPC_R, OFC_L, and OFC_R. The specific channel–ROI correspondence is shown in Fig. 1.

# fNIRS Data Preprocessing

The data preprocessing workflow first converts the raw light intensity signal into optical density. Bar-pattern interpolation is then used to correct motion artifacts to reduce the impact of transient interference. Next, a bandpass filter of 0.01–0.1 Hz is applied to remove physiological noise and drift, followed by delinearization. Changes in the concentrations of oxyhemoglobin (oxy-Hb),

deoxyhemoglobin (deoxy-Hb), and total hemoglobin (total-Hb) were subsequently calculated based on the modified Beer–Lambert law. Because oxy-Hb has a higher signal-to-noise ratio than does deoxy-Hb and is more strongly correlated with changes in cerebral blood flow, it was selected as the primary indicator for subsequent analysis. After the above preprocessing, the steady-state oxy-Hb time series of the middle 8 minutes of each subject's resting-state acquisition period was extracted as the unified input data for subsequent ALFF and zALFF analyses.

# fNIRS Data Analysis

Low-frequency oscillation amplitude (ALFF)

The amplitude of low-frequency fluctuations (ALFF) is a classic indicator for quantifying the intensity of spontaneous neural activity in the brain. Its principles and calculation methods originated from fMRI research, and it has been widely applied to resting-state data analysis in fNIRS in recent years. In this study, a fast Fourier transform (FFT) was performed on the preprocessed oxy-Hb time series of each channel for each participant to obtain its one-sided amplitude spectrum. The mean amplitude within the 0.01–0.08 Hz frequency band was extracted as the ALFF value for that channel. This frequency band selection is consistent with the typical setting of the dominant frequency band for resting-state spontaneous activity in fNIRS.

Standardized ALFF (zALFF)

To eliminate the influence of differences in overall hemodynamic levels among individuals on the absolute value of ALFF, the ALFF values of 22 channels were further standardized by the z score within the subject to obtain the standardized ALFF value (zALFF). zALFF reflects the relative prominence of a single channel relative to the overall prefrontal amplitude level of the individual and complements ALFF.

# Statistical Analysis

Between-group differences were tested using NirMaster software. Independent samples t tests were used to compare the differences between ALFF and zALFF. Welch correction was automatically applied when Levene's test of homogeneity of variance showed unequal variances ($p < .05$). Effect sizes were reported using Hedges' g with 95% confidence intervals. The interpretation of effect sizes followed Cohen (1988): $|g| < 0.2$ weak, $0.2 \le |g| < 0.5$ small, $0.5 \le |g| < 0.8$ moderate, and $|g| \ge 0.8$ large. To control for Type I errors in multiple comparisons, Benjamini–Hochberg error detection rate corrections were applied to ALFF and zALFF, independently within each of the 22-channel comparison families for each indicator ($m = 22$ each) [36].

Correlation analysis between training years, athletic level, and neurological indicators was conducted within an expert panel ($n = 21$). Given that both training years and athletic level did not follow a normal distribution, Spearman's rank correlation was used. Athletic level was recoded into three levels within the

expert panel (1 = no national level, 2 = Level 2 athlete, 3 = Level 2 or above). Correlation analysis was performed separately for 22 channels each of ALFF and zALFF, with FDR correction performed independently within each correlation family (m = 22). Correlation and trend analyses and corresponding FDR corrections were completed using IBM SPSS Statistics 27. All tests were two-tailed, with a significance level set at α = 0.05. p values were reported to three decimal places (e.g., .024, conforming to APA standards), and p < .001 was directly reported as p < .001.

# Statistical Power Analysis

To assess the ability of this study to detect differences between groups with the current sample size, a post hoc power analysis was performed using G*Power 3.1.9.7. The test family selected was the t test, specifically the “Means: Difference between two independent means, two groups” test. The sample sizes for the two groups were set as $n_1 = 21$ and $n_2 = 21$ (allocation ratio $N^2/N_1 = 1$), and the test was two-tailed. Given that this study used Benjamini–Hochberg false discovery rate (FDR) correction and that G*Power does not directly support the FDR threshold, the Bonferroni equivalent threshold (α/m) of the corresponding comparison family was used as a conservative lower bound estimate of the power. Because the FDR correction is statistically more lenient than the Bonferroni correction is, the actual detection power of this study should not be lower than the estimated value below.

At the uncorrected significance level (α = 0.05), the detection power of this study is approximately 0.716 for large effect sizes (Cohen’s d = 0.80) and approximately 0.353 for medium effect sizes (d = 0.50). At a conservative Bonferroni threshold (α = 0.05/22 ≈ 0.0023) equivalent to channel-level FDR correction (m = 22), the detection power is approximately 0.271 for large effect sizes and approximately 0.064 for medium effect sizes. These estimates indicate that the sample size of this study has an acceptable detection capability for large effect group differences but a relatively limited detection capability for medium and small effects. This power characteristic is consistent with the results of this study: only channels with large effect sizes (such as CH13 and CH17, |g| > 0.9) remained significant after 22-channel FDR correction, whereas channels with medium effect sizes did not reach significance after correction. The corresponding methodological limitations and their impact on the interpretation of the results are explained in the Discussion section.

