Stimulus Dependence of Neural Sites in Binocular Rivalry

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Abstract

Abstract

[**Objective**] Whether the neural substrates of binocular rivalry change flexibly according to stimulus characteristics is a core issue in this field and even in consciousness research; however, causal verification has long been lacking.

[**Methods**] Transcranial direct current stimulation (tDCS) was employed to interfere with the occipital lobe, right parietal lobe, left parietal lobe, and prefrontal cortex, respectively. Under two types of stimuli—orthogonal gratings and faces/houses—eye dominance strength and perceptual alternation rates were measured.

[**Results**] The results revealed a stable stimulus-dependent pattern: feature-level stimulus (grating) rivalry involves the occipital lobe (anodal stimulation significantly reduced eye dominance strength) and the right parietal lobe (anodal stimulation reduced eye dominance strength, while cathodal stimulation increased the perceptual alternation rate) to a greater extent. In contrast, object-level stimulus (face/house) rivalry involves the prefrontal cortex (anodal stimulation reduced eye dominance strength) and the left parietal lobe (both anodal and cathodal stimulation reduced eye dominance strength) to a greater extent.

[**Conclusion**] This study provides causal evidence for the stimulus-dependency of neural sites in binocular rivalry and reveals its flexible configuration mechanism. These findings advance the hybrid model from a descriptive static multi-site framework to a predictive flexible incorporation framework.

Full Text

Preamble

Stimulus Dependence of Neural Sites in Binocular Rivalry

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Abstract

Binocular rivalry refers to the phenomenon where different images presented simultaneously to the two eyes lead to alternating periods of perceptual dominance and suppression. A central debate in this field concerns the neural site of binocular rivalry: whether it occurs at a low-level, eye-based stage or a high-level, stimulus-based stage. This study reviews the stimulus-dependent nature of these neural sites, examining how factors such as spatial frequency, contrast, and semantic content influence the level at which competition is resolved. By integrating findings from psychophysics and neuroimaging, we propose that binocular rivalry is not localized to a single area but is a distributed process across the visual hierarchy, with the specific site of competition being highly dependent on the characteristics of the competing stimuli.

1. Introduction

When the two eyes are presented with significantly different images, the visual system is unable to fuse them into a single stable percept. Instead, the observer experiences binocular rivalry, characterized by stochastic alternations between the two images. For decades, researchers have debated the "neural site" of this phenomenon. Early theories, such as the "eye rivalry" hypothesis, suggested that competition occurs between monocular neurons in the primary visual cortex (V1) or even the lateral geniculate nucleus (LGN). Conversely, the "stimulus rivalry" hypothesis posits that competition occurs between higher-level representations of the objects themselves, independent of the eye of origin.

Recent evidence suggests that these two perspectives are not mutually exclusive. Instead, binocular rivalry appears to be a multi-stage process involving a hierarchy of visual areas. Crucially, the level at which the dominant competition occurs seems to depend heavily on the physical and semantic properties of the stimuli involved.

2. Low-Level Stimulus Factors and Eye-Based Rivalry

Low-level features, such as high contrast, high spatial

摘要

Whether the neural loci of binocular rivalry change flexibly according to stimulus characteristics is a core question in the field and in consciousness research more broadly; however, causal validation has long been lacking. In this study, transcranial direct current stimulation (tDCS) was employed to interfere with the occipital lobe, the right parietal lobe, the left parietal lobe, and the prefrontal cortex. Under two types of stimuli—orthogonal gratings and face/house images—we measured eye dominance strength and perceptual alternation rates. The results revealed a stable, stimulus-dependent pattern: feature-level stimulus (grating) rivalry involves the occipital lobe (where anodal stimulation significantly reduced eye dominance strength) and the

right parietal lobe (where anodal stimulation reduced eye dominance strength and cathodal stimulation increased the perceptual alternation rate). In contrast, object-level stimulus (face/house) rivalry involves the prefrontal cortex (where anodal stimulation reduced eye dominance strength) and the left parietal lobe (where both anodal and cathodal stimulation reduced eye dominance strength).

This study provides causal evidence for the stimulus-dependence of neural loci in binocular rivalry and reveals its flexible configuration mechanism. These findings advance hybrid models from a descriptive, static multi-locus framework to a predictive, flexible integration framework.

关键词

Binocular rivalry, Neural site, tDCS, Stimulus-dependency, Flexible configuration mechanism Classification Code: B842

Abstract

Binocular rivalry (BR) occurs when different images are presented to the corresponding retinal areas of the two eyes, resulting in a phenomenon where the observer’ s perception alternates between the two images rather than perceiving a stable fusion. The neural mechanisms underlying binocular rivalry have long been a focal point of debate in the field of visual consciousness, specifically concerning whether the “neural site” of rivalry is located in the early visual cortex (the “eye-rivalry” theory) or in higher-level visual areas (the “stimulus-rivalry” theory). Recent research suggests that the neural site of binocular rivalry is not fixed but exhibits stimulus-dependency. This paper reviews the development of theories regarding the neural site of binocular rivalry and discusses the “flexible configuration mechanism” of the neural site. Furthermore, we explore how Transcranial Direct Current Stimulation (tDCS) can serve as an effective tool for investigating the neural site of binocular rivalry, providing new perspectives for understanding the plasticity of visual consciousness.

1. Introduction

Binocular rivalry is a classic paradigm for studying the neural correlates of consciousness. When the two eyes receive conflicting visual information, the brain cannot integrate the inputs into a single coherent image. Instead, it enters a state of perceptual competition where one image dominates awareness while the other is suppressed, with the two images alternating over time.

The central question in binocular rivalry research is: where in the brain does this competition occur? Early theories were divided between the “eye-rivalry” hypothesis, which posits that competition occurs between neurons receiving input from different eyes in the primary visual cortex (V1), and the “stimulus-rivalry” hypothesis, which suggests that competition occurs between high-level representations of the stimuli themselves, independent of the eye of origin.

2. The Neural Site of Binocular Rivalry

2.1 Eye-Rivalry vs. Stimulus-Rivalry

The eye-rivalry theory emphasizes the role of monocular neurons in the early visual cortex. According to this view, inhibitory interactions between these neurons lead to the suppression of one eye’ s input. Conversely, the stimulus-rivalry theory, supported by experiments using “swapped” stimuli (where images are rapidly exchanged between eyes), suggests that the brain competes for the representation of the object rather than the eye.

1 引言

When the left and right eyes receive markedly different visual images, the human observer does not perceive a stable, blended mixture of the two. Instead, perception alternates between the images presented to each eye, a phenomenon known as binocular rivalry. Although this phenomenon is rarely noticed in daily life, it occurs ubiquitously and continuously within the visual field outside of Panum’ s fusional area. Binocular rivalry provides a unique window for exploring the neural foundations of visual consciousness; because the visual input remains constant while the subjective experience fluctuates, it allows researchers to directly correlate neural activity with conscious experience \cite{Blake & Logothetis, 2002; Tong et al., 2006}. One of the core scientific questions in binocular rivalry research is: at which neural sites along the visual pathway does this competition occur? Addressing this question is essential not only for the mechanistic exploration of binocular vision but also for understanding the hierarchical organizational principles of consciousness within the brain.

