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Research article

Neurosurgical and BCI approaches to visual rehabilitation in occipital lobe tumor patients

Jie Ma [a,b], Zong Rui [b], Yuhui Zou [c], Zhizhen Qin [a,b], Zhenyu Zhao [c], Yanyang Zhang [b], Zhiqi Mao [b], Hongmin Bai [c], Jianning Zhang [b,*]

[a] *PLA Medical School, Beijing, 100853, PR China*
[b] *Department of Neurosurgery, Chinese PLA General Hospital, Beijing, 100853, PR China*
[c] *Department of Neurosurgery, General Hospital of the Southern Theater Command of PLA, Guangzhou, Guangzhou, 510051, PR China*

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ABSTRACT

This study investigates the effects of occipital lobe tumors on visual processing and the role of brain-computer interface (BCI) technologies in post-surgical visual rehabilitation. Through a combination of pre-surgical functional magnetic resonance imaging (fMRI) and Diffusion Tensor Imaging (DTI), intra-operative direct cortical stimulation (DCS) and Electrocorticography (ECoG), and post-surgical BCI interventions, we provide insight into the complex dynamics between occipital lobe tumors and visual function. Our results highlight a discrepancy between clinical assessments of visual field damage and the patient's reported visual experiences, suggesting a residual functional capacity within the damaged occipital regions. Additionally, the absence of expected visual phenomena during surgery and the promising outcomes from BCI-driven rehabilitation underscore the complexity of visual processing and the potential of technology-enhanced rehabilitation strategies. This work emphasizes the need for an interdisciplinary approach in developing effective treatments for visual impairments related to brain tumors, illustrating the significant implications for neurosurgical practices and the advancement of rehabilitation sciences.

1. Introduction

The human visual system represents one of the most complex and finely tuned sensory systems, enabling individuals to interpret their surroundings through light and color [1]. At the core of this system lies the phototransduction process, occurring within the retina, where photons of light are converted into electrical signals that the brain can interpret. This initial stage of visual processing underscores the sophisticated nature of the human eye as not merely a passive receiver of light but an active participant in the conversion of visual stimuli into neural signals, as discussed by K. Palczewski and P. D. Kiser [2] in their exploration of the cisterns photoisomerization of the retinylidene chromophore, a crucial process in visual phototransduction in rod and cone photoreceptors.

Following phototransduction, these signals are relayed to the primary visual cortex (V1) in the occipital lobe, marking the commencement of cortical visual processing [3]. The primary visual cortex plays a pivotal role in decoding simple visual elements such as orientation, spatial frequency, and color. This region's activity is fundamental to the initial stages of constructing a coherent visual representation from disparate visual inputs.

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* Corresponding author. Department of Neurosurgery, Chinese PLA General Hospital, 28 Fuxing Road, Haidian District, Beijing 100853, PR China.
E-mail address: zhang_jianning@yeah.net (J. Zhang).

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Beyond the primary visual cortex, visual information undergoes further processing in higher-order cortical areas. These areas, encompassing regions within the occipital, temporal, and parietal lobes, are involved in more complex aspects of visual processing, such as motion detection, face recognition, and spatial awareness [4]. The perception of a rich, multidimensional visual world is facilitated by the integration of information across diverse cortical areas, highlighting the complexity and efficiency of the human visual processing system, which includes the identification of a third visual pathway specialized for the dynamic aspects of social perception, as uncovered by Pitcher and Ungerleider, thus challenging the traditional two-pathway model of vision [5].

The significance of visual processing extends beyond mere perception, influencing various aspects of daily life and human interaction. However, neurological disorders that impact any stage of this intricate system can profoundly affect an individual's ability to navigate and interpret their environment. Conditions such as stroke, traumatic brain injury, or tumors within the visual cortex can disrupt standard visual processing, leading to challenges in visual perception and, consequently, a diminished quality of life.

Given the critical role of visual processing in cognition and daily functioning, understanding the neural underpinnings of visual perception and the consequences of neurological disruptions is essential. Recent advances in neuroimaging and neurophysiology have begun to shed light on these complex processes, offering insights into the mechanisms of visual processing and the potential for rehabilitation following neurological damage.

Recent literature emphasizes the pivotal role of the occipital lobe in visual processing, identifying it as a hub for the initial stages of visual information interpretation [6]. Studies have detailed how visual signals after being processed by the retina, are conveyed to the occipital lobe's primary visual cortex (V1) [7]. This area is instrumental in deciphering essential visual elements, laying the groundwork for more complex visual understanding. Subsequent research has explored the neural pathways extending from V1 to higher-order visual areas across the occipital and parietal lobes, elucidating their roles in integrating visual information to form coherent perceptions of the environment [8]. The occurrence of tumors within the occipital lobe presents significant implications for visual function, a topic that has garnered considerable attention in recent studies [9,10]. Brain-Computer Interface (BCI) technology represents a frontier in neurorehabilitation research, particularly in its application to support or restore visual function. This technology has shown promise in enabling individuals with visual impairments to interact with their environment in new ways, such as controlling assistive devices or navigating computer interfaces. Integrating BCI with visual rehabilitation protocols offers a novel approach to enhancing the quality of life for individuals with occipital lobe tumors, marking a significant advancement in neurorehabilitation [11].

There is a notable gap in comprehensive case studies that delve into the effects of tumor resection on visual processing and the role of BCI technology in the rehabilitation process. Furthermore, there is a significant lack of detailed exploration into the absence of expected visual phenomena during direct cortical stimulation in occipital lobe surgeries [12,13].

Recent advancements in BCI technology have opened new avenues for visual rehabilitation in patients with visual cortex damage. Studies such as those by Brunner et al. and Chaudhary et al. have demonstrated the potential of BCIs to restore or augment visual functions in individuals with neurological impairments [14,15]. However, these studies often face limitations, including small participant numbers, short follow-up durations, and challenges in achieving consistent outcomes across diverse patient populations.

Furthermore, many existing protocols focus solely on BCI interventions without integrating them into the broader context of surgical treatment and neurorehabilitation. This siloed approach may overlook the benefits of a comprehensive strategy that addresses the patient's needs throughout the entire treatment continuum.

To address these gaps, our study adopts a multimodal protocol that combines pre-surgical fMRI and DTI, intra-operative Direct Cortical Stimulation (DCS) and ECoG, and post-surgical BCI interventions. This integrated method allows for a detailed mapping of the visual processing network, both structurally and functionally, before, during, and after tumor resection. By choosing this protocol over standalone methods, we aim to enhance the efficacy of visual rehabilitation and provide insights into the brain's adaptability following surgical intervention.

To fully understand the intricate effects of occipital lobe tumors on visual processing and to explore effective rehabilitation strategies, we adopted a multimodal methodological approach. The complexity of the visual system and its neural underpinnings require comprehensive assessment techniques. Utilizing a combination of fMRI, MRI, DTI, DCS and ECoG interventions allows us to examine both the structural and functional aspects of the brain.

While BCI technology represents a promising avenue for neurorehabilitation, our study is primarily focused on laying the theoretical groundwork necessary for future BCI development in visual rehabilitation. By investigating the neural dynamics and functional connectivity in patients with occipital lobe tumors, we aim to provide insights that can guide the design and implementation of effective BCI systems. This research does not involve the deployment of a specific BCI interface but seeks to contribute foundational knowledge to the field.

This study posits that patients can maintain visual capabilities following extensive occipital lobe resection, potentially due to adaptive neural pathways compensating for lost primary visual processing functions. It seeks to determine the absence of anticipated visual phenomena during surgical procedures and assess these outcomes' relevance to BCI-supported visual recovery efforts. The research primarily aims to understand the effects of occipital lobe tumor removal on visual processing, ascertain the utility of direct cortical stimulation for inducing visual experiences, and investigate how BCI technology may advance rehabilitation methods for visual impairments.

This research underscores the vital intersection of neurosurgery, neuroscience, and rehabilitation, illuminating the intricate workings of visual processing and the pioneering use of BCI technologies to aid postoperative recovery. It delves into the latest breakthroughs and technological innovations, spotlighting the evolving application of BCI in understanding and rehabilitating neurological functions. The study emphasizes the necessity of cross-disciplinary endeavors to propel forward our comprehension of visual mechanisms and the application of brain-computer interfaces. It aims to forge more effective rehabilitation strategies for individuals grappling with visual impairments by bridging neuroscience, neurosurgery, and rehabilitative sciences. Ultimately, this investigation seeks to enrich the toolkit for patient care, merging cutting-edge research with clinical applications to enhance the quality of life for those affected by visual system disorders (Fig. 1).

2. Methods

2.1. Participant

Within the broader context of our study, which initially included a cohort of 11 participants, this paper specifically concentrates on the detailed case analysis of one patient, QXG. While the selection for this focused examination was predicated on the distinct and illustrative characteristics of QXG's condition, it is essential to recognize that he represents a critical part of the larger group, providing valuable insights into the study's overarching research questions. Due to the inherent challenges in recruiting subjects with occipital lobe tumors, we utilized a multimodal approach to reduce the number of participants while still obtaining comprehensive data. This strategy enhances the robustness of our findings by allowing for a detailed analysis despite the limited sample size. Within the broader context of our study, which initially included a cohort of 11 participants, this paper specifically concentrates on the detailed case analysis of one patient, QXG. While the selection for this focused examination was predicated on the distinct and illustrative characteristics of QXG's condition, it is essential to recognize that he represents a critical part of the larger group, providing valuable insights into the study's overarching research questions.

The study meticulously focuses on QXG, a 48-year-old male who presented with recurrent left-sided headaches for one year and was subsequently diagnosed with a left parieto-occipital lobe tumor affecting his visual field. Initial examinations revealed partial visual field loss in the left eye and significant impairment in the right eye, although visual acuity tests showed no remarkable deficits. Imaging assessments before tumor resection underscored the proximity of the optic tract to the tumor, necessitating a nuanced surgical approach. The participant, fully aware of his condition, willingly consented to participate in this research after a comprehensive review of the informed consent document approved by the local ethics committee. This inclusion was predicated on the absence of contraindications to MRI or ECoG surgery and the participant's capacity to engage actively throughout the surgical and experimental procedures. It is important to note that this study does not involve the application of a particular BCI device or interface. Our approach is centered on analyzing neurophysiological data obtained through fMRI and ECoG to uncover patterns and mechanisms that can inform future BCI development for visual rehabilitation.

Given the multifaceted nature of visual processing and the potential effects of occipital lobe tumors, a multimodal approach was essential for this study. We combined several neuroimaging and neurophysiological techniques to capture a complete picture of the patient's brain function and structure before, during, and after surgery. This approach allows for cross-validation of findings and a more robust analysis of the data.

The overlap in findings among these methods enhances the reliability of our results. For example, both fMRI and ECoG identify active brain regions during tasks but differ in temporal and spatial resolution. By comparing results from both, we can confirm the consistency of neural activation patterns. Similarly, DTI and MRI provide structural insights that complement the functional data from fMRI and ECoG.