## Results

# ALFF Independent samples t-test results

Independent samples t tests at the channel level were used to compare the differences in ALFF between the two groups of subjects for 22 HbO channels. After Benjamini–Hochberg correction for multiple comparisons of the 22 channels, only channel CH13 maintained a significant difference and reached a large effect size (t = − 3.67, p = .001, FDR-p = .021, Hedges’ g = − 1.11). Moreover, the expert panel revealed that six channels differed significantly without Benjamini–Hochberg multiple comparison

correction. The three other channels showed numerical differences in opposite directions, but none reached statistical significance ($p > .05$). The effect size of CH16 was negligible ($t = 0.62$, $p = .541$; Hedges' $g = + 0.19$), whereas CH17 ($t = 1.27$, $p = .211$; Hedges' $g = + 0.39$) and CH19 ($t = 1.37$, $p = .179$; Hedges' $g = + 0.41$) had small effect sizes. See Table 3 for details.

Table 2
Results of the statistical power analysis ($n_1 = n_2 = 21$, df = 40, two-tailed test)

| **Alpha level** | **Corresponding correction scenario** | **d = 0.80 (large effect)** | **d = 0.50 (moderate effect)** |
|---|---|---|---|
| 0.05 | uncorrected | 0.716 | 0.353 |
| 0.0023 | Channel horizontal FDR equivalent (m = 22) | 0.271 | 0.064 |

Note: The critical t values are 2.021 ($\alpha = 0.05$) and 3.261 ($\alpha = 0.0023$), respectively. Power values were calculated using G*Power 3.1.9.7. The two α levels correspond to the Bonferroni equivalent conservative thresholds for multiple comparisons of the uncorrected threshold and the channel level ($\alpha = 0.05/22 \approx 0.0023$); the latter serves as a conservative lower bound estimate of the actual FDR correction power used. All correlation and trend analyses in this study also used FDR correction with m = 22, and its power estimate is consistent with that of the channel level; therefore, it is not listed separately.

Table 3
Results of the ALFF independent samples t test between the curling expert group and the novice control group.

| Channel | Experts (*n* = 21)M ± SD (×10⁻³) | Controls (*n* = 21)M ± SD (×10⁻³) | *t* | *df* | *p* | FDR-p | Hedges' *g* [95% CI] |
|---|---|---|---|---|---|---|---|
| CH1 | 11.81 ± 5.56 | 13.84 ± 8.08 | -0.95 | 40 | .349 | .366 | -0.29 [-0.88, + 0.31] |
| CH2 | 11.65 ± 3.48 | 14.61 ± 6.99 | -1.74 | 29.35 | .093 | .221 | -0.53 [-1.13, + 0.08] |
| CH3 | 11.50 ± 5.08 | 15.79 ± 6.17 | -2.46 | 40 | .018 | .101 | -0.74 [-1.36, -0.13] |
| CH4 | 11.31 ± 6.50 | 14.70 ± 6.98 | -1.63 | 40 | .111 | .221 | -0.49 [-1.10, + 0.11] |
| CH5 | 11.67 ± 5.22 | 16.00 ± 7.08 | -2.26 | 40 | .030 | .130 | -0.68 [-1.29, -0.07] |
| CH6 | 10.42 ± 4.03 | 14.46 ± 5.38 | -2.75 | 40 | .009 | .098 | -0.83 [-1.45, -0.21] |
| CH7 | 13.03 ± 7.57 | 15.67 ± 9.51 | -1.00 | 40 | .325 | .357 | -0.30 [-0.90, + 0.30] |
| CH8 | 9.76 ± 5.91 | 13.21 ± 7.59 | -1.64 | 40 | .109 | .221 | -0.50 [-1.10, + 0.11] |
| CH9 | 9.76 ± 4.14 | 11.33 ± 5.48 | -1.05 | 40 | .300 | .347 | -0.32 [-0.92, + 0.28] |
| CH10 | 10.17 ± 3.38 | 11.89 ± 4.27 | -1.44 | 40 | .157 | .266 | -0.44 [-1.04, + 0.16] |
| CH11 | 11.32 ± 5.20 | 13.26 ± 5.99 | -1.12 | 40 | .268 | .327 | -0.34 [-0.94, + 0.26] |
| CH12 | 10.40 ± 5.16 | 13.00 ± 5.74 | -1.55 | 40 | .130 | .238 | -0.47 [-1.07, + 0.13] |
| CH13 | 8.92 ± 3.02 | 14.32 ± 6.02 | -3.67 | 29.48 | < .001 | .021* | -1.11 [-1.75, -0.47] |
| CH14 | 9.70 ± 4.46 | 13.90 ± 6.19 | -2.52 | 40 | .016 | .101 | -0.76 [-1.38, -0.15] |
| CH15 | 10.21 ± 6.72 | 17.57 ± 24.40 | -1.33 | 40 | .190 | .270 | -0.40 [-1.00, + 0.20] |

*Note.* | *g* | < 0.2 negligible, 0.2–0.5 small, 0.5–0.8 medium, ≥ 0.8 large. * FDR-p < .05. HbO = oxygenated hemoglobin.