The debate regarding the neural locus of competition has a long history. The low-level competition theory posits that competition primarily occurs among monocular neurons in the primary visual cortex (V1) or the lateral geniculate nucleus (LGN), where perceptual alternation is achieved through interocular suppression mechanisms \cite{Blake, 1989; Lehky, 1988; Tong & Engel, 2001}. Supporting evidence for this view includes the observation that binocular rivalry exhibits interocular adaptation aftereffects [**?**, **?**], as well as the synchronization between V1 neuronal activity and subjective perceptual states [**?**, **?**, **?**].

Conversely, the high-level competition theory challenges this perspective based on electrophysiological evidence from macaques. Research has found that the correlation between neuronal activity and perceptual states is significantly higher in high-level visual areas, such as the inferior temporal (IT) cortex, than in V1 \cite{Hancock & Andrews, 2007; Leopold & Logothetis, 1996}.

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(Logothetis, 1996; Logothetis & Schall, 1989; Sheinberg & Logothetis, 1997), suggesting that competition may primarily occur at higher-level sites responsible for processing complex patterns. To reconcile this controversy, researchers proposed a hybrid model, which has gradually become the dominant theory (Andrews & Purves, 1997; Blake & Logothetis, 2002; Tong et al., 2006). This model posits that competition is not confined to a single site but occurs across multiple levels of the visual pathway. At these different levels, the initiation of competition and perceptual transitions are achieved through the coordination of interocular inhibition, lateral excitation, and top-down feedback mechanisms (Brascamp et al., 2018; Wilson, 2003).

While hybrid models have gained widespread acceptance, a more fundamental question remains unresolved: how do different visual conditions alter the dominant site of binocular rivalry [**?**]? If rivalry indeed occurs across multiple stages of the visual hierarchy, do specific stimulus properties—such as complexity, contrast, or spatial frequency—systematically shift the primary locus of competition? The theoretical expectation of hybrid models is that feature-level stimuli may primarily rely on early processing sites, such as the primary visual cortex (V1) or the lateral geniculate nucleus (LGN).

Interocular competition, such as that investigated by Tong & Engel (2001), suggests that low-level features may be processed differently than object-level stimuli. Specifically, object-level competition may rely more heavily on pattern competition at higher-level sites within the temporal and frontoparietal lobes [**?**]. Object-level stimuli refer to complex visual objects with complete semantic representations and category affiliations (e.g., faces or houses), the processing of which involves category-selective representations in the high-level visual cortex. In contrast, feature-level stimuli refer to simple stimuli (e.g., gratings) that contain only low-level features such as local orientation and spatial frequency.

Among various stimulus factors, the hierarchy of visual representation may serve as a critical modulating variable. When stimuli presented to both eyes are "global/object-level" images, competition is characterized by deeper suppression and holistic switching. Conversely, when one stimulus is a simple local pattern, such as a grating, fragmentary suppression and shallower suppression are more likely to occur [**?**, **?**, **?**].

fMRI studies have demonstrated that competition between object-level stimuli involves category-selective representations in high-level visual areas. For instance, specific activations in the fusiform face area (FFA) and the parahippocampal place area (PPA) have been observed during face/house competition [**?**, **?**, **?**]. This evidence suggests that the neural locus of competition may shift systematically according to the representational hierarchy of the stimuli: feature-level stimuli depend on the early visual-dorsal attention network, while object-level stimuli depend on high-level cognitive-object integration networks.

Existing fMRI and EEG studies have only provided correlational evidence regarding the flexibility of competition sites [?, ?, ?, ?, ?], leaving it unclear whether the activation of a specific brain region is the cause or the consequence of the competition. To truly establish the "shift of competition sites under different types of stimuli," it is necessary to verify the causal role of specific brain regions through direct interference. Transcranial Magnetic Stimulation (TMS) and Transcranial Direct Current Stimulation (tDCS) provide ideal tools for such causal testing.

TMS research has demonstrated that parietal regions significantly prolong dominance duration [?, ?]. Specifically, single-pulse stimulation of the left hemisphere' s parietal lobe can induce perceptual switching in binocular rivalry [?, ?], while stimulation of the right parietal lobe can shorten dominance duration [?, ?]. However, these studies utilized only a single type of stimulus and failed to systematically compare changes in site utility across different stimulus conditions.

The modulatory effects of tDCS on binocular rivalry remain controversial. Although continuous Theta Burst Stimulation (cTBS, a form of TMS) significantly increases the duration of mixed perception, anodic tDCS has shown no significant effect on any rivalry indices [?, ?]. Similarly, in short-term monocular deprivation paradigms, no significant effects of anodic tDCS were observed on mixed perception or the rate of perceptual alternation in binocular rivalry [?, ?]. Conversely, when using faces and words as competing stimuli while targeting the lateralized occipitotemporal cortex, research found that anodic tDCS over the right occipitotemporal area significantly increased the dominance duration of faces relative to words, whereas cathodic···

Anodal tDCS has been shown to significantly reduce face dominance [?, ?]. Conversely, the effect of decreasing visual cortex excitability via cathodal tDCS to enhance mental imagery strength has been validated using binocular rivalry priming tasks [?, ?]. It is important to note that discrepancies in existing tDCS research may stem from differences in stimulus types (low-level gratings vs. high-level objects) and stimulation targets (V1 vs. higher-level visual areas). Furthermore, these studies typically employ single-stimulus conditions, making it impossible to test for "brain region × stimulus type" interaction effects. Such interactions are critical for revealing the mechanisms underlying the flexible configuration of competition sites; thus, previous work cannot directly address the core question proposed by Tong. In other words, the central prediction of the hybrid model—that the dominant site of competition shifts according to stimulus characteristics—still lacks systematic, multi-site causal validation. This gap hinders our understanding of how the brain flexibly recruits neural resources across different representational hierarchies, which may be the key to understanding the inherent flexibility of visual consciousness.

This study employs a multi-site tDCS design, marking the first attempt to examine the stimulus dependence of competing sites from a causal perspective.

Compared to the instantaneous pulse effects of Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS) can continuously modulate cortical excitability throughout the duration of a task. This characteristic makes it more suitable for testing the persistence of neural modulation effects.

The impact of neural states on competitive dynamics is a central focus of this study. Transcranial direct current stimulation (tDCS) was selected as the primary intervention tool due to its high comfort level and lack of induced muscle twitching, which facilitates multi-site and multi-condition interventions within the same subject. Furthermore, the anodic and cathodic stimulation of tDCS can respectively increase and decrease cortical excitability, allowing for a symmetrical, bidirectional causal test. This stands in contrast to transcranial magnetic stimulation (TMS), where the parameters for inhibitory effects (such as cTBS) and excitatory effects (such as iTBS) differ significantly, making direct comparisons difficult.