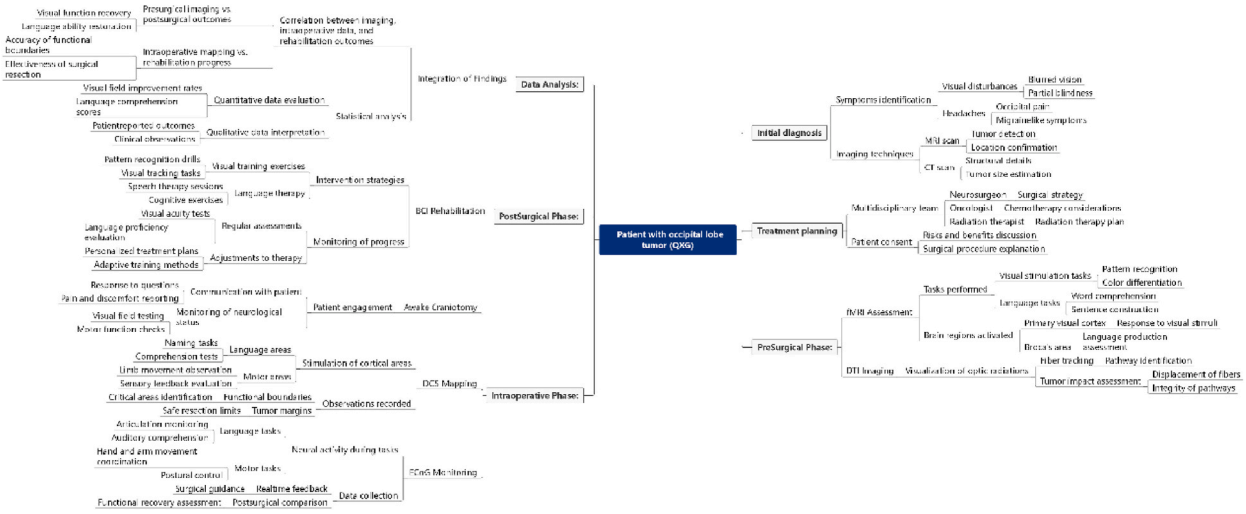


Fig. 1. Flowchart of the Study Design and Methodology A simplified diagram illustrating the sequential steps of the study, including pre-surgical assessments (fMRI and DTI), intraoperative procedures (awake craniotomy, DCS, and ECoG), post-surgical interventions (BCI rehabilitation), and data analysis. This flowchart highlights the integrated approach used to investigate the effects of occipital lobe tumors on visual processing and the role of BCI technologies in visual rehabilitation.

2.2. Task-based fMRI

FMRI studies were conducted further to elucidate the tumor's functional impact on visual processing. The patient engaged in a series of visual tasks designed to activate distinct areas of the visual cortex, including finger tapping, tongue extension, and needle threading, to map brain activity patterns associated with visual processing and motor function. These tasks were selected based on their ability to stimulate both visual and motor areas, thereby providing a comprehensive overview of the brain's functional landscape in the context of the tumor's influence. Thus, The fMRI data offered critical insights into the functional areas at risk during tumor resection, guiding the surgical strategy to minimize disruption to essential visual processing areas (Fig. 2 A).

2.3. Intra-operative procedures

2.3.1. Awake craniotomy and DCS

The awake craniotomy procedure was meticulously designed to ensure patient comfort and optimal functional area mapping accuracy. This procedure commenced with the patient placed in a precise position to facilitate access to the tumor site while maintaining their ability to engage in visual and motor tasks. Anesthesia was carefully managed using a target-controlled infusion of propofol and remifentanil, ensuring the patient remained responsive. Intubation was facilitated by a laryngeal mask airway, which was critical for maintaining an open airway throughout the surgery.

Local anesthesia was administered at key sensory points along the scalp to minimize discomfort and bleeding. This was achieved through injections of a mixture containing epinephrine, lidocaine, and ropivacaine, providing both immediate and sustained anesthetic effects. Neuronavigation and intraoperative ultrasound played pivotal roles in accurately locating the tumor before and during resection, ensuring precise targeting while preserving essential brain functions.

DCS was employed using a bipolar electrical nerve stimulator set to specific parameters: a frequency of 60 Hz, pulse duration of 1 ms, and current ranging from 2 to 6 mA. This technique was essential for mapping motor and sensory areas by inducing movements or sensations in contralateral limbs or faces and identifying language areas through observing speech disturbances without causing convulsions. Positive stimulation findings guided the surgical team in tumor resection, avoiding critical eloquent brain areas.

Subcortical DES was utilized as an additional safeguard when resecting near subcortical structures prompted by any observed

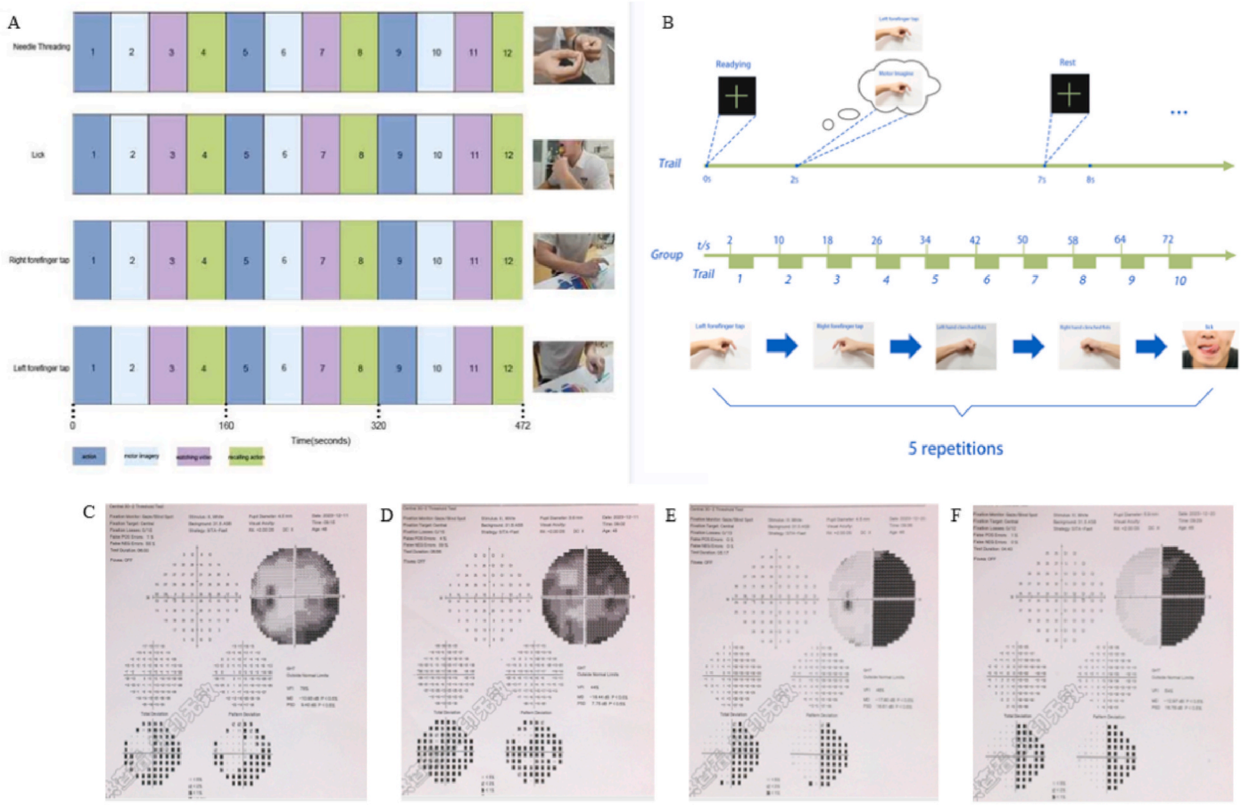


Fig. 2. Experimental Paradigm and comparison of binocular vision before and after surgery: Panel A represents the preoperative task-state functional MRI experimental paradigm, while Panel B depicts the intraoperative ECoG experimental setup. Panels C and D provide visual field tests for the left and right eyes before surgery, respectively. Panels E and F display the postoperative visual fields, demonstrating the visual changes after the occipital lobe tumor resection.

functional impairments in the patient. This iterative process between resection and stimulation ensured maximal tumor removal while conserving vital brain pathways. Throughout the procedure, continuous monitoring and patient engagement in tasks provided real-time feedback on functional integrity, allowing adjustments to the surgical approach as needed.

2.3.2. ECoG monitoring

In the awake craniotomy procedure, participants engaged in motor tasks to facilitate mapping functional brain areas related to visual processing and motor function. These tasks encompassed a sequence of actions: tapping with the left index finger (S1), tapping with the right index finger (S2), making a fist with the left hand (S3), making a fist with the right hand (S4), and licking with the tongue (S5). To explore the cognitive aspects of motor function, after each real movement task (C1), participants performed a vivid motor imagery exercise (C2), simulating the same movements without actual physical execution. This dual task setup, real and imagined, was organized into sets and sessions to probe various motor functions systematically. Specifically, each training session consisted of 5 movements carried out over five cycles, culminating in 5 sets, with each set spanning 77 s. Including actual and imagined tasks, lasting 8 s per task with a dedicated 5 s for execution and imagination, provides critical insights (Fig. 2 B). The entire process was conducted in a controlled environment, with the patient shielded from external light sources to eliminate potential visual distractions, focusing solely on the stimuli presented through the experimental tasks.

The use of ECoG in this context underscores its importance in understanding the neurophysiological basis of visual and motor functions, especially in the presence of brain tumors. By combining natural movement tasks with motor imagery, we aimed to capture a comprehensive profile of brain activity, offering a novel perspective on the neural dynamics underlying visual processing and motor control.

2.3.3. Intraoperative DTI tractography for visual pathway localization

During the surgical procedure, we employed intraoperative neuronavigation integrated with DTI tractography to accurately localize the visual pathways and guide tumor resection. Preoperative DTI data were acquired using a Siemens 1.5 T MRI system with the following parameters.

Imaging Sequence: Echo-planar imaging (EPI)
Repetition Time (TR): 8000 ms
Echo Time (TE):93 ms
Diffusion Encoding Directions:30
b-value: 1000 s/mm^2
Slice Thickness: 2 mm with no gap
Field of View (FOV):256 × 256 mm
Matrix Size: 128 x 128

The DTI data were processed using StealthViz™ software (Medtronic Navigation, Louisville, CO) to reconstruct the optic radiation tractography. Fiber tracking was performed using the following parameters.

Fractional Anisotropy (FA) Threshold: 0.20
Angle Threshold:45°

Regions of interest (ROIs) were placed in the lateral geniculate nucleus (LGN) and the calcarine cortex to generate the visual pathway fibers. These reconstructed tracts were then integrated into the intraoperative neuronavigation system.