| Channel | Experts (*n* = 21)M ± SD (×10⁻³) | Controls (*n* = 21)M ± SD (×10⁻³) | *t* | *df* | *p* | FDR-p | Hedges' *g* [95% CI] |
|---|---|---|---|---|---|---|---|
| CH16 | 11.39 ± 6.78 | 10.24 ± 5.17 | 0.62 | 40 | .541 | .541 | 0.19 [-0.41, + 0.78] |
| CH17 | 13.38 ± 6.50 | 11.18 ± 4.54 | 1.27 | 40 | .211 | .272 | 0.39 [-0.21, + 0.98] |
| CH18 | 9.57 ± 4.50 | 12.13 ± 7.73 | -1.31 | 40 | .196 | .270 | -0.40 [-1.00, + 0.20] |
| CH19 | 13.45 ± 9.38 | 10.27 ± 5.07 | 1.37 | 40 | .179 | .270 | 0.41 [-0.19, + 1.01] |
| CH20 | 9.90 ± 4.26 | 16.74 ± 14.68 | -2.05 | 40 | .047 | .148 | -0.62 [-1.23, -0.01] |
| CH21 | 11.13 ± 4.07 | 14.16 ± 5.21 | -2.09 | 40 | .043 | .148 | -0.63 [-1.24, -0.03] |
| CH22 | 10.07 ± 5.77 | 14.05 ± 8.28 | -1.81 | 40 | .078 | .215 | -0.55 [-1.15, + 0.06] |

*Note.* | *g* | < 0.2 negligible, 0.2–0.5 small, 0.5–0.8 medium, ≥ 0.8 large. * FDR-p < .05. HbO = oxygenated hemoglobin.

## zALFF Independent samples t-test results

To further examine whether the differences between groups stemmed from whole-brain amplitude variations or localized differences in specific channels, we performed a within-subject z-transformation of the ALFF for each participant across the 22 channels to obtain the zALFF and repeated the channel-level independent samples t test (see Table 4). After Benjamini–Hochberg multiple comparison correction, the two channels reached significant FDR differences and large effect sizes, with opposite directions of difference. One was CH13 (t = − 3.11, p = .003, FDR-p = .038, Hedges' g = − 0.94), and the other was CH17 (t = 3.99, p < .001, FDR-p = .006, Hedges' g = + 1.21).

Table 4
Results of Independent Samples t test between Curling Experts and Novices (zALFF)

| Channel | Experts (n = 21)M ± SD | Controls (n = 21)M ± SD | t | df | p | FDR-p | Hedges' g [95% CI] |
|---|---|---|---|---|---|---|---|
| CH1 | + 0.289 ± 1.142 | -0.017 ± 1.118 | 0.88 | 40 | .386 | .708 | + 0.27 [-0.33, + 0.86] |
| CH2 | + 0.314 ± 0.623 | + 0.210 ± 0.947 | 0.42 | 40 | .675 | .873 | + 0.13 [-0.47, + 0.72] |
| CH3 | + 0.047 ± 0.748 | + 0.592 ± 0.805 | -2.27 | 40 | .029 | .157 | -0.69 [-1.30, -0.08] |
| CH4 | + 0.028 ± 1.171 | + 0.424 ± 1.102 | -1.13 | 40 | .266 | .668 | -0.34 [-0.94, + 0.26] |
| CH5 | + 0.268 ± 0.889 | + 0.604 ± 0.956 | -1.18 | 40 | .244 | .668 | -0.36 [-0.96, + 0.24] |
| CH6 | + 0.005 ± 0.814 | + 0.250 ± 0.811 | -0.98 | 40 | .334 | .668 | -0.30 [-0.89, + 0.30] |
| CH7 | + 0.410 ± 1.338 | + 0.176 ± 0.938 | 0.65 | 40 | .517 | .713 | + 0.20 [-0.40, + 0.79] |
| CH8 | -0.409 ± 0.854 | -0.232 ± 0.906 | -0.65 | 40 | .519 | .713 | -0.20 [-0.79, + 0.40] |
| CH9 | -0.293 ± 0.592 | -0.514 ± 0.779 | 1.03 | 40 | .308 | .668 | + 0.31 [-0.28, + 0.91] |
| CH10 | -0.121 ± 0.645 | -0.259 ± 0.434 | 0.81 | 40 | .421 | .712 | + 0.25 [-0.35, + 0.84] |
| CH11 | + 0.029 ± 0.873 | + 0.123 ± 1.109 | -0.30 | 40 | .763 | .883 | -0.09 [-0.69, + 0.50] |
| CH12 | + 0.009 ± 1.104 | + 0.028 ± 0.722 | -0.07 | 34.47 | .946 | .986 | -0.02 [-0.61, + 0.57] |
| CH13 | -0.438 ± 0.556 | + 0.223 ± 0.798 | -3.11 | 40 | .003 | .038* | -0.94 [-1.57, -0.32] |
| CH14 | -0.233 ± 0.930 | -0.051 ± 0.628 | -0.74 | 40 | .463 | .713 | -0.22 [-0.82, + 0.37] |
| CH15 | -0.200 ± 1.008 | -0.182 ± 1.422 | -0.05 | 40 | .964 | .986 | -0.01 [-0.61, + 0.58] |

*Note.* * FDR-p < .05; ** FDR-p < .01. zALFF was computed by z-transforming each participant's channel-wise ALFF values across all 22 channels (within-subject standardization), yielding dimensionless scores. The independent-samples t statistic (Welch correction applied to CH12, where Levene's test indicated unequal variances; reflected in noninteger df).