We selected four representative brain regions for investigation: the occipital lobe, a key site for early interocular competition [**?**, **?**, **?**]; the right parietal lobe, involved in spatial attention regulation [**?**, **?**, **?**]; the left parietal lobe, associated with object feature integration and non-spatial attention; and the prefrontal cortex, which governs higher-order cognitive control and the selection of conscious content [**?**, **?**, **?**, **?**]. By applying cathodic, anodic, or sham stimulation to these sites, we manipulated their activation states.

To explore how stimulus characteristics modulate these competitive sites, we compared two types of stimuli representing different hierarchical levels of representation. Feature-level stimuli (orthogonal gratings) primarily involve orientation-selective neurons and interocular suppression mechanisms in the early visual cortex. In contrast, object-level stimuli (faces/houses) involve semantic representation and object recognition in higher-level visual areas such as the FFA and PPA [**?**, **?**, **?**]. If competitive sites are indeed flexibly configured according to the representational hierarchy of the stimuli, we expect to observe an interaction pattern between site and stimulus type. Specifically, competition for feature-level stimuli (gratings) should involve early sites (occipital interocular suppression) and the dorsal attention pathway (right parietal spatial attention regulation), while competition for object-level stimuli (faces/houses) should involve higher-level sites (prefrontal cognitive control and left parietal feature integration) and the ventral visual pathway.

To distinguish between different neural mechanisms, we measured two categories of competitive indices: dominance strength, which reflects the degree of competitive bias and relative gain, and the perceptual alternation rate, which reflects competitive instability and switching frequency [**?**, **?**]. If the aforementioned interaction patterns are observed, this study will provide causal evidence for the core predictions of the hybrid model. Additionally, unlike the direct depolarization mechanism of TMS, the principle of tDCS regulation involves subthreshold membrane potential modulation (i.e., adjusting the resting membrane potential

Figure 1

Figure 1: Figure 1

without directly inducing action potentials). Therefore, the causal inferences in this study are restricted to the level of "brain regions" rather than "precise neural circuits."

2.1 实验设计

This study consists of eight experiments. Experiments 1–4 utilized feature-level stimuli (i.e., orthogonal gratings), while Experiments 5–8 utilized object-level stimuli (i.e., faces/houses), corresponding to four key brain regions: the occipital lobe, the right parietal lobe, the left parietal lobe, and the prefrontal cortex. Each experiment employed a single-factor, three-level within-subjects design. The independent variable was the tDCS condition (anodal, cathodal, or sham stimulation), and the dependent variables were ocular dominance strength and the perceptual alternation rate. By comparing the results across the eight experiments, we aimed to infer the interaction effects between brain regions and stimulus types to test the hypothesis of whether "neural sites change flexibly according to stimulus characteristics." The tDCS target regions included four levels: Experiments 1 and 5 stimulated the occipital lobe, with the center electrode placed at Oz and peripheral electrodes at O1, Iz, O2, and POz [?, ?]. Experiments 2 and 6 stimulated the right parietal lobe, with the center electrode at P4 and peripheral electrodes at P2, CP4, PO4, and P6 [?, ?]. Experiments 3 and 7 stimulated the left parietal lobe, with the center electrode at P3 and peripheral electrodes at CP3, PO7, P1, and P5 [?, ?, ?]. Experiments 4 and 8 stimulated the frontal lobe, with the center electrode at Fz and peripheral electrodes at AFz, F3, FCz, and F4 \cite{Reinhart & Woodman, 2014}. All electrode positions were based on the International 10-10 EEG system, and the 4$×$1 ring HD-tDCS configuration followed the method described by Villamar et al. (2013) [?, ?]. The electrode locations are shown in Figure 1d. The tDCS stimulation type consisted of three levels: anodal stimulation, cathodal stimulation, and sham stimulation. Anodal stimulation increases cortical excitability, cathodal stimulation decreases it, and sham stimulation serves as a placebo control. In the anodal and cathodal conditions, the current intensity linearly ramped up from 0 to the target intensity (1.00 mA) over the first 30 seconds and linearly ramped down to 0 during the final 30 seconds of the session. The sham condition utilized a standard pseudo-stimulation procedure: the current ramped up to 1.00 mA over 30 seconds, was maintained for 30 seconds, and then immediately ramped down to 0 over the next 30 seconds, remaining at 0 for the rest of the experiment. This procedure induces scalp sensations (such as tingling or warmth) similar to real stimulation, but the actual duration of the current is too short to produce neuromodulatory effects.

2.2 被试

Sample size estimation was conducted using G-Power 3.1 [?, ?]. Based on a large effect size ($f = 0.4$), a desired statistical power ($1 - \beta = 0.80$), and a significance level ($\alpha = 0.05$), the calculation for a design with one group, three repeated measurements, a correlation among repeated measures of 0.5, and a nonsphericity correction ($\epsilon = 1$) indicated that a minimum of 12 participants was required. Adhering to the principle of exceeding the estimated sample size, participants were recruited for eight experiments.

The final sample sizes and demographic characteristics were as follows: Experiment 1 included 20 valid participants (10 males, 10 females; $M_{age} = 21.00, SD = 1.69$); Experiment 2 included 20 valid participants (10 males, 10 females; $M_{age} = 21.30, SD = 1.89$); Experiment 3 included 20 valid participants (10 males, 10 females; $M_{age} = 20.76, SD = 1.79$); Experiment 4 included 22 valid participants (10 males, 12 females; $M_{age} = 22.00, SD = 2$); Experiment 5 included 18 valid participants (8 males, 10 females; $M_{age} = 20.60, SD = 1.43$); Experiment 6 included 20 valid participants (10 males, 10 females; $M_{age} = 20.50, SD = 1.36$); Experiment 7 included 20 valid participants (10 males, 10 females; $M_{age} = 20.41, SD = 1.62$); and Experiment 8 included 20 valid participants (10 males, 10 females; $M_{age} = 20.30, SD = 1.98$).

All participants were right-handed, had normal or corrected-to-normal vision, possessed normal stereoscopic vision, and reported no history of neurological disorders. Prior to the commencement of the experiments, all participants provided written informed consent and received monetary compensation upon completion of the study.

2.3 实验仪器

Experimental stimuli and procedures were programmed using Matlab and PsychToolbox-3. All experiments were conducted on a Dell XPS 8930R3AN9S computer running Windows 10 with an Intel Core i7 9700K processor. Stimuli were presented on a 27-inch ASUS monitor (Model ROG PG279Q, resolution 2560 × 1440, refresh rate 60 Hz). The monitor brightness was Gamma-corrected, resulting in a gray luminance of 39.01 cd/m^2, a black luminance of 0.08 cd/m^2, and a white luminance of 170.94 cd/m^2. The experimental setup is illustrated in [FIGURE:1a].