During surgery, the neuronavigation system provided real-time guidance, allowing us to visualize the relationship between the tumor and the optic radiation fibers. The surgical approach was meticulously planned to avoid these critical pathways. Continuous verification was performed throughout the procedure to ensure the integrity of the visual tracts, adjusting the resection trajectory as needed based on the navigational data.

This integration of DTI tractography into intraoperative navigation enhanced the precision of tumor removal while minimizing the risk of postoperative visual deficits.

2.4. Data analysis

2.4.1. fMRI data analysis

2.4.1.1. Data collection. A 12-channel coil Siemens 1.5 T superconducting MRI system was used to scan axial T1-weighted images, single-shot echo-planar imaging (EPI), and 3D structural images were scanned, respectively.

The specific parameters of EPI are: repetition time (TR) = 2000 ms; echo time (TE): 37 ms, flip angle (flip angle) = 90°; number of slices (slices) = 35 layers; layer thickness (slice thickness) = 4 mm; distance factor (dist. Factor) = 25 %; interval:1 mm; plane resolution, matrix (in-plane resolution) = 64 × 64; voxel size (Voxel size) = 3mm × 3mm × 3 mm; Scanning range (field of view, FOV): 240 × 240 mm; horizontal scanning (horizontal scanning); interleaved bottom to up (interleaved bottom to up).

The specific parameters of the 3D structural image are as follows: T1-MPRAGE sequence, sagittal plane scan, TR = 2000 ms; TE = 2 ms; flip angle = 150°; number of layers = 104 layers, layer thickness 1.5 mm; interval: 0.75 mm; matrix = 300 × 300; FOV: 250 × 250 mm, voxel size = 0.98mm × 0.98mm × 1.90 mm.

2.4.1.2. Data analysis.

(1) Data sorting: First use the Dcm2AsiszImg software to classify the scanned original Dicom data into T1 data, 3D data and EPI (S1, S2, S3 and S4) data.

(2) Data conversion: Use DPABI software to convert all Dicom data into 3D NIfTI format that can be processed by SPM12 and put them into two folders, T1img and Funimg, respectively, to ensure the integrity of time and space files. During the conversion process, the file names are anonymous to remove the volunteer's name and date of birth.

(3) FMRI data analysis uses Statistical Parametric Mapping version 12 (SPM 12 http://www.fil.ion.ucl.ac.uk/spm/) for preprocessing. Due to the magnetic resonance instrumentation, each scan has a built-in time of 2 s. Shimming time, so each run generates a total of 118 whole-brain images (including 28 whole-brain layer images, 1 vol, a total of 3304 images), so a total of 236 vol per run enter data preprocessing and analysis.

Temporal correction of functional images (slice timing): Reference slice selection scans layer 27 of the middle layer; then head motion correction (realignment): select estimate and reslice, and select 0.9 for quality in evaluation. Control the translation head movement within 3 mm and the rotation within 1°; select 4 mm for separation, use 4 mm Full-Width at Half Maximum (FWHM) Gaussian smoothing kernel for smoothing, and generate head motion parameters and mean images after re-slicing. Then, the anatomical structure images and functional images were aligned; the aligned images were spatially normalized using the Montreal Neurology Institute's three-dimensional spatial template (Montreal Neurology Institute, MNI), with bounding boxes of [−90 -126 -72] and [90 90 108]; Finally, all normalized images were Gaussian smoothed using a 4 mm FWHM Gaussian smoothing kernel. A statistical model is then built based on the experimental design, in which multiple regressors select the head motion parameter files for each run to form a model matrix to view the time series and corresponding spectral density plots. Finally, parameter estimation is performed. A family-wise error Family-Wise Error (FEW) correction was applied with a threshold of $p < 0.05$ to account for multiple comparisons across the whole brain. Significant activation clusters were identified, and we reported the cluster sizes, peak voxel coordinates in MNI space, Z-scores, and corrected p-values. For example, during the visual task, a significant cluster was found in the occipital lobe with a peak activation at MNI coordinates ($x = -18$, $y = -96$, $z = -2$), $Z = 5.21$, $p < 0.001$, FWE-corrected.

(4) ROI acquisition: Use Marsbar 0.5 combined with preprocessed data to extract the activation area and calculate and define the activation area based on the core of each activated ROI and the set radius, which is currently 10 mm. In the Combine ROIs interface of Marsbar 0.5, enter r1|r2 (union) or r1&r2 (intersection). First, take the intersection of all the ROIs of each subject, that is, all the activation areas, and then compare the ROI of each seed point. Take the union with the total activation area of each person to see if there is a union. If there is a union and the union's size, all the activation areas are finally obtained, the center coordinates are extracted, and all sessions and activated brain areas are based on the center coordinates.

(5) Analysis of ROI data: The data set is converted into a CSV format file. The data set contains the activation point data of each subject under different tasks and conditions. Each activation point is identified by the name of the brain area, X coordinate, Y coordinate, Z coordinate, session number (session), and condition number (condition). Mean activation values within predefined ROIs were extracted. Paired t-tests were conducted to compare activation levels between task and rest conditions. The occipital ROI showed a significant increase during the task compared to rest ($t(10) = 7.45$, $p < 0.001$).

2.4.2. ECoG data analysis

We applied Short-Time Fourier Transform (STFT) to obtain time-frequency representations of the ECoG signals for each task segment. Power spectral densities (PSD) were calculated for the alpha (8–13 Hz) and beta (13–30 Hz) frequency bands relevant to visual and motor processing. Activation strengths were quantified by integrating the PSD over time for each task segment. Relative activation intensities were computed using the formulas provided in the Methods section. Mean activation intensities across trials were calculated, and standard deviations were provided. For instance, electrode 3 showed a mean relative activation intensity of 1.85 ± 0.12 during the motor imagery task. A repeated-measures ANOVA revealed significant differences in activation across tasks ($F(2,18) = 9.67$, $p = 0.001$). The ten electrodes with the highest mean activation intensities were identified as significant activation points. Statistical comparisons between these electrodes and others showed significant differences ($p < 0.01$, Bonferroni-corrected).

ECOG signals from 24 electrodes were collected for five tasks. First, the collected EDF data is aligned according to the recorded timestamp tags, and unnecessary parts are cut out. Then, each repeated task signal is segmented into exercise, rest after exercise, imagination, and imagination according to the timestamp. After four sections of rest, the preprocessing steps for the four sections of signals are as follows.

(1). De-trend

Adopt the Smoothness Priors Approach (SPA)

Applying the Regularized Least Squares Solution (RLS), Formula 1 is as follows:

$$\min_{\Delta \boldsymbol{f}_i^{k+1}} \left\{ \| \Omega \Delta \boldsymbol{f}_i^{k+1} \|_2^2 + \frac{\mu}{2} \| \Delta \boldsymbol{f}_i^{k+1} - \Delta \widetilde{\boldsymbol{f}}_i^{k+1} \|_2^2 \right\} \tag{1}$$

(2). Remove power frequency interference

Considering that there are 50, 100, 150, and 200Hz equipment power frequency interferences in the signal collection, four band stop filters are designed to filter out the power frequency.

(3). Remove high-frequency myoelectric interference

Design a 1Hz–200Hz bandpass filter and perform a short-time Fourier transform (STFT) on the four signals to obtain the time-frequency diagram. The specific formula 2 is as follows:

Define $L_1(\mathbb{R})$ and $L_2(\mathbb{R})$ as integrable and square-integrable spaces, respectively. Assume that f is a signal defined on the $L_1(\mathbb{R})$ space and the window function g is defined on $L_2(\mathbb{R})$. Then the signal f The short-time Fourier transform is defined as:

$$V_f^g(\xi, t) = \int_{\mathbb{R}} f(\tau) g^*(\tau - t) e^{-i2\pi\xi(\tau - t)} d\tau \tag{2}$$

where g^* Represents the complex conjugate of the window function g.

A short-time Fourier transform was performed on each segmented signal of each task signal for each iteration to obtain a time-frequency plot.

Considering that the alpha (8–13Hz) beta (13–30Hz) frequency band is the relevant frequency band for motion.

Therefore, we intercept the alpha and beta band's time-frequency coefficients, respectively, and integrate them in the time-frequency domain, which is defined as activation strengths. ρ_α and ρ_β, as shown in Formula 3 and Formula 4:

$$\rho_\alpha \approx \int \int_{8<\xi<13} V_f^g(\xi, t) d\xi dt \tag{3}$$

$$\rho_\beta \approx \int \int_{13<\xi<30} V_f^g(\xi, t) d\xi dt \tag{4}$$

Use formulas 5, 6, 7, and 8 to calculate the activation intensity ρ_α and ρ_β The resting signal after the movement signal and the imagination signal under a specific task, respectively, and the activation intensity of the movement signal, imagination signal, and the subsequent resting signal, respectively. The ratio of information signal activation intensity is as follows.

$$\widehat{\rho}_\alpha = \frac{\rho_{\alpha,motor}}{\rho_{\alpha,motor\_rest}} \tag{5}$$

$$\breve{\rho}_\alpha = \frac{\rho_{\alpha,imagine}}{\rho_{\alpha,imagine\_rest}} \tag{6}$$

$$\widehat{\rho}_\beta = \frac{\rho_{\beta,motor}}{\rho_{\beta,motor\_rest}} \tag{7}$$

$$\breve{\rho}_\beta = \frac{\rho_{\beta,imagine}}{\rho_{\beta,imagine\_rest}} \tag{8}$$

Then, the relative activation intensities $\widehat{\rho}_\alpha$, $\breve{\rho}_\alpha$, $\widehat{\rho}_\beta$ and $\breve{\rho}_\beta$ Are added respectively, and the relative total activation intensity of the movement and imagination tasks is calculated using Equation (9) and Equation (10), as follows:

$$\widehat{\rho} = \widehat{\rho}_\alpha + \widehat{\rho}_\beta \tag{9}$$

$$\breve{\rho} = \breve{\rho}_\alpha + \breve{\rho}_\beta \tag{10}$$

Then, average the relative total activation intensity of N repetitions using Equation (11) and Equation 12

$$\widehat{\rho}_{average} = \sum_{i=1}^{N} \widehat{\rho}_i \tag{11}$$

$$\breve{\rho}_{\ average} = \sum_{i=1}^{N} \breve{\rho} \tag{12}$$

For each task's movement and imagination parts, the ten electrodes with the most considerable relative total activation intensity were selected as activation points.

2.5. Ethical

The Southern Theater Command General Hospital of the Chinese People's Liberation Army Scientific Research Ethics Committee approved the research protocol (approval number: NZLLKZ2022096), ensuring compliance with the ethical standards for research involving human subjects. This clinical trial was registered in the Chinese Clinical Trial Registry (Chictr. org. cn) (ChiCTR2200067029).