| Channel | Experts (n = 21)M ± SD | Controls (n = 21)M ± SD | t | df | p | FDR-p | Hedges' g [95% CI] |
|---|---|---|---|---|---|---|---|
| CH16 | -0.014 ± 1.138 | -0.709 ± 0.573 | 2.50 | 40 | .017 | .122 | + 0.76 [+ 0.14, + 1.37] |
| CH17 | + 0.548 ± 0.892 | -0.383 ± 0.588 | 3.99 | 40 | < .001 | .006** | + 1.21 [+ 0.56, + 1.86] |
| CH18 | -0.447 ± 0.988 | -0.098 ± 1.053 | -1.11 | 40 | .275 | .668 | -0.33 [-0.93, + 0.26] |
| CH19 | + 0.305 ± 1.458 | -0.505 ± 0.969 | 2.12 | 40 | .040 | .177 | + 0.64 [+ 0.03, + 1.25] |
| CH20 | -0.201 ± 0.876 | + 0.335 ± 1.360 | -1.52 | 40 | .137 | .502 | -0.46 [-1.06, + 0.14] |
| CH21 | + 0.201 ± 0.805 | + 0.196 ± 0.897 | 0.02 | 40 | .986 | .986 | + 0.01 [-0.59, + 0.60] |
| CH22 | -0.097 ± 1.080 | -0.210 ± 1.015 | 0.35 | 40 | .729 | .883 | + 0.11 [-0.49, + 0.70] |

*Note.* * FDR-p < .05; ** FDR-p < .01. zALFF was computed by z-transforming each participant's channel-wise ALFF values across all 22 channels (within-subject standardization), yielding dimensionless scores. The independent-samples t statistic (Welch correction applied to CH12, where Levene's test indicated unequal variances; reflected in noninteger df).

## Dose-response evidence in intergroup difference analysis

To supplement the dose-effect evidence in the intergroup difference analysis, this study further examined the association between training intensity and the prefrontal cortex amplitude index within the expert group (n = 21). Considering that the training years in the novice control group were always 0 and that there was no sports level, if the entire sample were included in the correlation analysis, the training years and sports level would be highly collinear with the group, making the correlation results essentially equivalent to a restatement of the intergroup differences. Therefore, the correlation analysis in this section was conducted only within the expert group to obtain training dose information independent of the results of the intergroup t test. Given that both training years and sports level did not follow a normal distribution, Spearman's rank correlation was used for the correlation analysis; sports level was coded into three levels within the expert group (1 = no national level, n = 7; 2 = Level 2 athlete, n = 11; 3 = Level 2 and above, i.e., Level 1 athlete and Master Athlete combined, n = 3). The significance of all correlation analyses was corrected for multiple comparisons (m = 22) for 22 channels using the Benjamini–Hochberg method.

## Correlation between training years and the amplitude index

Correlation analysis between training years and zALFF revealed that the zALFF of channel CH14 (VLPFC_R) was significantly positively correlated with training years and remained significant even after correction by 22-channel FDR (ρ = +0.631, p = .002, FDR-p = .044) (see Table 5 for details).

Table 5
Correlation analysis between years of training within the expert group and zALFF's Spearman rank.

| Channel | ROI | Spearman ρ | p | FDR-p |
|---|---|---|---|---|
| CH1 | VLPFC_L | + 0.003 | .989 | .989 |
| CH2 | DLPFC_L | + 0.278 | .222 | .534 |
| CH3 | OFC_L | -0.289 | .204 | .534 |
| CH4 | OFC_L | -0.260 | .254 | .534 |
| CH5 | OFC_R | -0.117 | .615 | .902 |
| CH6 | DLPFC_R | + 0.148 | .523 | .822 |
| CH7 | VLPFC_R | + 0.068 | .769 | .989 |
| CH8 | VLPFC_L | + 0.009 | .968 | .989 |
| CH9 | VLPFC_L | + 0.376 | .093 | .468 |
| CH10 | FPC_L | -0.236 | .303 | 0.555 |
| CH11 | OFC_L | -0.431 | .051 | .468 |
| CH12 | OFC_R | -0.326 | .149 | .468 |
| CH13 | FPC_R | -0.012 | .959 | .989 |
| CH14 | VLPFC_R | + 0.631 | .002 | .044* |
| CH15 | VLPFC_R | + 0.094 | .685 | .942 |
| CH16 | VLPFC_L | + 0.036 | .875 | .989 |
| CH17 | DLPFC_L | -0.347 | .124 | .468 |
| CH18 | FPC_L | -0.205 | .372 | .630 |
| CH19 | FPC_R | -0.034 | .882 | .989 |
| CH20 | FPC_R | + 0.254 | .267 | .534 |
| CH21 | DLPFC_R | + 0.356 | .113 | .468 |
| CH22 | VLPFC_R | + 0.340 | .132 | .468 |

Note: DLPFC = dorsolateral prefrontal cortex; VLPFC = ventrolateral prefrontal cortex; FPC = frontal polar cortex; OFC = orbitofrontal cortex; L = left side; R = right side. * FDR-p < .05; ** FDR-p < .01.