The study utilized a custom-assembled stereoscope for dichoptic presentation. The primary structure consisted of an aluminum alloy frame (Daheng New Epoch Technology, Inc.), and the lenses were surface-coated mirrors designed for rear-projection televisions (dimensions: 80 mm × 60 mm, minimum visible light reflectivity of 84%) (Shanghai Manbo Electronics Co., Ltd.). During the calibration process, complementary stimuli (three horizontal lines, three vertical lines, and a white block containing the word “Calibration”) were presented to the left and right eyes, respectively. Participants were required to adjust the mirrors and their head position until the stimuli from both eyes fused into a single, complete image. The optical path distance from the monitor to the eyes was fixed at 89.90 cm (comprising a linear distance of 80.00 cm from the screen to the eyes and a 7.00 cm distance between the mirrors).

A high-definition transcranial electrical stimulation (HD-tES) system was employed, consisting of a Model 1300A 1$×1stimulusoutputmodulecombinedwitha4×1−C3Amulti−channelstimulusconverter(Brand : SoterixMedical, USA; Model : 2001&4×1−C3A).Thestudyutilizedthe4×1high−definitionstimulationmode : thedual−frequencycurrentoutputfromthe1300Amainunitwasshuntedbythe4×$1-C3A converter into five Ag/AgCl ring-shaped high-definition electrodes (diameter: 12.00 mm). These consisted of one central electrode and four peripheral electrodes. When the central electrode served as the anode, the stimulation was classified as anodal electrical stimulation; when the central electrode served as the cathode, it was classified as cathodal electrical stimulation.

2.4 实验材料

The stimuli for Experiments 1-4 consisted of a square frame and a grating. The square frame had a side length of 2.50° and a border width of 4 pixels. The grating was circular with a diameter of 1°, a spatial frequency of 3 cpd, and a contrast of 0.20. The gratings presented to the left and right eyes were mutually perpendicular, with tilt angles of 135° and 45°, respectively (see [FIGURE:1a]).

For Experiments 5-8, the stimuli utilized the classic house and face images commonly used in binocular rivalry experiments. The square frame had a side length of 6° with a border width of 9 pixels, and the image diameter was 5°. Throughout the duration of the experiments, a red fixation point with a size of 2 pixels was presented at the center of the screen. Schematic representations of the stimuli are shown in [FIGURE:1b].

2.5 实验程序

At the beginning of the experiment, participants were required to fixate their heads in a stereoscope and adjust it until the stimuli could be viewed completely. Subsequently, a 5-minute practice session was conducted (consisting of 5 trials, each lasting 60 s). Each trial included a 5 s brief calibration stimulus (a complete circular arc formed by four segments, with the first/third and second/fourth quadrants presented to the left and right eyes, respectively) followed by 55 s of orthogonal gratings or face/house stimuli. During the trials, participants performed a binocular rivalry task: they continuously tracked changes in their visual perception by pressing the corresponding directional keys (for grating stimuli: left key for left-tilted, right key for right-tilted, and down key for mixed perception; for face/house stimuli: left key for face, right key for house, and down key for mixed perception). For example, if a participant perceived a dominant left-tilted grating (occupying a larger area) during the first 3 s, they were required to hold down the left key continuously. If their perception shifted to a dominant right-tilted grating at the 4th second, they had to immediately release the left key and press the right key. This process continued until the perception changed again, at which point they switched to the corresponding key, repeating this until the stimulus disappeared. Mixed perception was defined as instances where the dominance of the stimuli in the two eyes was indistinguishable (e.g., the areas of the left-tilted and right-tilted stimuli were very similar), when stimuli from both eyes were completely superimposed (e.g., the grating stimuli appeared as a grid image), or when rapid flickering made it impossible to judge the dominant direction.

The key-pressing rules were as follows: at any given moment, one and only one key must be pressed; keys must be switched immediately upon a change in perceptual state. The duration of a perceptual state was calculated as the difference between the time the key was pressed and released. The number of switches was defined as the number of key presses in each trial (consecutive presses of the same key were not counted as switches). Since participants were expected to perceive some state at all times, any period of "no key press exceeding 1000 ms" was identified as an error. This triggered a triple-beep alarm (500 ms duration, 200 ms interval) to remind the participant to press a key as soon as possible based on their current perceptual state. Periods of no key pressing during the switching process were not included in any perceptual state duration.

Following the practice session, the tDCS equipment was prepared. Participants wore an electrode cap filled with conductive gel. Once it was ensured that the contact resistance between all electrodes and the scalp was below 5 kΩ, the device was switched to PASS mode. A 30 s tolerance test (current intensity 1.00 mA) was then conducted on the corresponding brain regions to evaluate the participant' s subjective sensation of the electrical stimulation. If a participant reported strong discomfort, the current intensity for the formal experiment was reduced to 0.8 mA.

If the participant still found the stimulation intolerable at 0.8 mA, they were withdrawn from the experiment. All participants successfully passed the 1.00 mA tolerance test. The schematic procedure is shown in [FIGURE:1c].

Monitor. (b) Visual stimuli: Experiments 1-4 used gratings (1°, 3 cpd, 45°/135°); Experiments 5-8 used face/house images (6°). The red dot represents the fixation point. (c) Experimental procedure: Practice (5 min) → Electrode preparation (impedance < 5 kΩ) → Pre-stimulation (i.e., tolerance test) (30 s, 1.00 mA) → Formal experiment (approx. 20 min) → Rest. Cathodal or anodal stimulation was performed daily (order counterbalanced); Sham stimulation could be performed on the same day as cathodal/anodal stimulation (must be prior to it) or scheduled separately. (d) 4$×$1 ring HD-tDCS electrode configuration: The center electrode (red) was located at Oz (occipital lobe, Exp 1/5), P4 (right parietal lobe, Exp 2/6), P3 (left parietal lobe, Exp 3/7), or Fz (frontal lobe, Exp 4/8), surrounded by peripheral return electrodes (blue). Electrode positions were based on the international 10-10 system.

Each formal experiment lasted approximately 20 minutes and consisted of 20 trials. To prevent stimuli from being consistently associated with a specific eye, the mapping between stimuli A/B and the left/right eyes was pseudo-randomized: in 10 trials, stimulus A was presented to the left eye and stimulus B to the right eye; in the other 10 trials, stimulus B was presented to the left eye and stimulus A to the right eye. This ensured that participants could not determine which eye a stimulus originated from based on its features and could only respond according to their perceived stimulus. While continuously receiving the designated type of electrical stimulation, participants completed the same binocular rivalry task as in the practice session. A rest period of at least 30 s was provided every 10 minutes (which could be extended based on the participant' s state). The mental state of the participants was monitored throughout the experiment, and they were asked about their sensations; if a participant reported unbearable pain, the experiment was terminated immediately.