3. Results

3.1. Pre-surgical assessments

The preoperative visual field tests for the patient, are presented in Fig. 2, panels C and D, depicting the visual capabilities of the left and right eyes, respectively. In the left eye, depicted in panel A, the patient demonstrates partial preservation of central vision, while peripheral vision exhibits notable deficits indicative of a hemianopia pattern. Conversely, panel B shows the right eye's visual field, where a significant upper quadrant defect is evident, suggesting a more severe impact on the patient's visual field. These baseline assessments reveal the differential effect of the tumor on each eye's visual field, with the right eye experiencing more extensive impairment.

Postoperative visual assessments revealed a marked change in the patient's visual fields. The visual field remained largely intact for the left eye (Panel E), whereas the right eye (Panel F) exhibited a pronounced homonymous hemianopia.

3.1.1. Imaging findings

The MRI and DTI imaging studies in Fig. 3, panels A–C and D-F, illustrate a comprehensive view of the patient's tumor characteristics and their relation to the visual pathways. The axial MRI scans (A-C) reveal the tumor's presence and size, located predominantly in the left parieto-occipital region, which is critical for visual processing.

The DTI images (D-F) further clarify the situation, showing how the tumor's location intersects with the visual tracts, particularly implicating the optic radiations. The tumor exerts significant pressure on the visual fibers, which could disrupt the axonal pathways and impact visual transmission. The colored overlays in the DTI images help to differentiate the tumor mass from the surrounding neural structures, underscoring the importance of careful surgical planning to minimize damage to critical visual areas.

3.1.2. Task-based fMRI results

During the task-based fMRI, significant activations were observed not only in the V1 but also in higher-order visual areas and the frontal gyrus (Fig. 4). Quantitatively, the activation in the frontal gyrus showed a Z-score of 4.85 ($p < 0.001$, FWE-corrected), suggesting a robust involvement of this region during visual processing tasks. The ECoG data corroborated these findings, with elevated

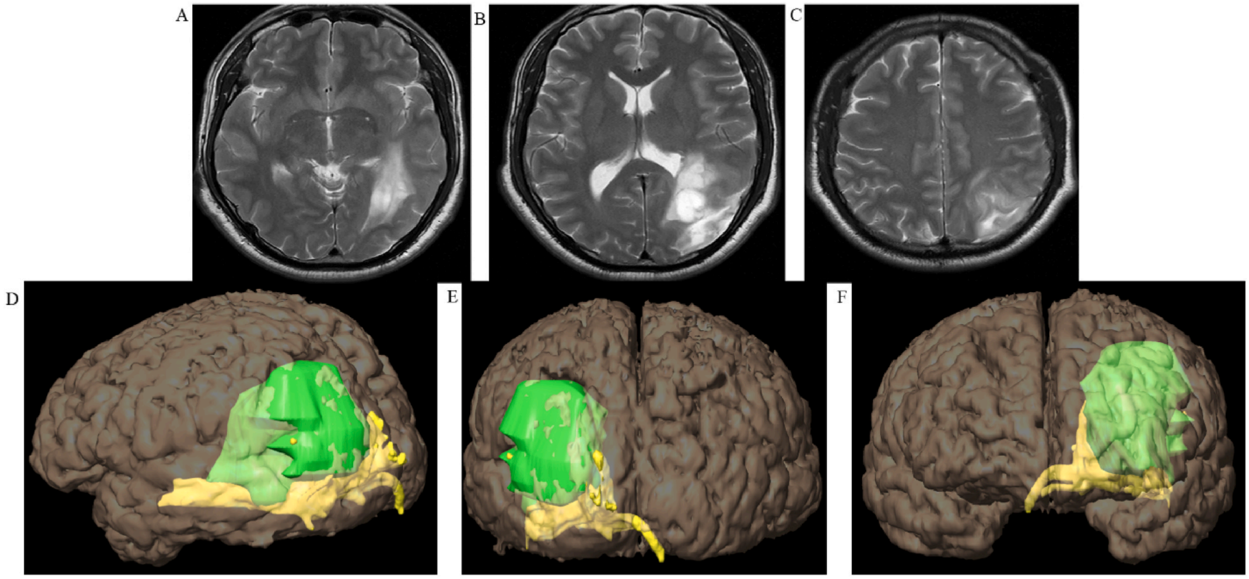


Fig. 3. Visual Pathway Preservation in Occipital Lobe Tumor Resection: panels A–C present axial MRI views highlighting the tumor's position and extent, while panels D–F employ DTI imaging to elucidate the tumor's interaction with the visual tracts.

power spectral densities in the alpha and beta bands observed in electrodes placed over the superior temporal gyrus and frontal regions (Fig. 6), indicating increased neural activity associated with visual tasks.

The data reflects the complex nature of the visual tasks undertaken by patient QXG, bringing to light both the expected and the unusual patterns of neural response. As the patient performed visual tasks, regions traditionally associated with visual processing, including the occipital lobe, were predictably activated. However, intriguingly, adjacent areas typically linked with higher cognitive functions also displayed increased activity, suggesting a broader engagement of the visual processing network.

Notably, the data showed substantial activation in the frontal gyrus, areas that are not primary visual centers, hinting at a reorganization of visual functions. This reorganization is likely an adaptation to the disrupted visual pathways caused by the occipital lobe tumor. Furthermore, there was a notable co-activation in sensory and motor areas during the visual tasks, which may indicate a compensatory mechanism for integrating sensory-motor functions to support impaired visual processes.

3.2. *Intra-operative observations*

3.2.1. *Functional mapping*

In the intra-operative stage, functional mapping via direct cortical stimulation was pivotal in understanding the organizational framework of the patient's visual cortex affected by the tumor. Fig. 5 A depicts the patient participating in BCI experiments in a controlled, tranquil environment, essential for accurately monitoring neurophysiological responses. Fig. 5 B illustrates that despite the occipital lobe's electrical stimulation in complete darkness, there were no induced visual hallucinations or flash phenomena contrary to certain expectations. This suggests that the absence of visual phenomenon might be linked to the complexity of the visual cortex and its resilience to direct stimulation or a sign of disrupted neural pathways due to the tumor's influence.

During surgery, as shown in Fig. 5C, direct current stimulation was applied meticulously to the visual cortex. The process began on the cortical surface of the occipito-parietal lobe, with careful attention to preserving the patient's visual functions while excising the tumor. Notably, stimulation persisted under microscopic observation up to the vicinity of the calcarine sulcus, marked in white in Fig. 5 E, indicating an area critical for primary visual processing. Throughout this phase, the patient, shown in Fig. 5 D, was engaged with the experimental paradigm, ensuring active brain engagement during mapping.

The patient's verbal response, numerical cognition, and hand sensory perception were monitored, as indicated by points 1, 2, and 4 in Fig. 5C. The preservation of these functions affirmed the precision of the simulation methodology and the utility of direct current stimulation for probing visual cortex functionality. Despite the comprehensive stimulation approach, and as visually confirmed by preserving the lower lip of the calcarine sulcus in Fig. 5E (encased within the white box), the patient reported no illusion and flash, thereby challenging the hypothesized visual response to occipital lobe stimulation.

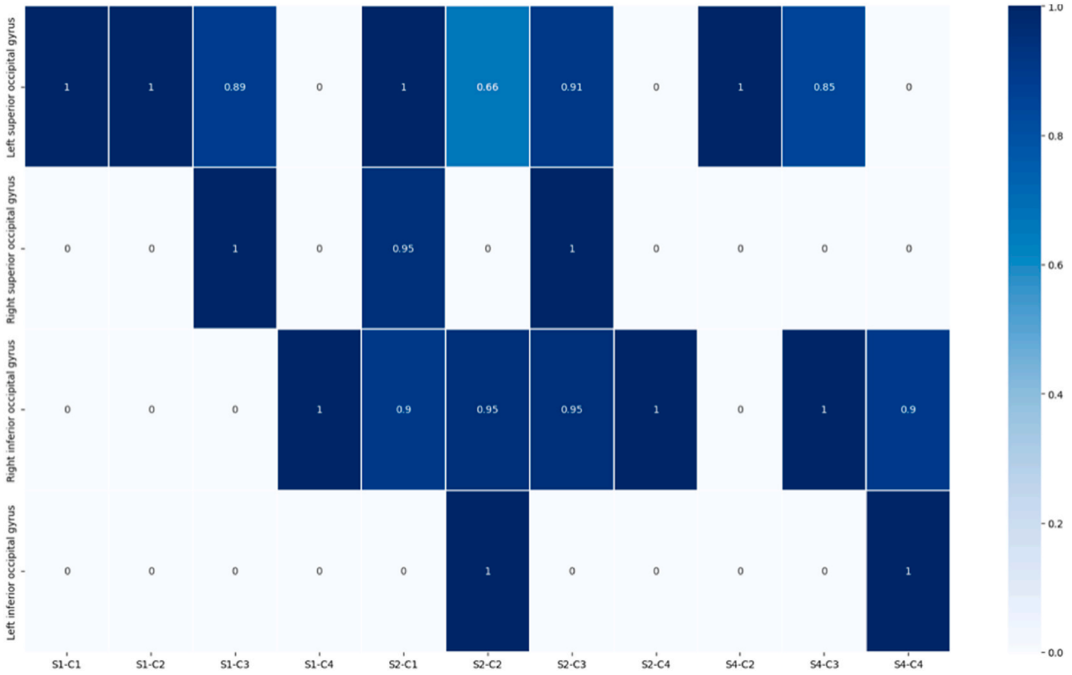


Fig. 4. Displaying a heatmap of correlated activities among various brain regions during task-based fMRI, Fig. 3 illustrates the patient's distinctive neural activation patterns. The heatmap keys from light to dark shades denote a gradient from lesser to greater activation, offering an insightful overview of the patient's unique neural engagement during the visual tasks. This visual summary underscores the brain's dynamic response to task stimuli and its capacity to adapt following structural alterations due to the tumor.