In the correlation analysis between training years and ALFF, channel CH11 (OFC_L) showed a negative correlation trend at the uncorrected level (ρ = −0.443, p = .045), but it did not reach statistical significance after correction by 22-channel FDR (FDR-p = .480). The other channels did not reach significant levels before and after correction (see Appendix Table S1 for details).

## Correlation between motion level and the amplitude index

In the correlation analysis between motion level and ALFF, channels CH19 (FPC_R, ρ = +0.571, p = .007) and CH15 (VLPFC_R, ρ = −0.472, p = .031) were statistically significant at the uncorrected level, but none remained significant after 22-channel FDR correction (FDR-p = .154 and .341, respectively; see Appendix Table S2 for details). In the correlation analysis between motion level and zALFF, none of the 22 channels were statistically significant at either the uncorrected or FDR-corrected levels, except for channel CH13 (FPC_R), which showed a near-significant positive correlation trend (ρ = +0.414, p = .062; see Appendix Table S3 for details).

## Discussion

# Overview of Key Findings

In this study, a resting-state fNIRS system was used to compare the low-frequency oscillation amplitudes in the 22 channels of the prefrontal cortex between curling experts and novices with no training experience, and the correlations between these indicators and training level within the expert group were further examined. Under 22-channel independent FDR correction, this study revealed three independent core pieces of evidence: First, in the right frontal cortex (FPC_R, CH13), both the ALFF and zALFF in the expert group were significantly lower than those in the novice group (g = − 1.11/−0.94), indicating a convergent downward adjustment of the two indicators; second, in the left dorsolateral prefrontal cortex (DLPFC_L, CH17), the zALFF in the expert group was significantly greater than that in the novice group (g = + 1.21), in the opposite direction to FPC_R; third, in the right ventrolateral prefrontal cortex (VLPFC_R, CH14), the zALFF in the expert group showed a significant positive correlation with years of training (ρ = +0.631), suggesting that this area continues to change with accumulated training during the expert stage. Based on this evidentiary framework, the main argument of this study is that long-term curling-specific training is associated with region-specific and bidirectional redistribution of resting-state spontaneous activity in the prefrontal cortex.

## Activity savings in areas related to high-level forward-looking planning

The most robust finding in this study is in the right frontal cortex (FPC_R, CH13). This channel is the only one among all amplitude-level analyses to pass 22-channel FDR correction for both ALFF and zALFF, with large effect sizes (ALFF: g = − 1.11; zALFF: g = − 0.94). The consistent downregulation of both

indicators in CH13 rules out the possibility of “global baseline shift” or “normalization artifacts”, indicating that the right FPC shows a genuine, region-specific reduction in spontaneous activity. This phenomenon can be explained from an anatomical and functional perspective. The frontal cortex (FPC) is the most anterior prefrontal cortex in the human brain and the most indirect in its interaction with external sensory input. Its core functions include forward planning across time, maintenance of long-term goals, multitask coordination, and metacognitive monitoring[35,37]. The cognitive demands of curling align with this functional spectrum: curling matches typically unfold in multiple ends, requiring athletes to anticipate the trajectory of subsequent stones before each throw, maintain strategic goals across ends, and flexibly switch between offensive and defensive strategies when leading or trailing[29]. This type of time-spanning, long-term goal-oriented high-order planning aligns with the functional characteristics of functional planning (FPC). Long-term, repetitive specialized training may automate and proceduralize this type of processing, resulting in a reduced efficiency of spontaneous activity in the corresponding brain regions during the resting state—a pattern consistent with the neural efficiency hypothesis’s prediction that “experts exhibit more economical use of neural resources in specialty-related brain regions”. Recent studies using the resting-state paradigm have also provided more direct evidence for this phenomenon. For example, in sports requiring high levels of physical control and cognitive strategies, such as Tai Chi, elite athletes exhibit a specific reduction in spontaneous activity in skill-related brain regions during the resting state[25]. This finding is consistent with the pattern of spontaneous neural activity downregulation observed in the right prefrontal pole (FPC_R) in this study, which together support the idea that long-term specialized training can reshape the brain’s resting-state functional architecture, making it more economical.

# Highlighting the functions of areas related to online execution control

In contrast to FPC_R, the left dorsolateral prefrontal cortex (DLPFC_L, CH17) had a significantly greater zALFF in this channel in the expert group than in the novice group (t = 3.99, FDR-p = .006, g = + 1.21), with the largest effect size among all the significant FDR channels in this study. However, the intergroup difference in the raw ALFF index of CH17 did not reach a significant level (g = + 0.39, p = .211), only showing a robust difference in the standardized zALFF. This means that the training-related changes in DLPFC_L are more reflective of the relative salience of this area within the individual prefrontal cortex, rather than a significant increase in absolute amplitude, which is consistent with the explanation of the redistribution of prefrontal resources among regions rather than a single “energy increase” in this area.

Functionally, the DLPFC has long been considered a core region for working memory, executive control, and goal maintenance in cognitive neuroscience[38]. Curling demands online executive control throughout every throw: athletes must complete ice surface readings, force and spin parameter estimations, communication of sweeping strategies, and immediate throw decisions within seconds. This process requires continuous and high-intensity investment of working memory and executive resources. Unlike higher-order prospective planning, which tends to automate at the expert stage, online executive control

needs to be restarted and finely adjusted with each throw, thus potentially experiencing a similar degree of “saving”; in contrast, long-term training may enhance the region’s spontaneous activity at rest to maintain a rapidly accessible pool of executive resources[39,40].