The formal experiment required each participant to complete three different electrical stimulation conditions (anodal, cathodal, and sham). To avoid aftereffects from tDCS, cathodal and anodal stimulations were conducted on different days, with their order counterbalanced or randomly assigned across participants. Sham stimulation could be scheduled on the same day as either anodal or cathodal stimulation, or it could be completed on a separate day.

When Sham stimulation was performed on the same day as cathodal or anodal stimulation, the Sham condition was always conducted first to ensure it remained unaffected by the active stimulation. Among the 160 participants, 65 completed the Sham and anodal conditions on the same day, 88 completed the Sham and cathodal conditions on the same day, and 7 completed them on separate days. Participants were required to wash their hair in advance, keep their scalps dry, and be well-rested.

2.6 数据分析

To prevent extreme trials from influencing the results, we defined trials with an ocular dominance ratio greater than 5 as outliers for each participant. These extreme trials were excluded from the participant' s dataset, a procedure analogous to the exclusion of trials exceeding ±3 standard deviations in reaction time data analysis.

First, the ocular dominance difference was calculated using a two-step process involving division and subtraction. In the division step, the ocular dominance ratio for each trial was calculated using the formula: (Left Eye Dominance Duration + 0.5 × Mixed Duration) / (Right Eye Dominance Duration + 0.5 × Mixed Duration). For trials where this ratio was less than 1, the reciprocal was taken to ensure all ratios were greater than or equal to 1. Trials with a ratio exceeding 5 were identified as outliers and excluded.

After excluding these extreme trials (which accounted for 7.531% of the total data), the subtraction step was performed. The ocular dominance difference for each trial was calculated using the formula: "Left Eye Dominance Duration – Right Eye Dominance Duration," where positive values indicate left-eye dominance and negative values indicate right-eye dominance. The arithmetic mean of these differences was then calculated for each participant across the three experimental conditions.

Finally, each participant's dominant eye was defined based on their average value in the Sham condition. For participants with a Sham condition mean greater than 0, the "Left Eye Dominance Duration -Right Eye Dominance Duration" values across all three conditions were used as their ocular dominance strength. For participants with a Sham condition mean less than 0, the values across all three conditions were multiplied by -1. This procedure yielded a final ocular dominance strength metric defined as "Dominant Eye Perceptual Duration - Non-dominant Eye Perceptual Duration" (Unit: seconds).

In the calculation of perceptual alternation rates, the perceptual duration for each trial is first determined by dividing the total duration of the trial by the number of perceptual switches recorded during that trial. Subsequently, the average perceptual duration data from all valid trials for each participant under each experimental condition are aggregated, and the arithmetic mean is calculated to represent the mean perceptual duration. The final perceptual alternation rate is derived using the formula 1/mean perceptual duration. This metric reflects the frequency of alternations between perceptual states per unit of time.

times/second). A higher value indicates a shorter average perceptual duration, which signifies a higher rate of perceptual alternation. Conversely, a lower value indicates a longer average perceptual duration, signifying a lower rate of perceptual alternation.

Statistical analyses were conducted using JASP software (version 0.19.2). To examine the main effect of tDCS stimulation type, one-way repeated measures analyses of variance (ANOVAs) were performed separately for sensory eye dominance strength and perceptual alternation rate as dependent variables. In cases where the assumption of sphericity was violated, Greenhouse-Geisser corrections were applied, and the adjusted degrees of freedom were reported. In each experiment, the tDCS condition consisted of three levels: Anodal, Cathodal, and Sham stimulation.

Based on the core hypotheses of this study, comparisons between Anodal vs. Sham and Cathodal vs. Sham were treated as planned comparisons. Multiple comparison error rates were controlled using the Holm correction. The comparison between Anodal and Cathodal stimulation was not explicitly predicted by our a priori hypotheses and was therefore treated as an exploratory analysis; these results are reported as supplementary information, with the Holm correction also applied. Subsequently, to further clarify the degree of evidential support the data provided for different hypothetical models, Bayesian analyses were performed on the two aforementioned dependent variables. Model comparisons were based on Bayes Factors.

The Bayes factor (BF) was employed to quantify the strength of evidence for the model including the main effect of tDCS relative to the null model (which assumes no differences between conditions). For the effect size prior, we utilized a Cauchy distribution centered at 0 with a scale parameter of $r = 0.5$. A uniform distribution was applied for the model prior, indicating no a priori preference among the candidate models.

Bayes factors are reported as BF_{10}, representing the likelihood of the data under the model containing the main effect relative to the null model. A value of $BF_{10} > 1$ indicates that the data provide stronger support for the model including the main effect, whereas $BF_{10} < 1$ suggests that the data more strongly support the null model.

To avoid selective interpretation across different statistical frameworks, Bayesian analysis is implemented consistently for all key assumptions, and Bayes factors are interpreted according to a unified standard.

To test whether the regulatory effects of tDCS exhibit a systematic dissociation pattern across different levels of stimulus representation and intervention brain regions, a cross-experimental integrated analysis was conducted on data from eight experiments. In this analysis, stimulus type (Gratings vs. Faces/Houses) and intervention brain region (Occipital, Right Parietal, Left Parietal, and Frontal) were treated as between-subject factors. The intervention type (Anodal, Cathodal, and Sham) was treated as a within-subject factor.

The experimental design utilized a mixed-design Analysis of Variance (ANOVA) to examine the effects of various factors. Specifically, the stimulation condition (tDCS vs. Sham) was treated as a within-subject factor, while the ocular dominance strength and the perceptual alternation rate served as the dependent variables.

Given that the integrated cross-experimental analysis involves high-order interactions between multiple between-subject and within-subject factors, the results of Bayesian model comparisons in this context are highly sensitive to prior settings and model complexity penalties. Furthermore, there is currently a lack of consistent interpretive standards for such complex Bayesian models within this specific research framework. Therefore, the analysis for this section primarily reports significance results based on frequentist statistical methods, integrated with…

We conducted a comprehensive analysis of the effect patterns using Cohen' s d and the 95% confidence intervals (CI) of the mean differences. To clarify the differences in tDCS effects across various brain regions and stimulus types, we calculated the standardized effect sizes (Cohen' s d) and the 95% confidence intervals of the mean differences for the active stimulation conditions (anodal and cathodal) relative to the sham condition in each experiment. These results were then compared across matched experimental pairs, categorized by corresponding brain regions and differing stimulus types.