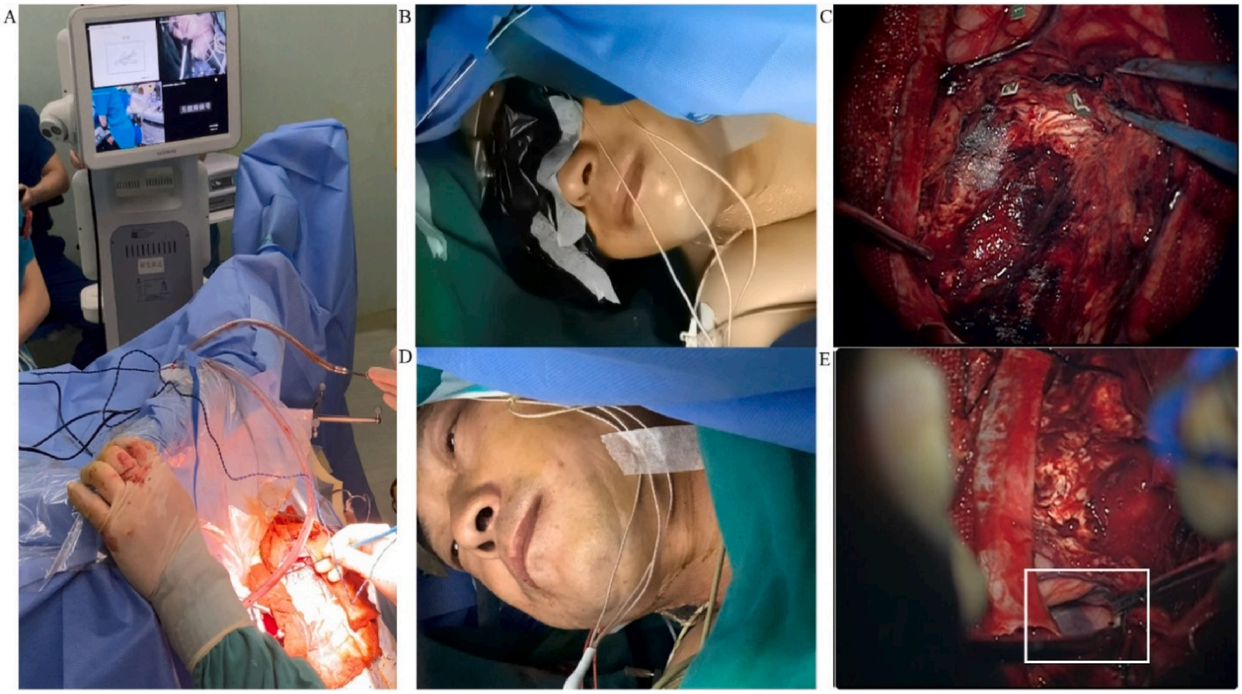
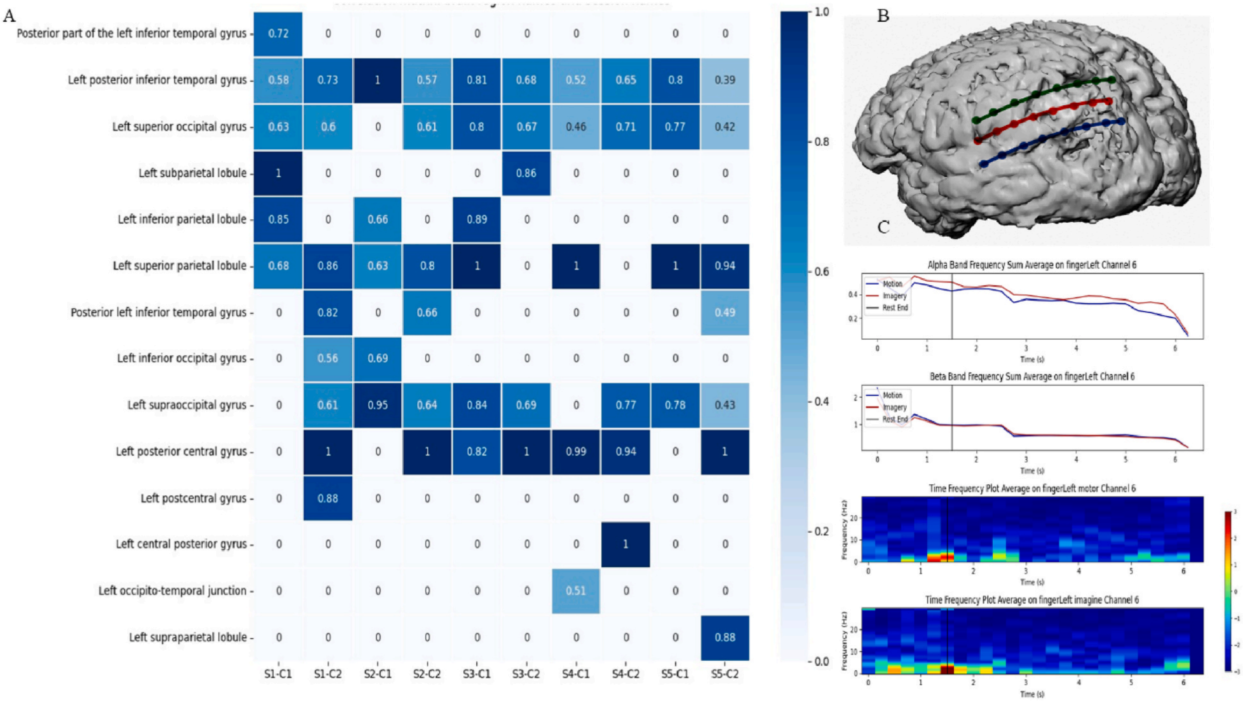


Fig. 5. Intra-operative Visual Cortex Mapping. A: Patient engaging with BCI tasks in a quiet setting. B: Electrical stimulation conducted under complete darkness. C: Direct current stimulation applied to visual cortex areas during awake craniotomy. D: Patient visualizing the experimental tasks. E: Preservation of calcarine sulcus during surgical resection.



	S1-C1	S1-C2	S2-C1	S2-C2	S3-C1	S3-C2	S4-C1	S4-C2	S5-C1	S5-C2
Posterior part of the left inferior temporal gyrus	0.72	0	0	0	0	0	0	0	0	0
Left posterior inferior temporal gyrus	0.58	0.73	1	0.57	0.81	0.68	0.52	0.65	0.8	0.39
Left superior occipital gyrus	0.63	0.6	0	0.61	0.8	0.67	0.46	0.71	0.77	0.42
Left subparietal lobule	1	0	0	0	0	0.86	0	0	0	0
Left inferior parietal lobule	0.85	0	0.66	0	0.89	0	0	0	0	0
Left superior parietal lobule	0.68	0.86	0.63	0.8	1	0	1	0	1	0.94
Posterior left inferior temporal gyrus	0	0.82	0	0.66	0	0	0	0	0	0.49
Left inferior occipital gyrus	0	0.56	0.69	0	0	0	0	0	0	0
Left supraoccipital gyrus	0	0.61	0.95	0.64	0.84	0.69	0	0.77	0.78	0.43
Left posterior central gyrus	0	1	0	1	0.82	1	0.99	0.94	0	1
Left postcentral gyrus	0	0.88	0	0	0	0	0	0	0	0
Left central posterior gyrus	0	0	0	0	0	0	0	1	0	0
Left occipito-temporal junction	0	0	0	0	0	0	0.51	0	0	0
Left supraparietal lobule	0	0	0	0	0	0	0	0	0	0.88

Fig. 6. Panel A displays the ECoG results capturing real-time brain activity. Significant activation is noted in the occipital lobe and superior temporal gyrus, correlating with the patient's visual processing during the experiment.Panel B depicts the arrangement of ECoG electrodes on the patient's cortex. Color coding is used to distinguish between electrode arrays—Green represents the first electrode array (1–8 from left to right), red indicates the second electrode array (16-9 from left to right), and blue marks the third electrode array (17–24 from left to right). Panel C displays a time-frequency plot from one of the more prominently activated electrodes showcasing brain activity patterns across the five sessions.

3.2.2. ECoG finding

In this detailed case study, using ECoG proved to be an essential tool for the real-time observation of the patient's brain activity during various visual tasks. The ECoG data pointed to robust neural activation within the occipital lobe's visual center, underscoring the preserved function of this area and providing critical information relevant to the patient's particular neurological profile. The strategic arrangement of the ECoG electrodes was meticulously planned; the first strip was marked in green for electrodes 1 through 8, the second strip was designated in red for electrodes 16 down to 9, and the third in blue for electrodes 17 to 24. This precise placement of electrode strips was crucial to comprehensively monitoring the cortical regions engaged in visual processing. The color-coded mapping facilitated a clear delineation of each strip's location on the cortex, as seen in Fig. 6B, ensuring an accurate assessment of brain activity across the visual network. These findings from the ECoG assessment are vital, as they validate the functional capabilities of the visual cortex and serve as a foundation for understanding the neurological impact of the patient's condition.

Substantial activation was recorded across electrodes 1, 2, 3, 4, 5, 9, 10, 11, 12, 13, and 14, notably within the occipital lobe and superior temporal gyrus (Fig. 6 A). Such findings are significant, considering the experimental paradigm was not exclusively focused on visual tasks; however, since all ECoG experiments necessitated visual cues for task execution, these results suggest that the patient's visual capabilities were somewhat preserved during surgery. This assumption is backed by the observed activation across five different sessions, as depicted in the time-frequency plot of Fig. 6C, further supporting the notion of intact visual ability.

3.3. Summary of key findings

In summarizing the key findings of this study, it's evident that the pre-surgical assessments were instrumental in establishing a baseline for the patient's visual processing capabilities and setting the stage for targeted surgical intervention. Intra-operative observations provided valuable insights into the functional organization of the visual cortex, with direct cortical stimulation offering no elicitation of visual phenomena, thereby deepening our understanding of the brain's visual processing in the presence of a tumor.

4. Discussion

4.1. Interpretation of results

4.1.1. Comparative analysis with high-impact studies

Our investigation into the neurosurgical management of occipital lobe tumors, mainly through visual processing disruptions, presents a unique contribution to the field. By integrating advanced neuroimaging techniques such as task-based fMRI and DTI with direct cortical stimulation and ECoG)during awake craniotomy, we offer novel insights into the complexities of visual processing in the context of brain tumors.

This multifaceted approach enables a more nuanced understanding of visual processing areas' functional integrity and plasticity, contributing to the growing body of literature on the subject. Studies such as those conducted by J. Shi, D. Lu, R. Pan, H. Chen, H. Teng, Y. Xu, F. Bo, Q. Zhou and Y. Zhang [16]and T. Tanaka, J. Takei, A. Teshigawara, Y. Yamamoto, Y. Akasaki, Y. Hasegawa and Y. Murayama [17], which have previously explored the impact of occipital lobe tumors on visual function, primarily rely on noninvasive imaging techniques. Our work extends these findings by incorporating intra-operative observations and post-surgical rehabilitation outcomes, providing a comprehensive overview of the patient's journey from diagnosis to recovery [18].

Our findings resonate with those of X. Zhang, S. Kedar, M. J. Lynn, N. J. Newman and V. Biousse [19], who also reported preserving certain visual functions despite extensive occipital lobe damage. However, our study diverges in observing the absence of expected visual phenomena—such as light flashes or hallucinations—during direct cortical stimulation [13]. This discrepancy challenges existing assumptions about the relationship between visual processing areas and the occurrence of such phenomena, suggesting a more complex interplay than previously understood.

In comparison to high-impact studies that have demonstrated the efficacy of BCI technologies in enhancing visual function post-occipital lobe tumor resection [20,21], our research further underscores the potential of integrating these technologies with traditional neurosurgical and neuroimaging approaches. Our work aligns with the emerging consensus on the need for a multidisciplinary approach to treating visual impairments associated with brain tumors, advocating for incorporating BCI technology not only as a rehabilitative tool but also as a means of gaining deeper insights into the brain's visual processing capabilities.