Theoretically, this phenomenon is conceptually consistent with the “selective, on-demand allocation of neural resources” emphasized by the neural efficiency hypothesis, and it exhibits specific directional differentiation patterns in different subregions of the prefrontal cortex. This bidirectional redistribution pattern also suggests that the resting-state plasticity associated with motor expertise is not unidirectional overall savings but rather a resource reorganization structured according to the cognitive needs of the project[41,42].

# Persistent changes related to inhibition control and salience monitoring

In the correlation analysis between training years and amplitude indices within the expert group, this study identified the only significant association after 22-channel FDR correction among 44 channel-index combinations (2 sets of correlations × 22 channels); the zALFF of the right ventrolateral prefrontal cortex (VLPFC_R, CH14) was significantly positively correlated with training years (ρ = +0.631, p = .002, FDR-p = .044), indicating that the longer the training years within the expert group were, the greater the relative salience of spontaneous activity in this area.

In cognitive neuroscience, the right-side VLPFC is often classified as a network related to response inhibition, salience information detection, and attentional redirection[43]. Curling is associated with a distinctly sport-specific demand for this type of processing: athletes must suppress impulsive throws when facing opponent placement induction, suppress risky strategies under score pressure, and maintain rapid redirection to sudden disruptive stimuli during long matches. Unlike higher-order programming, which tends to automate early in specialization, this type of processing, tightly coupled with contextual salience, may require longer-term, higher-density training accumulation to stabilize, which is consistent with the “monotonically increasing within the expert group with years of training” pattern observed in this study. CH14 did not significantly differ according to the results of the intergroup t test (zALFF: t = − 0.74, p = .463, g = − 0.22), indicating that the training-related effects in this region are reflected mainly in the continuous accumulation within the expert group rather than the steady-state gap that has already widened between experts and novices.

Furthermore, owing to the cross-sectional design of this study, this correlation cannot directly support the causal direction of “training driving a sustained increase in spontaneous VLPFC_R activity”. One possible explanation is that initial differences in individuals’ salience monitoring/inhibition control abilities may affect their retention time in curling; that is, individuals with higher baseline spontaneous VLPFC_R activity may be more suited to curling and more inclined to persist long term, thus forming a cross-sectional association between training years and neurometrics within the expert group. Current

data cannot distinguish between these two explanations and require direct testing using a longitudinal tracking design.

## Hemispheric Differentiation of Prefrontal Training-Related Changes

The three core findings of this study exhibit spatially specific characteristics in terms of their hemispheric distribution: the difference in channels between the core groups was in the right FPC (CH13) and the left DLPFC (CH17), whereas the dose-effect channel within the expert group was in the right VLPFC (CH14). Regardless of the results of the ALFF, zALFF, or correlation analyses, the significant results were concentrated on one side of the corresponding region of interest rather than on the other side or both sides simultaneously. One reason for this finding might be the randomness resulting from an insufficient sample size, leading to this unilateral characteristic. However, the following three pieces of evidence suggest that this pattern is more likely to reflect the functional-hemispheric correspondence of the prefrontal subregions than random detection is.

First, resting-state spontaneous neural activity inherently exhibits hemispherical asymmetry. Studies based on large-sample resting-state fMRI and fNIRS have shown that even in the absence of external stimuli, the various subregions of the prefrontal cortex still display stable and reproducible left–right asymmetry patterns in indices such as ALFF and ReHo[16,44]. This baseline asymmetry provides a neurophysiological basis for the idea that “training-related effects may preferentially occur on one side”. Simply put, if the spontaneous activity pattern on one side better matches the functional localization of item-related processing, then training-induced changes are more likely to reach the statistically detectable threshold on that side.

Second, both the DLPFC and the VLPFC tend to exhibit mild but stable hemispheric lateralization tendencies in executive control-related functions. Previous studies suggest that the left DLPFC has relative advantages in tasks involving verbal-sequential strategy processing, goal maintenance, and rule encoding, whereas the right VLPFC has relative advantages in salient information monitoring, attentional redirection, and nonverbal response inhibition[45]. Notably, the hemispheric differentiation of prefrontal cortex function is a “relative tendency” rather than “strict specialization,” and contralateral brain regions are usually also involved in the corresponding processing[46,47]. Therefore, the unilateral findings in this study should be interpreted as “the detectable effect is achieved first on the side most aligned with the project requirements,” rather than “the training effect occurs only on that side”.