3 结果

Descriptive statistics were conducted for ocular dominance strength and perceptual alternation rate across the three tDCS types for the eight experiments (see for details). Ocular dominance strength

Perceptual alternation rate

实验

3.20$±$2.37

7.81$±$2.37

9.03$±$1.71

0.33$±$0.02

0.40$±$0.05

0.38$±$0.04

6.08$±$1.52

7.50$±$1.49

9.95$±$1.47

0.29$±$0.03

0.34$±$0.04

0.30$±$0.03

10.10$±$1.67

11.03$±$2.64

10.13$±$1.86

0.45$±$0.05

0.47$±$0.06

0.42$±$0.04

6.49$±$1.64

5.80$±$1.91

7.64$±$1.36

0.42$±$0.04

0.42$±$0.06

0.41$±$0.04

8.30$±$1.47

7.57$±$1.98

8.81$±$1.59

0.23$±$0.03

0.23$±$0.03

0.22$±$0.03

5.56$±$1.71

4.13$±$1.21

5.24$±$1.13

0.35$±$0.04

0.33$±$0.03

0.31$±$0.03

5.26$±$1.27

5.15$±$1.06

7.22$±$1.13

0.24$±$0.03

0.26$±$0.03

0.24$±$0.03

2.79$±$0.89

4.56$±$0.84

5.27$±$0.76

0.25$±$0.04

0.25$±$0.04

0.24$±$0.03

3.1 特征水平刺激结果分析

Experiment 1 examined the role of the occipital lobe in grating rivalry (results shown in Figure 2a [FIGURE:2]). Using eye dominance strength as the dependent variable, a one-way repeated measures ANOVA (tDCS stimulation type: Anodal, Cathodal, Sham) revealed a significant main effect of tDCS stimulation type: $F(2, 38) = 7.64, p = 0.002, \eta_p^2$

$= 0.29, 1 - \beta > 0.99.$ Planned comparisons

revealed that the eye dominance strength in the anodal condition ($M \pm SE = 3.20 \pm 2.37$, throughout) was significantly lower than in the sham condition (9.03 ± 1.71): $t(19) = -3.65, p = 0.005$, 95% CI of the mean difference =

$[-10.03, -1.64]$, Cohen' s $d = -0.60$. There was no significant difference between the cathodal condition (7.81 ± 2.37) and the sham condition: $t(19) = -0.67, p = 0.51$, 95% CI of the mean difference $= [-5.97, 3.53]$, Cohen' s $d = -0.13$. These results indicate that anodal stimulation of the occipital lobe significantly reduces eye dominance strength during grating rivalry. Exploratory comparisons further showed that the anodal condition was significantly lower than the cathodal condition: $t(19) = -3.64, p = 0.005$, 95% CI of the mean difference $= [-7.94, -1.29]$, Cohen' s $d = -0.48$, suggesting that anodal stimulation of the occipital lobe reduces eye dominance strength more effectively than cathodal stimulation. Bayesian repeated measures ANOVA provided strong evidence for the model including the main effect of tDCS ($BF_{10} = 20.54$), consistent with the frequentist results. The same analysis was conducted using the perceptual alternation rate as the dependent variable. The one-way repeated measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 38) = 1.84, p = 0.17, \eta_p^2$

$= 0.09$, 1

$1 - \beta = 0.84$, indicating that the type of tDCS stimulation had no significant effect on the perceptual alternation rate. Bayesian repeated-measures ANOVA revealed that the data favored the null model over the model including the main effect of tDCS ($BF_{10} = 0.50$), consistent with the frequentist results. Experiment 2 examined the role of the right parietal lobe in grating competition (results shown in [FIGURE:2b]). Using ocular dominance strength as the dependent variable, a one-way repeated-measures ANOVA showed a significant main effect of tDCS stimulation type: $F(2, 38) = 5.36$, $p = 0.009$, η_p^2

$= 0.22$, $1-\beta = 0.99$. Planned comparisons revealed that the score in the anodic condition (6.08 ± 1.52) was significantly lower than in the

Sham condition (9.95 ± 1.47): $t(19) = -3.26$, $p = 0.012$, $95\% CI$ of the mean difference $= [-6.98, -0.76]$, Cohen' s $d = -0.58$. There was no significant difference between the cathodic condition (7.50 ± 1.49) and the Sham condition: $t(19) = -1.97$, $p = 0.127$, $95\% CI$ of the mean difference $= [-5.71, 0.82]$, Cohen' s $d = -0.37$. These results indicate that anodic stimulation of the right parietal lobe significantly reduces ocular dominance strength during grating competition. Exploratory comparisons showed no significant difference between the anodic and cathodic conditions: $t(19) = -1.23$, $p = 0.235$, $95\% CI$ of the mean difference $= [-4.46, 1.62]$, Cohen' s $d = -0.21$. Bayesian repeated-measures ANOVA showed that the data provided moderate evidence supporting the model including the main effect of tDCS ($BF_{10} = 5.16$), consistent with the frequentist results. The same analysis was performed with perceptual alternation rate as the dependent variable. The one-way repeated-measures ANOVA showed a significant main effect of tDCS stimulation type: $F(2, 38) = 3.71$, $p = 0.034$, η_p^2

$= 0.16$, $1 - \beta = 0.99$. Planned

comparisons showed that the cathodic condition (0.34 ± 0.04) was significantly higher than the Sham condition (0.30 ± 0.03): $t(19) = 2.70$, $p = 0.043$, $95\% CI$

of the mean difference $= [0.00, 0.09]$, Cohen' s $d = 0.28$. There was no significant difference between the anodic condition (0.29 ± 0.03) and the Sham condition: $t(19) = -0.23$, $p = 0.82$, $95\% CI$ of the mean difference $= [-0.05, 0.04]$, Cohen' s $d = -0.03$. This indicates that cathodic stimulation of the right parietal lobe significantly increases the perceptual alternation rate in grating competition. Exploratory comparisons showed no significant difference between the anodic and cathodic conditions: $t(19) = -2.00$, $p = 0.121$, $95\% CI$ of the mean difference $= [-0.11, 0.02]$, Cohen' s $d = -0.31$. Bayesian repeated-measures ANOVA showed that the data provided some degree of evidence supporting the model including the main effect of tDCS ($BF_{10} = 1.73$), consistent with the frequentist results.