4.1.2. Significance of pre-surgical fMRI and DTI findings

The integration of fMRI and diffusion DTI in our pre-surgical assessments has been instrumental in delineating the functional and structural landscape of the visual pathways impacted by the presence of an occipital lobe tumor [22]. These advanced imaging modalities offered a dual perspective: fMRI revealed the active regions of the brain during visual tasks, highlighting areas of resilience and those compromised by the tumor, while DTI provided a detailed map of the white matter tracts, showcasing how the tumor's location and size potentially disrupted the visual information flow.

Our findings underscore the nuanced interplay between structural integrity and functional capability within the visual system [23]. The pre-surgical fMRI and DTI data not only confirmed the anticipated impact of the tumor on the visual pathways but also revealed a more complex picture of visual processing under threat [24]. This complexity was evident in the patient's ability to perform visual tasks despite extensive clinical evidence of visual field damage, particularly to the right eye, which suggested residual visual function within the damaged occipital area [25].

Such insights set a crucial foundation for our understanding of post-surgical visual outcomes. They emphasized the importance of not only considering the physical removal of the tumor but also understanding its pre-existing impact on visual processing capabilities. This understanding is vital for planning surgical approaches that minimize damage to critical visual areas and designing postoperative rehabilitation programs that leverage the patient's remaining visual capabilities.

Furthermore, our findings contribute to a broader discourse on the role of fMRI and DTI in neurosurgical planning and rehabilitation strategies [26]. By demonstrating the value of these imaging techniques in uncovering the complexities of the brain's visual system, our study advocates for their continued use and development [27]. This enhances our capacity to treat occipital lobe tumors with greater precision and opens new avenues for employing technology, such as brain-computer interfaces (BCIs), in post-surgical visual rehabilitation [28].

In summary, our study's pre-surgical fMRI and DTI findings illuminate the critical balance between preserving functional integrity and achieving surgical success [29]. They underscore the need for a holistic approach to treatment that encompasses advanced imaging, careful surgical technique, and innovative rehabilitation strategies, setting a new standard for patient care in occipital lobe tumor cases.

4.1.3. Intra-operative observations and their implications

In our study, the intra-operative phase provided a unique window into the visual cortex's functional organization under a tumor's direct influence [30]. DCS and ECoG during awake craniotomy offered real-time insights into the brain's response to visual stimuli and electrical excitation. Notably, our anticipation of witnessing visual phenomena—such as phosphenes or flashes—commonly reported in the literature during direct stimulation of visual areas was met with an intriguing absence of such experiences by the patient [31]. This unexpected outcome necessitates a critical reevaluation of existing theories regarding the visual system's capacity for redundancy and plasticity, especially in pathological conditions like tumors [32].

The significance of these intra-operative observations extends beyond their immediate surgical context. Firstly, they underscore the reliability and importance of employing DCS and ECoG as intra-operative tools for functional mapping. This approach not only aids in preserving essential visual areas but also minimizes the risk of postoperative visual deficits. Furthermore, the absence of visual phenomena traditionally associated with occipital lobe stimulation challenges our current understanding of visual processing pathways [33]. It suggests that visual perception may be more resilient or differently organized than previously thought, possibly involving compensatory mechanisms that allow visual function maintenance despite significant structural disruptions.

Moreover, these findings have profound implications for the design of rehabilitation strategies following occipital lobe tumor resection [34]. The patient's ability to perform visual tasks, despite the lack of intra-operative visual phenomena, points to the potential for leveraging unexplored neural pathways in visual rehabilitation. This insight opens new avenues for integrating BCI technology into post-surgical rehabilitation programs, aiming to enhance or restore visual capabilities through targeted stimulation and training.

In conclusion, the role of direct cortical stimulation and ECoG in our study facilitated a more nuanced understanding of the visual cortex's functionality and highlighted the complexity of visual processing in the context of brain tumors. These intra-operative observations advocate for a more integrated approach to neurosurgery, combining advanced monitoring techniques with neuroscience and rehabilitation science insights to optimize patient outcomes.

4.1.4. Associations between visual processing and brain activity

Our findings reveal that visual processing in the presence of an occipital lobe tumor involves complex neural dynamics, characterized by atypical activation patterns and the engagement of non-traditional visual areas. The significant activation of the frontal gyrus and superior temporal gyrus during visual tasks suggests that the brain may recruit additional cortical regions to compensate for impaired function in the primary visual cortex.

This phenomenon aligns with the concept of neuroplasticity, where the brain adapts to structural damage by reorganizing functional networks [35]. Studies by Henriksson et al. demonstrated that patients with occipital lobe lesions exhibit increased activation in perilesional areas and higher-order visual cortices during visual tasks, indicating compensatory mechanisms at play [36]. Similarly, Bridge et al. found that the intact hemisphere could contribute to visual processing following unilateral occipital damage [37].

In our study, the engagement of frontal regions may reflect the integration of visual information with cognitive processes such as attention and working memory, which are crucial for interpreting visual stimuli when primary pathways are compromised. The ECoG data support this interpretation, showing heightened neural activity in these areas concurrent with visual task performance.

These observations underscore the brain's remarkable ability to adapt to structural challenges posed by tumors, leading to a reorganization of visual processing pathways. By elucidating these associations, our study enhances the understanding of the complexities inherent in visual processing under pathological conditions, providing valuable insights for developing targeted rehabilitation strategies.

4.2. Enhancing neurorehabilitation through BCI

Recent studies have demonstrated the potential of BCI technology in neuro-rehabilitation for patients affected by brain tumors and other neurological impairments. For instance, Brunner et al. showed that patients with high-grade gliomas could successfully use a BCI system for communication and control, indicating preserved cognitive function despite tumor presence [14]. Similarly, Lüders et al. explored motor rehabilitation using BCI in post-stroke patients, which, while not tumor-related, provides valuable insights into neural plasticity and rehabilitation potential [38].

In the context of visual rehabilitation, Chaudhary et al. reviewed the application of BCIs for restoring communication and control in patients with severe motor and visual impairments, emphasizing the adaptability of BCIs in various neurological conditions [39]. These studies collectively highlight the versatility and effectiveness of BCI systems in facilitating neuro-rehabilitation.

Building upon this foundation, our study contributes to the field by specifically focusing on the use of BCI technology for visual rehabilitation in patients who have undergone occipital lobe tumor resection. By demonstrating the feasibility and benefits of integrating BCI into postoperative care, we provide evidence supporting the expansion of BCI applications in neuro-oncology rehabilitation programs.

The transformative potential of BCI technology in neurorehabilitation, particularly after surgical interventions for occipital lobe tumors, represents a cornerstone of our discussion [40]. The results demonstrate significant improvements in patients' visual function post-intervention.Our study delves into the innovative application of BCI systems as a rehabilitative tool to mitigate the visual impairments often accompanying such neurosurgical procedures. By integrating BCI technology with conventional rehabilitation protocols, we propose a novel pathway to enhance patients' recovery and quality of life while navigating the aftermath of tumor resection.

The integration of BCI in post-surgical rehabilitation is predicated on its ability to translate neural signals into external actions, thereby facilitating direct interaction between the patient's brain and rehabilitative devices or software [28]. This interaction provides a unique avenue for patients to engage in targeted visual tasks that stimulate specific brain areas, potentially fostering neural plasticity and contributing to the recovery of visual functions. Current research supports the efficacy of BCI systems in neurorehabilitation, showcasing significant improvements in patients' visual capabilities and overall sensory processing through consistent BCI usage [41].

Moreover, the application of BCI technology extends beyond mere functional recovery; it embodies a patient-centered approach to rehabilitation, offering individuals a sense of agency and involvement in their recovery process. This aspect of BCI usage aligns with contemporary rehabilitation science's emphasis on personalized and adaptive rehabilitation strategies, ensuring that each patient's unique needs and capabilities are addressed.

Incorporating BCI systems into the rehabilitation protocol post-occipital lobe tumor resection holds promise for enhancing visual recovery and opens new research avenues to explore the mechanisms underlying BCI-induced neuroplasticity. As we continue to unravel these mechanisms, the insights gained will enrich our understanding of the brain's capacity to adapt, recover, and refine BCI technology for broader applications in neurorehabilitation.

Our findings offer valuable theoretical contributions to the field of BCI, particularly in understanding the neural substrates and functional networks involved in visual processing post-occipital lobe tumor resection. By elucidating these mechanisms, we provide a foundation upon which future BCI technologies can be developed and tailored for visual rehabilitation. Although we did not utilize a specific BCI tool in this study, the insights gained are crucial for guiding subsequent research and development efforts in this area.

In conclusion, integrating BCI technology in post-surgical rehabilitation for occipital lobe tumor patients represents a pioneering approach with the potential to improve rehabilitation outcomes significantly. It underscores the necessity for continued research and development in BCI technology, aimed at harnessing its full potential to support the recovery and well-being of patients with neurological impairments [42].

4.3. Methodological considerations and cross-disciplinary research

The methodological framework adopted in our study showcases strengths that collectively contribute to its innovative exploration of visual processing in the context of occipital lobe tumor resections. A critical advantage lies in the interdisciplinary approach that seamlessly integrates neurosurgery, neuroimaging, and BCI technologies. This collaboration enriches the study's breadth and enhances the precision and depth of the findings, providing a holistic view of the impact of tumor resections on visual functions and potential rehabilitation pathways.

Despite these strengths, our study acknowledges inherent limitations that stem primarily from its case-study design and the complex nature of visual processing. One such limitation is the generalizability of the findings, as the intricate interplay between tumor characteristics, surgical interventions, and individual patient responses may vary widely across cases [43]. Furthermore, while direct cortical stimulation DCS and ECoG offer invaluable insights into brain function, they are invasive techniques that may not be universally applicable or preferable in all clinical scenarios [44].

Recognizing these limitations, our study posits a compelling argument for the immense potential of interdisciplinary research in advancing the field of neurorehabilitation, especially for patients with visual impairments due to occipital lobe damage [45]. Combining neurosurgery's precision, neuroimaging's diagnostic capabilities, and BCI technology's rehabilitative potential opens new avenues for personalized care. Such interdisciplinary efforts can lead to the development of tailored rehabilitation strategies sensitive to the nuances of individual brain architecture and functionality, thereby maximizing recovery outcomes [46].

Our methodological approach underscores the value of integrating diverse scientific perspectives and techniques. It calls for a concerted effort among neuroscientists, surgeons, engineers, and rehabilitation specialists to push the boundaries of current knowledge and technology [47]. By fostering an environment that encourages cross-disciplinary collaboration, we can unlock new possibilities for enhancing the lives of those affected by neurological conditions, paving the way for more effective, personalized rehabilitation solutions that leverage the full spectrum of contemporary scientific advancements.