Third, the specific hemispherical distribution in this study is consistent with the cognitive needs structure of curling in terms of direction. First, the upward adjustment of CH17 to the left DLPFC rather than the right initially seems to contradict the prominent visuospatial attributes of curling (ice trajectory interpretation, distance and angle estimation—generally considered to be associated with right-hemisphere-oriented processing). However, in addition to visuospatial components, curling also involves a large amount of verbal-sequential strategic communication (real-time ice-scraping instructions

between teammates, cross-stone tactical discussions, and verbal strategy reviews at critical moments) and goal maintenance components. These processes align functionally with the left DLPFC[48]. Therefore, the training-related upward adjustment of DLPFC_L may reflect the shaping effect of verbal strategy and goal maintenance components on resting-state spontaneous activity in the context of the cognitive needs of the sport. Second, the location of CH14 in the right VLPFC rather than the left aligns with the relative advantage of the right VLPFC in attentional redirection under nonverbal salience monitoring and external interference. Curling requires athletes to continuously monitor changes in opponent stone placement and ice dynamics and suppress interference from nongoal cues on decision-making. This contextual salience monitoring requirement aligns with that of the right VLPFC. This aligns with functional positioning. Third, CH13 is located on the right-hand FPC rather than on the left-hand one, suggesting that FPC processing related to nonverbal prospective planning in curling (multistep prediction based on spatial layout and trajectory probability) is more efficient in the right hemisphere; this inference is consistent with previous reports on the relative advantage of the right-hand FPC in spatial-context integrated prospective planning[49].

In summary, the hemispheric differentiation pattern observed in this study can be interpreted as a training-related redistribution based on the inherent functional lateralization of different prefrontal subregions and the structured presentation according to item cognitive needs. Finally, although hand-handicappedness is a potential influencing factor for prefrontal lateralization, it was controlled for in this study by including all right-handed participants and therefore does not constitute a major alternative explanation for the aforementioned hemispheric distribution characteristics[50].

# Spatial separation of intergroup difference channels and dose-effect channels

An interesting phenomenon emerged at the channel level in this study: channels showing significant intergroup differences in FDR (CH13 and CH17) did not show significant correlations in years of training within the expert group ($\rho = -0.012$, $p = .959$; $\rho = -0.347$, $p = .124$, respectively), whereas the channel showing significant FDR correlations in years of training within the expert group (CH14) did not show statistically significant differences in the intergroup t test ($g = -0.22$, $p = .463$). The intergroup difference channel and the dose-effect channel were spatially separated.

This separation may be consistent with the hypothesis that training-related resting-state plasticity has different temporal structures. One hypothesis is threshold/plateau-type plasticity: neural changes occur mainly in the binary transition of “whether systematic specialized training has been experienced” and tend to stabilize after a certain training volume is reached; the evidence features of CH13 and CH17 are consistent with this hypothesis. Another hypothesis is cumulative/refinement-type plasticity: neural changes continue to advance with the number of years of training in the expert stage, but the early group differences have not yet established a stable threshold; the evidence features of CH14 are consistent with this hypothesis. Both of these temporal structures have conceptual correspondences in the early-

late stage model of motor skill learning literature and the “expansion–renormalization” framework of brain plasticity[51,52].

However, because this study is a cross-sectional study, the “two time structures” mentioned in this section should be understood as possible explanations that are compatible with existing evidence and worthy of future investigation rather than conclusions supported by this study.

# Practical Significance

The findings of this study have practical implications at multiple application levels.

First, in terms of sport talent selection and identification, this study reveals the region-specific characteristics of the resting-state spontaneous activity of the prefrontal cortex, especially the activity conservation of the right frontal pole cortex and the functional prominence of the left dorsolateral prefrontal cortex, which provides potential objective neural markers for curling and similar cognition-strategy-driven sports.

Second, regarding training monitoring, this study revealed a sustained increase in the salience of spontaneous activity in the right ventrolateral prefrontal cortex within the expert group, suggesting that certain neural adaptations related to inhibitory control and salience monitoring may require long-term training accumulation to stabilize. These findings provide a neural-level reference for coaching teams to understand the long-term nature of skill consolidation and to rationally arrange the cognitive load at different training stages.

Third, this study validated the neural efficiency hypothesis in curling, a sport with low physical load and high cognitive demands, and provided corresponding interpretations based on the sport’s specificity. This approach helps promote the expansion of sports-related cognitive neuroscience from open, highly competitive sports to cognitive-strategy-driven sports and provides an empirical foundation for the development of more sport-specific expert brain models.

# Limitations

This study has several limitations that need to be clearly noted. First, this study has a cross-sectional design, and the self-selection effect cannot be ruled out; that is, the neural characteristics observed by the expert group may be partly due to individuals whose corresponding prefrontal cortex characteristics are more inclined to persist in curling training rather than being entirely induced by the training itself. Second, the sample size (n = 42, n = 21 per group) has acceptable power for differences between large-effect groups, but its power for detecting moderate and small effects and for dose–response analysis within the expert group is relatively limited; only 1 of the 44 correlation tests in this study passed the FDR correction, a finding density consistent with the power estimate. Furthermore, the expert group had few high-level athletes (1 Level 1 and 2 Master Athletes), forcing the merging of three levels within the expert group, which to some extent limited the fine characterization of the level ladder. Third, the fNIRS probes in this study covered only the prefrontal cortex and did not include the motor cortex, parietal lobe, or

subcortical structures; thus, the motor–sensory network changes directly related to curling movements were not characterized. Furthermore, the spatial resolution of the prefrontal cortex channels is limited, and detailed anatomical mapping inferences regarding hemispheric differentiation require further validation at higher spatial resolutions (such as fMRI). Fourth, this study included only right-handed male university students to control for potential interference from hand-handicap and sex on prefrontal lateralization, but this also limits the extrapolation of the results to female and left-handed athletes.