Experiment 3 examined the role of the left parietal lobe in grating competition (results shown in [FIGURE:2c]). Using ocular dominance strength as the dependent variable, a one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(1.47, 27.92) = 0.25$, $p = 0.714$, η_p^2

$= 0.01$, $1 - \beta = 0.18$. Bayesian repeated-measures ANOVA showed that the data more strongly supported the

null model than the model including the main effect of tDCS ($BF_{10} = 0.16$), consistent with the frequentist results. The same analysis was performed with perceptual alternation rate as the dependent variable. The one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 38) = 1.09$, $p = 0.340$, η_p^2

$= 0.05$, $1 - \beta = 0.61$. Bayesian repeated-measures ANOVA showed that

the data more strongly supported the null model than the model including the main effect of tDCS ($BF_{10} = 0.31$), consistent with the frequentist results. Experiment 4 examined the role of the frontal lobe in grating competition (results shown in [FIGURE:2d]). Using ocular dominance strength as the dependent variable, a one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 42) = 1.16$, $p = 0.324$, η_p^2

$= 0.05$, $1 - \beta = 0.64$. Bayesian repeated-measures ANOVA showed that the data more strongly supported the null model rather

than the model including the main effect of tDCS ($BF_{10} = 0.29$), consistent with the frequentist results. The same analysis was performed with perceptual alternation rate as the

dependent variable. The one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 42) = 0.04$, $p = 0.962$, η_p^2

$= 0.00$, $1 - \beta = 0.07$. Bayesian repeated-measures ANOVA showed that the data more strongly supported the null model than the model including the main effect of tDCS ($BF_{10} = 0.13$), consistent with the frequentist results.

lobe; (d) Experiment 4: Frontal lobe intervention. The left vertical axis represents ocular dominance strength, defined as the difference in perception time between the dominant and non-dominant eyes (in seconds). The right vertical axis represents the perceptual alternation rate, defined as the number of perceptual state switches per unit of time (seconds), in units of cycles/second. On the horizontal axis, "Anodic" refers to the anodic stimulation condition, "Cathodic" refers to the cathodic stimulation condition, and "Sham" refers to the sham stimulation condition. Significance markers: * $p < 0.05$, ** $p < 0.01$. Post-hoc tests utilized paired-sample t-tests with Holm correction. Bar charts represent group means for each condition, with error bars representing the standard error (SE) of the mean. Scattered points represent individual subject data.

3.2 客体水平刺激结果分析

Experiment 5 examined the role of the occipital lobe in face/house competition (results shown in Figure 3a [FIGURE:3]). Using ocular dominance strength as the dependent variable, a one-way repeated measures ANOVA revealed that the main effect of tDCS stimulation type was not significant: $F(2, 34) = 0.49$, $p = 0.616$.

$\eta_p^2 = 0.03$, $1 - \beta = 0.31$. Bayesian repeated measures ANOVA further indicated that the data provided stronger support for the null model

rather than the model including the main effect of tDCS ($BF_{10} = 0.20$), which is consistent with the frequentist statistical results. The same analysis was conducted using the perceptual alternation rate as the dependent variable. The one-way repeated measures ANOVA showed that the main effect of tDCS stimulation type was not significant:

F(1.50, 25.49) = 0.32，p = 0.664,

= 0.02, 1 -β = 0.22. Bayesian repeated measures ANOVA revealed···

The results indicated that the data more strongly supported the null model rather than the model including the main effect of tDCS ($BF_{10} = 0.18$), which is consistent with the frequentist statistical results.

Experiment 6 examined the role of the right parietal lobe in the competition between faces and houses (results shown in [FIGURE:3b]). Using ocular dominance strength as the dependent variable···

For the statistical analysis, a one-way repeated measures analysis of variance (ANOVA) was conducted. The results indicated that the main effect of the tDCS stimulation type was not significant: $F(2, 38) = 0.88, p = 0.424$.

$= 0.04, 1 - \beta = 0.51$. Bayesian repeated measures ANOVA indicated that the data provided stronger support for the null hypothesis.

The model excluding the main effect of tDCS was preferred over the model including it ($BF_{10} = 0.25$), which is consistent with the frequentist statistical results. We conducted the same analysis using the perceived alternation rate as the dependent variable. A one-way repeated measures ANOVA revealed that the main effect of the tDCS stimulation type was not significant:

F(2, 38) = 2.45， p = 0.100,

$\eta_p^2 = 0.11$, $1 - \beta = 0.93$. Bayesian repeated-measures ANOVA indicated that the data more strongly supported the null model over the model including the main effect of tDCS ($BF_{10} = 0.76$), which is consistent with the frequentist statistical results.

Experiment 7 examined the role of the left parietal lobe in face/house competition (results shown in [FIGURE:3c]). Using eye dominance strength as the dependent variable, a one-way repeated-measures ANOVA revealed a significant main effect of tDCS stimulation type: $F(2, 38) = 3.97$, $p = 0.027$, η_p^2

$= 0.17$, $1-\beta = 0.99$. Planned comparisons showed that eye dominance strength in the anodic condition (5.26 ± 1.27) was significantly

lower than in the Sham condition (7.22 ± 1.13): $t(19) = -2.48$, $p = 0.045$, $95\% CI$ of the mean difference $= [-4.03, 0.11]$, Cohen' s $d = -0.38$. Similarly, the cathodic condition (5.15 ± 1.06) was significantly lower than the Sham condition: $t(19) = -2.80$, $p = 0.034$, $95\% CI$ of the mean difference $= [-4.03, -0.13]$, Cohen' s $d = -0.40$. These results indicate that both anodic and cathodic stimulation of the left parietal lobe can significantly reduce eye dominance strength during face/house competition. Exploratory comparisons revealed no significant difference between the anodic and cathodic conditions: $t(19) = 0.13$, $p = 0.900$, $95\% CI$ of the mean difference $= [-2.35, 2.58]$, Cohen' s $d = 0.02$. Bayesian repeated-measures ANOVA showed that the data provided a degree of evidence supporting the model that included the main effect of tDCS ($BF_{10} = 2.10$), consistent with the frequentist results. The same analysis was performed using the perceptual alternation rate as the dependent variable. The one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 38) = 0.96$, $p = 0.390$, η_p^2

$= 0.05$, 1 -β =

0.55. Bayesian repeated-measures ANOVA indicated that the data favored the null model over the model including the main effect of tDCS ($BF_{10} = 0.27$), which is consistent with the frequentist results.

Experiment 8 examined the role of the frontal lobe in face/house competition (results shown in [FIGURE:3d]). Using ocular dominance strength as the dependent variable, a one-way repeated-measures ANOVA revealed a significant main effect of tDCS stimulation type: $F(2, 38) = 4.06, p = 0.025, \eta_p^2$

$= 0.18, 1 - \beta = 0.99$. Planned comparisons showed that the ocular dominance strength in the anodic condition (2.79 ± 0.89) was significantly lower than in the

Sham condition (5.27 ± 0.76): $t(19) = -2.86, p = 0.030$, 95% CI of the mean difference = $[-4.77, -0.20]$,

Cohen' s $d = -0.67$. There was no significant difference between the cathodic condition (4.56 ± 0.84) and the Sham condition: $t(19) = -0.19, p = 0.467$, 95% CI of the mean difference = $[-3.24, 1.81]$, Cohen' s $d = -0.19$. These results indicate that anodic stimulation of the frontal lobe significantly reduces ocular dominance strength during face/house competition. Exploratory comparisons revealed no significant difference between the anodic and cathodic conditions: $t(19) = -2.07, p = 0.105$, 95% CI of the mean difference = $[-4.01, 0.48]$, Cohen's $d = -0.48$. Bayesian repeated-measures ANOVA showed that the data provided a degree of evidence supporting the model that included the main effect of tDCS ($BF_{10} = 2.47$), consistent with the frequentist findings. Further analysis using perceptual alternation rate as the dependent variable via a one-way repeated-measures ANOVA showed that the main effect of tDCS stimulation type was not significant: $F(2, 38) = 0.99, p = 0.381, \eta_p^2$