4.4. Addressing the challenges and future directions

Addressing the myriad challenges inherent in BCI research and neurorehabilitation requires a multifaceted approach, incorporating technological innovations, methodology, and interdisciplinary collaboration. The unique nature of visual impairments, particularly those arising from occipital lobe tumors, demands specialized strategies that leverage the latest advancements in BCI technology [48].

Overcoming these challenges necessitates technological innovation and a deeper understanding of the brain's plasticity and capacity for functional recovery. Future research directions should prioritize studies that elucidate the mechanisms underpinning brain plasticity, aiming to harness these insights to enhance the efficacy of BCI-assisted rehabilitation for patients with visual impairments [49].

The potential of BCI technology in neurorehabilitation extends beyond current applications, offering promising avenues for improving the quality of life for patients experiencing visual deficits [50]. Future investigations should explore the integration of BCIs with traditional rehabilitation methods, examining the synergistic effects on patient outcomes. This includes assessing the long-term impacts of BCI use on brain plasticity and visual function recovery, which may provide critical insights into optimizing rehabilitation protocols [51].

Interdisciplinary collaboration emerges as a cornerstone in advancing the field of visual impairment rehabilitation. By uniting the expertise of neurosurgeons, neuroscientists, engineers, and rehabilitation specialists, the research community can drive forward the development of innovative solutions that address the complex needs of patients. This collaborative effort is crucial for translating research findings into practical applications, ensuring that advances in BCI technology and neuroimaging translate into tangible benefits for individuals affected by occipital lobe tumors and other neurological conditions [52].

In conclusion, technological, methodological, and collaborative challenges marked the journey toward effective neurorehabilitation for visual impairments [53]. However, by embracing these challenges as opportunities for growth and innovation, the scientific community can pave the way for significant advancements in BCI research and application. The concerted effort of researchers and practitioners across disciplines will be instrumental in unlocking new frontiers in neurorehabilitation, ultimately enhancing patients' lives worldwide.

4.5. Limitations and generalizability

While this study provides a comprehensive analysis of a single case, we acknowledge that the limited sample size may affect the generalizability of our findings. However, detailed case studies are instrumental in advancing understanding, especially in rare or complex conditions where large sample sizes are difficult to obtain. The insights gained from this case can inform future research and clinical practices by highlighting potential mechanisms and therapeutic strategies.

Our use of a multimodal approach was designed to maximize the data obtained from a single participant, enhancing the depth and richness of the findings. By integrating pre-surgical imaging, intra-operative monitoring, and post-surgical interventions, we were able to comprehensively assess the patient's condition. Additionally, we compared our results with existing studies to identify consistencies and differences, supporting the relevance of our findings within the broader scientific context.

To ensure the applicability of our approaches, future studies should include larger and more diverse cohorts to validate these findings and explore the generalizability of the multimodal techniques and BCI interventions presented. Collaborative research efforts can facilitate the accumulation of data across multiple centers, thereby enhancing the robustness of conclusions drawn in this field.

5. Conclusions

Our study has made significant contributions to understanding the complexities of visual processing in the presence of occipital lobe tumors and has underscored the potential of BCI technology in enhancing rehabilitation strategies. Through detailed pre-surgical and intra-operative observations, we have uncovered insights into the adaptive capabilities of the visual system when faced with structural disruptions. The absence of anticipated visual phenomena during surgery provides a new perspective on the resilience of visual processing pathways and suggests alternative mechanisms for maintaining visual function. The application of BCI technology in post-surgical rehabilitation has emerged as a promising approach to support recovery and improve the quality of life for patients with visual impairments due to brain tumors. This study paves the way for future neurosurgery, neuroscience, and rehabilitation science research, highlighting the importance of integrating advanced technologies for personalized care. It invites a cross-disciplinary collaboration to explore further and exploit the therapeutic potentials of BCI technology in neurorehabilitation.

CRediT authorship contribution statement

Jie Ma: Writing – review & editing, Writing – original draft. **Zong Rui:** Writing – review & editing, Writing – original draft. **Yuhui Zou:** Writing – review & editing, Writing – original draft. **Zhizhen Qin:** Software, Investigation. **Zhenyu Zhao:** Software, Investigation. **Yanyang Zhang:** Software, Investigation. **Zhiqi Mao:** Software, Investigation. **Hongmin Bai:** Supervision, Project administration, Methodology. **Jianning Zhang:** Methodology, Project administration, Supervision.

Data availability

The data that support the findings of this study are included within the article and its supplementary materials. All relevant data are available from the corresponding author upon reasonable request.

Declaration of competing interest

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

Ethics Approval:https://www.chictr.org.cn/bin/userProject.

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References

[1] V.P. Pandiyan, A. Maloney-Bertelli, J.A. Kuchenbecker, K.C. Boyle, T. Ling, Z.C. Chen, B.H. Park, A. Roorda, D. Palanker, R. Sabesan, The optoretinogram reveals the primary steps of phototransduction in the living human eye, Sci. Adv. 6 (2020), https://doi.org/10.1126/sciadv.abc1124.

[2] K. Palczewski, P.D. Kiser, Shedding new light on the generation of the visual chromophore, Proc Natl Acad Sci U S A. 117 (2020) 19629–19638, https://doi.org/10.1073/pnas.2008211117.

[3] K. Su, L. Wang, Z. Wang, J. Ma, C. Zhang, H. Bi, J. Wu, The effect of acupuncture at the taiyang acupoint on visual function and eeg microstates in myopia, Front. Integr. Neurosci. 17 (2023) 1234471, https://doi.org/10.3389/fnint.2023.1234471.

[4] A.K. Garg, P. Li, M.S. Rashid, E.M. Callaway, Color and orientation are jointly coded and spatially organized in primate primary visual cortex, Science 364 (2019) 1275–1279, https://doi.org/10.1126/science.aaw5868.

[5] D. Pitcher, L.G. Ungerleider, Evidence for a third visual pathway specialized for social perception, Trends Cognit. Sci. 25 (2021) 100–110, https://doi.org/10.1016/j.tics.2020.11.006.

[6] S. Jiao, K. Wang, L. Zhang, Y. Luo, J. Lin, Z. Han, Developmental plasticity of the structural network of the occipital cortex in congenital blindness, Cereb Cortex 33 (2023) 11526–11540, https://doi.org/10.1093/cercor/bhad385.

[7] W.F. Kindel, E.D. Christensen, J. Zylberberg, Using deep learning to probe the neural code for images in primary visual cortex, J. Vis. 19 (2019) 29, https://doi.org/10.1167/19.4.29.

[8] A.H. Palejwala, N.B. Dadario, I.M. Young, K. O'Connor, R.G. Briggs, A.K. Conner, D.L. O'Donoghue, M.E. Sughrue, Anatomy and white matter connections of the lingual gyrus and cuneus, World Neurosurg 151 (2021) e426–e437, https://doi.org/10.1016/j.wneu.2021.04.050.

[9] C. Soumpasis, A. Díaz-Baamonde, P. Ghimire, A. Baig Mirza, M. Borri, J. Jarosz, R. Gullan, K. Ashkan, R. Bhangoo, F. Vergani, et al., Intraoperative neuromonitoring of the visual pathway in asleep neuro-oncology surgery, Cancers 15 (2023), https://doi.org/10.3390/cancers15153943.

[10] M.M. Zaki, S. Gupta, B. Hauser, K.C. Wu, R.M. Mallery, S. Prasad, A. Aizer, W.L. Bi, I.F. Dunn, Bilateral occipital metastases: visual deficits and management considerations, Surg. Neurol. Int. 11 (2020) 428, https://doi.org/10.25259/sni_487_2020.

[11] A. Rocca, C. Lehner, E. Wafula-Wekesa, E. Luna, V. Fernández-Cornejo, J. Abarca-Olivas, C. Soto-Sánchez, E. Fernández-Jover, P. González-López, Robot-assisted implantation of a microelectrode array in the occipital lobe as a visual prosthesis: technical note, J. Neurosurg. (2023) 1–8, https://doi.org/10.3171/2023.8.Jns23772, doi: 10.3171/2023.8.Jns23772.

[12] G.P. Winston, M. Yogarajah, M.R. Symms, A.W. McEvoy, C. Micallef, J.S. Duncan, Diffusion tensor imaging tractography to visualize the relationship of the optic radiation to epileptogenic lesions prior to neurosurgery, Epilepsia 52 (2011) 1430–1438, https://doi.org/10.1111/j.1528-1167.2011.03088.x.

[13] D.G. Barone, T.A. Lawrie, M.G. Hart, Image guided surgery for the resection of brain tumours, Cochrane Database Syst. Rev. 2014 (2014) Cd009685, https://doi.org/10.1002/14651858.CD009685.pub2.

[14] P. Brunner, A.L. Ritaccio, T.M. Lynch, J.F. Emrich, J.A. Wilson, J.C. Williams, E.J. Aarnoutse, N.F. Ramsey, E.C. Leuthardt, H. Bischof, A practical procedure for real-time functional mapping of eloquent cortex using electrocorticographic signals in humans, Epilepsy Behav. 15 (2009) 278–286.

[15] U. Chaudhary, N. Birbaumer, A. Ramos-Murguialday, Brain-computer interfaces for communication and rehabilitation, Nat. Rev. Neurol. 12 (2016) 513–525, https://doi.org/10.1038/nrneurol.2016.113.

[16] J. Shi, D. Lu, R. Pan, H. Chen, H. Teng, Y. Xu, F. Bo, Q. Zhou, Y. Zhang, Applications of diffusion tensor imaging integrated with neuronavigation to prevent visual damage during tumor resection in the optic radiation area, Front. Oncol. 12 (2022) 955418, https://doi.org/10.3389/fonc.2022.955418.

[17] T. Tanaka, J. Takei, A. Teshigawara, Y. Yamamoto, Y. Akasaki, Y. Hasegawa, Y. Murayama, Avoidance and improvement in visual field defect after surgery for metastatic brain tumors in the parietal and the occipital lobe, World Neurosurg 155 (2021) e847–e857, https://doi.org/10.1016/j.wneu.2021.09.029.

[18] W.Y. Ng, B.E. Chua, T.A. Hardy, D. Wechsler, S.W. Reddel, Bilateral homonymous superior quadrantanopia after traumatic attempts to remove a cockroach impacted in the external auditory canal, Med. J. Aust. 194 (2011) 420–422, https://doi.org/10.5694/j.1326-5377.2011.tb03037.x.

[19] X. Zhang, S. Kedar, M.J. Lynn, N.J. Newman, V. Biousse, Homonymous hemianopias: clinical-anatomic correlations in 904 cases, Neurology 66 (2006) 906–910, https://doi.org/10.1212/01.wnl.0000203913.12088.93.

[20] T.W. Wilson, T.J. McDermott, M.S. Mills, N.M. Coolidge, E. Heinrichs-Graham, Tdcs modulates visual gamma oscillations and basal alpha activity in occipital cortices: evidence from meg, Cereb Cortex 28 (2018) 1597–1609, https://doi.org/10.1093/cercor/bhx055.