Based on the above limitations, future research can be advanced in the following directions. First, a longitudinal tracking design should be adopted to repeatedly collect resting-state data at different training stages for the same group of curlers to directly examine the temporal structure of threshold/cumulative plasticity. Second, the sample size should be expanded, and the proportion of high-level athletes should be increased to improve the ability to detect intermediate effects and training-related effects within expert groups. Third, the probe coverage should be expanded to key areas such as the motor-sensory cortex and parietal lobe. Fourth, female athletes and athletes with different dominant hands should be included to construct a more complete map of curling-related neural adaptations.

# Conclusion

In this study, resting-state fNIRS was used to compare the spontaneous neural activity of the prefrontal cortex between curling experts and untrained novices. Long-term specialized training was associated with region-specific changes in resting-state prefrontal cortex activity. Moreover, this change was not a general increase or decrease in activity but a directional redistribution of resources based on the cognitive needs of the project. Specifically, higher-order prospective planning tended to be automated, and activity was conserved in the expert stage, whereas online execution control resources were relatively prominent in the resting state.

Training-related changes in different subregions of the prefrontal cortex revealed directional and hemispheric differentiation: right frontal cortex activity, associated with higher-order prospective planning, was downregulated, whereas left dorsolateral prefrontal cortex activity, associated with online executive control, was upregulated. The two activity levels changed in opposite directions and were located in the left and right hemispheres, suggesting that curling training shapes the resting-state spontaneous activity of the prefrontal cortex according to the lateralization of the inherent functions of each subregion and the structuring according to the cognitive needs of the project.

Neural adaptations associated with inhibitory control and salience monitoring may continue to advance in a cumulative manner during the expert phase, with a temporal structure different from those of channels whose steady-state differences have already been established between groups.

# Declarations

# Ethical Approval

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board (or Ethics Committee) of Harbin Institute of Physical Education (No. 2026089).

**Informed Consent**

Written informed consent was obtained from all individual participants included in the study.

# Additional Information

**Competing interests**

The author declare no competing interests.

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# Author Contribution

A was responsible for the literature review and drafting the initial manuscript. B and C carried out experimental operations and conducted data analysis. D participated in the experimental design. E and F were involved in experimental operations and data collection. G provided project guidance. H and I offered theoretical guidance and conducted preliminary review and revision of the manuscript. All authors reviewed and approved the final version of the paper.

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# Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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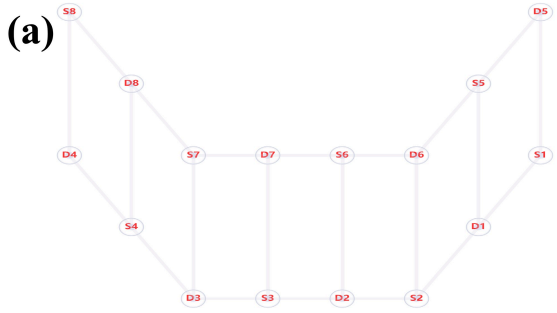
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# Figures




(b)

| Region of Interest (ROI) | Left Hemisphere (Channels) | Right Hemisphere (Channels) |
|---|---|---|
| Dorsolateral Prefrontal Cortex (DLPFC) | 2, 17 | 6, 21 |
| Ventrolateral Prefrontal Cortex (VLPFC) | 1, 8, 9, 16 | 7, 14, 15, 22 |
| Frontopolar Cortex (FPC) | 10, 18 | 13, 20 |
| Orbitofrontal Cortex (OFC) | 3, 11 | 5, 12 |

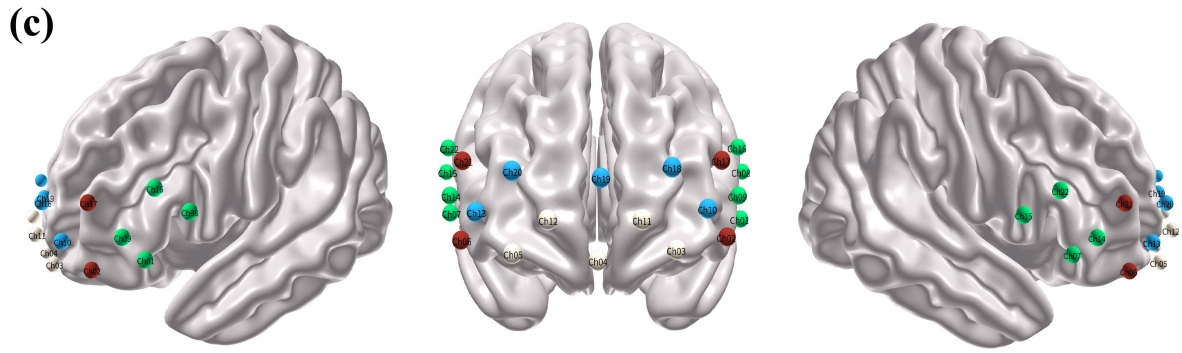



**Figure 1**

(a)shows the 2D channel layout. (b) shows the channel numbers contained in each region of interest in the left and right hemispheres. (c) shows the positions of each channel on the 3D head model.

# Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- TableS1.docx
- TableS2.docx

- TableS3.docx