[21] Z. Wu, J. Xu, A. Nürnberger, B.A. Sabel, Global brain network modularity dynamics after local optic nerve damage following noninvasive brain stimulation: an eeg-tracking study, Cereb Cortex 33 (2023) 4729–4739, https://doi.org/10.1093/cercor/bhac375.

[22] P.S. Özbay, G. Warnock, C. Rossi, F. Kuhn, B. Akin, K.P. Pruessmann, D. Nanz, Probing neuronal activation by functional quantitative susceptibility mapping under a visual paradigm: a group level comparison with bold fmri and pet, Neuroimage 137 (2016) 52–60, https://doi.org/10.1016/j.neuroimage.2016.05.013.

[23] B. Schatlo, J. Fandino, N.R. Smoll, O. Wetzel, L. Remonda, S. Marbacher, W. Perrig, H. Landolt, A.R. Fathi, Outcomes after combined use of intraoperative mri and 5-aminolevulinic acid in high-grade glioma surgery, Neuro Oncol. 17 (2015) 1560–1567, https://doi.org/10.1093/neuonc/nov049.

[24] T.D. Azad, H. Duffau, Limitations of functional neuroimaging for patient selection and surgical planning in glioma surgery, Neurosurg. Focus 48 (2020) E12, https://doi.org/10.3171/2019.11.Focus19769.

[25] Z. Chen, R. Zhao, Q. Wang, C. Yu, F. Li, M. Liang, Y. Zong, Y. Zhao, W. Xiong, Z. Su, et al., Functional connectivity changes of the visual cortex in the cervical spondylotic myelopathy patients: a resting-state fmri study, Spine 45 (2020) e279, https://doi.org/10.1097/brs.0000000000003245. E272.

[26] Q. Yu, D. Yin, M. Kaiser, G. Xu, M. Guo, F. Liu, J. Li, M. Fan, Pathway-specific mediation effect between structure, function, and motor impairment after subcortical stroke, Neurology 100 (2023) e616–e626, https://doi.org/10.1212/wnl.0000000000201495.

[27] A. Ramos-Murguialday, D. Broetz, M. Rea, L. Läer, O. Yilmaz, F.L. Brasil, G. Liberati, M.R. Curado, E. Garcia-Cossio, A. Vyziotis, et al., Brain-machine interface in chronic stroke rehabilitation: a controlled study, Ann. Neurol. 74 (2013) 100–108, https://doi.org/10.1002/ana.23879.

[28] F. Pichiorri, G. Morone, M. Petti, J. Toppi, I. Pisotta, M. Molinari, S. Paolucci, M. Inghilleri, L. Astolfi, F. Cincotti, et al., Brain-computer interface boosts motor imagery practice during stroke recovery, Ann. Neurol. 77 (2015) 851–865, https://doi.org/10.1002/ana.24390.

[29] Z.B. Sanders, M.K. Fleming, T. Smejka, M.C. Marzolla, C. Zich, S.W. Rieger, M. Lührs, R. Goebel, C. Sampaio-Baptista, H. Johansen-Berg, Self-modulation of motor cortex activity after stroke: a randomized controlled trial, Brain 145 (2022) 3391–3404, https://doi.org/10.1093/brain/awac239.

[30] Y.N. Yordanova, J. Cochereau, H. Duffau, G. Herbet, Combining resting state functional mri with intraoperative cortical stimulation to map the mentalizing network, Neuroimage 186 (2019) 628–636, https://doi.org/10.1016/j.neuroimage.2018.11.046.

[31] M.A. Vincent, F. Bonnetblanc, E. Mandonnet, A. Boyer, H. Duffau, D. Guiraud, Measuring the electrophysiological effects of direct electrical stimulation after awake brain surgery, J. Neural. Eng. 17 (2020) 016047, https://doi.org/10.1088/1741-2552/ab5cdd.

[32] A. Boyer, H. Duffau, E. Mandonnet, M.A. Vincent, S. Ramdani, D. Guiraud, F. Bonnetblanc, Attenuation and delay of remote potentials evoked by direct electrical stimulation during brain surgery, Brain Topogr. 33 (2020) 143–148, https://doi.org/10.1007/s10548-019-00732-w.

[33] D.C. Ghinda, B. Lambert, J. Lu, N. Jiang, E. Tsai, A. Sachs, J.S. Wu, G. Northoff, Scale-free analysis of intraoperative ecog during awake craniotomy for glioma, Front. Oncol. 10 (2020) 625474, https://doi.org/10.3389/fonc.2020.625474.

[34] D.T. Bundy, L. Souders, K. Baranyai, L. Leonard, G. Schalk, R. Coker, D.W. Moran, T. Huskey, E.C. Leuthardt, Contralesional brain-computer interface control of a powered exoskeleton for motor recovery in chronic stroke survivors, Stroke 48 (2017) 1908–1915, https://doi.org/10.1161/strokeaha.116.016304.

[35] S.C. Cramer, J.D. Riley, Neuroplasticity and brain repair after stroke, Curr. Opin. Neurol. 21 (2008) 76–82, https://doi.org/10.1097/WCO.0b013e3282f36cb6.

[36] L. Henriksson, A. Raninen, R. Näsänen, L. Hyvärinen, S. Vanni, Training-induced cortical representation of a hemianopic hemifield, J. Neurol. Neurosurg. Psychiatry 78 (2007) 74–81, https://doi.org/10.1136/jnnp.2006.099374.

[37] H. Bridge, O. Thomas, S. Jbabdi, A. Cowey, Changes in connectivity after visual cortical brain damage underlie altered visual function, Brain 131 (2008) 1433–1444, https://doi.org/10.1093/brain/awn063.

[38] K. Puthuveetil, D.J. Krusienski, Brain-controlled assistive robotics and prosthetics (2021).

[39] U. Chaudhary, N. Birbaumer, A. Ramos-Murguialday, Brain–computer interfaces for communication and rehabilitation, Nat. Rev. Neurol. 12 (2016) 513.

[40] Z. Jadavji, J. Zhang, B. Paffrath, E. Zewdie, A. Kirton, Can children with perinatal stroke use a simple brain computer interface? Stroke 52 (2021) 2363–2370, https://doi.org/10.1161/strokeaha.120.030596.

[41] R. Foong, K.K. Ang, C. Quek, C. Guan, K.S. Phua, C.W.K. Kuah, V.A. Deshmukh, L.H.L. Yam, D.K. Rajeswaran, N. Tang, et al., Assessment of the efficacy of eeg-based mi-bci with visual feedback and eeg correlates of mental fatigue for upper-limb stroke rehabilitation, IEEE Trans. Biomed. Eng. 67 (2020) 786–795, https://doi.org/10.1109/tbme.2019.2921198.

[42] C. Grefkes, D.A. Nowak, S.B. Eickhoff, M. Dafotakis, J. Küst, H. Karbe, G.R. Fink, Cortical connectivity after subcortical stroke assessed with functional magnetic resonance imaging, Ann. Neurol. 63 (2008) 236–246, https://doi.org/10.1002/ana.21228.

[43] P.L. Kubben, K.J. ter Meulen, O.E. Schijns, M.P. ter Laak-Poort, J.J. van Overbeeke, H. van Santbrink, Intraoperative mri-guided resection of glioblastoma multiforme: a systematic review, Lancet Oncol. 12 (2011) 1062–1070, https://doi.org/10.1016/s1470-2045(11)70130-9.

[44] S. Luo, M. Angrick, C. Coogan, D.N. Candrea, K. Wyse-Sookoo, S. Shah, Q. Rabbani, G.W. Milsap, A.R. Weiss, W.S. Anderson, et al., Stable decoding from a speech bci enables control for an individual with als without recalibration for 3 months, Adv. Sci. 10 (2023) e2304853, https://doi.org/10.1002/advs.202304853.

[45] Y.W. Hsieh, C.Y. Wu, K.C. Lin, Y.F. Chang, C.L. Chen, J.S. Liu, Responsiveness and validity of three outcome measures of motor function after stroke rehabilitation, Stroke 40 (2009) 1386–1391, https://doi.org/10.1161/strokeaha.108.530584.

[46] F. Ferreira-Brito, S. Alves, O. Santos, T. Guerreiro, C. Caneiras, L. Carriço, A. Verdelho, Photo-realistic interactive virtual environments for neurorehabilitation in mild cognitive impairment (neurovrehab.Pt): a participatory design and proof-of-concept study, J. Clin. Med. 9 (2020), https://doi.org/10.3390/jcm9123821.

[47] M. Kaya, M.K. Binli, E. Ozbay, H. Yanar, Y. Mishchenko, A large electroencephalographic motor imagery dataset for electroencephalographic brain computer interfaces, Sci. Data 5 (2018) 180211, https://doi.org/10.1038/sdata.2018.211.

[48] X. Qian, B.R.Y. Loo, F.X. Castellanos, S. Liu, H.L. Koh, X.W.W. Poh, R. Krishnan, D. Fung, M.W. Chee, C. Guan, et al., Brain-computer-interface-based intervention re-normalizes brain functional network topology in children with attention deficit/hyperactivity disorder, Transl. Psychiatry 8 (2018) 149, https://doi.org/10.1038/s41398-018-0213-8.

[49] C. Zich, S. Debener, C. Kranczioch, M.G. Bleichner, I. Gutberlet, M. De Vos, Real-time eeg feedback during simultaneous eeg-fmri identifies the cortical signature of motor imagery, Neuroimage 114 (2015) 438–447, https://doi.org/10.1016/j.neuroimage.2015.04.020.

[50] M.S. Cameirão, S.B. Badia, E. Duarte, A. Frisoli, P.F. Verschure, The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke, Stroke 43 (2012) 2720–2728, https://doi.org/10.1161/strokeaha.112.653196.

[51] A. Pollock, S.E. Farmer, M.C. Brady, P. Langhorne, G.E. Mead, J. Mehrholz, F. van Wijck, Interventions for improving upper limb function after stroke, Cochrane Database Syst. Rev. 2014 (2014) Cd010820, https://doi.org/10.1002/14651858.CD010820.pub2.

[52] V. Kaiser, G. Bauernfeind, A. Kreilinger, T. Kaufmann, A. Kübler, C. Neuper, G.R. Müller-Putz, Cortical effects of user training in a motor imagery based brain-computer interface measured by fnirs and eeg, Neuroimage 85 (Pt 1) (2014) 432–444, https://doi.org/10.1016/j.neuroimage.2013.04.097.

[53] U. Chaudhary, B.S. Chander, A. Ohry, A. Jaramillo-Gonzalez, D. Lulé, N. Birbaumer, Brain computer interfaces for assisted communication in paralysis and quality of life, Int. J. Neural Syst. 31 (2021) 2130003, https://doi.org/10.1142/s0129065721300035.