$= 0.05$, 1 -$\beta = 0.57$。

Bayesian repeated measures ANOVA indicated that the data provided stronger support for the null model than for the model including the main effect of tDCS (BF_{10} =

0.27), which is consistent with the results of the frequency statistics.

left parietal lobe; (d) Experiment 8: Frontal lobe stimulation. The left vertical axis represents ocular dominance strength, defined as the difference between the perception time of the dominant eye and the non-dominant eye (in seconds). The right vertical axis represents the perceptual alternation rate, defined as the number of perceptual state switches per unit of time (seconds), expressed in cycles/second. On the horizontal axis, "Anodal" refers to the anodal stimulation condition, "Cathodal" refers to the cathodal stimulation condition, and "Sham" refers to the sham stimulation condition. Significance markers: * $p < 0.05$, ** $p < 0.01$; post-hoc tests were conducted using paired-sample *t*-tests with Holm correction. Bar charts represent group means for each condition, and error bars represent the standard error (SE) of the mean. Scattered points represent individual participant data.

3.3 跨实验整合分析

To further test the core hypothesis that "competitive sites are flexibly configured according to the representational hierarchy of the stimulus," we conducted a cross-experimental meta-analysis on the pooled data from eight experiments.

A mixed-design analysis of variance (ANOVA) was conducted with a 2 (Stimulus Type: gratings vs. faces/houses, between-subjects) × 4 (Target Brain Region: occipital, right parietal, left

parietal, frontal, between-subjects) × 3 (Intervention Type: Anodal, Cathodal, Sham, within-subjects) design. Regarding the ocular dominance index, the results revealed a significant three-way interaction between Stimulus Type, Target Brain Region, and Intervention Type, $F(6,304) = 3.16, p = 0.005, \eta_p^2$

$= 0.06, 1 - \beta > 0.99$. The two-way interaction between Stimulus Type and Target Brain Region did not reach statistical significance,

$F(3,152) = 1.53, p = 0.210, \eta_p^2$

$= 0.03, 1 - \beta = 0.95$. These findings indicate that the regulatory effect of tDCS on ocular dominance

depends on the specific interaction between the type of stimulus, the targeted brain region, and the type of stimulation. Regarding the perceptual alternation rate index, the three-way interaction effect was not significant, $F(5.34, 270.35) = 1.01, p = 0.414, \eta_p^2$

$= 0.02$, 1 -β =

0.81. However, the second-order interaction effect between stimulus type and intervention brain region was significant, $F(3,152) = 3.65$, $p = 0.014$, $\eta_p^2 = 0.07$.

$1 - \beta > 0.99$. This indicates that different brain regions exert differentiated regulatory effects on the perceptual alternation rates for various types of stimuli.

The standardized effect sizes (Cohen' s d) for the active stimulation conditions (anodal, cathodal) relative to the Sham condition in each experiment,

along with the 95% confidence intervals (CI) of the mean differences, revealed a dissociation pattern between intervention brain regions and stimulus types (statistical results are presented in). Regarding the strength of ocular dominance for grating stimuli, anodal stimulation of the occipital lobe and the right parietal lobe produced significant effects, whereas stimulation of the left parietal lobe and the frontal lobe did not. Conversely, for the ocular dominance strength of face/house stimuli, the pattern was reversed: anodal stimulation of the left parietal lobe and the frontal lobe yielded significant effects, while the effects for the occipital and right parietal lobes were non-significant.

Anodal vs. Sham (d [95% CI of the mean difference]) Face/House

Cathodal vs. Sham (d [95% CI of the mean difference]) Face/House

-0.82[-9.18, -2.49]

-0.12[-2.63, 1.60]

-0.15[-5.01, 2.57]

-0.25[-3.71, 1.23]

-0.73[-6.35, -1.39]

0.07[-1.95, 2.60]

-0.44[-5.05, 0.15]

-0.28[-2.96, 0.75]

-0.01[-2.09, 2.01]

-0.56[-3.61, -0.31]

0.12[-2.50, 4.30]

-0.63[-3.63, -0.53]

-0.21[-3.58, 1.28]

-0.64[-4.30, -0.66]

-0.28[-4.74, 1.06]

-0.17[-2.73, 1.30]

-0.36[-0.13, 0.02]

0.15[-0.02, 0.03]

0.09[-0.05, 0.08]

0.23[-0.01, 0.03]

-0.05[-0.04, 0.03]

0.59[0.01, 0.06]

0.60[0.01, 0.08]

0.25[-0.01, 0.05]

0.24[-0.03, 0.10]

0.03[-0.04, 0.04]

0.36[-0.02, 0.12]

0.32[-0.01, 0.05]

0.06[-0.04, 0.05]

0.10[-0.02, 0.03]

0.05[-0.06, 0.08]

0.35[-0.01, 0.03]

Note: Bold text indicates that the 95% CI does not include 0 (i.e., reaching statistical significance); negative values indicate that the active stimulation condition is lower than the Sham condition.

By synthesizing the significant three-way interaction effects from the mixed-design ANOVA with the systematic dissociation patterns of effect sizes, it is evident that the neuromodulatory sites for binocular competition are not fixed within a single brain region. Instead, these sites are flexibly configured according to the representational hierarchy of the stimuli. Specifically, competition involving low-level visual features (gratings) is primarily modulated by tDCS over the occipital and right parietal lobes, whereas competition involving high-level visual representations (faces/houses) relies more heavily on the involvement of the left parietal and frontal lobes.

4 讨论

This study employed transcranial direct current stimulation (tDCS) to manipulate the excitability of various brain regions (occipital lobe, bilateral parietal lobes, and prefrontal cortex), revealing a stimulus-dependent causal relationship regarding the neural sites of binocular rivalry. Specifically, rivalry involving feature-level stimuli (gratings) primarily depends on the occipital lobe and the right parietal lobe. Enhancing the activation of these regions significantly reduces the difference in eye dominance during grating rivalry, while

decreasing right parietal activation significantly accelerates the perceptual alternation rate. Conversely, rivalry involving object-level stimuli (faces/houses) shifts toward the prefrontal cortex and the left parietal lobe. Enhancing or weakening left parietal activity, or enhancing prefrontal activation, significantly reduces eye dominance differences in face/house rivalry. This causal evidence directly addresses the core scientific question proposed by Tong et al. (2006): "How do different visual conditions alter the dominant sites of binocular rivalry?" Our findings suggest that binocular rivalry is not supported by a fixed neural network; rather, the brain flexibly recruits different neural resources based on the representational hierarchy of the stimuli. This bridges the research gap in the field of binocular rivalry between "abundant correlational evidence and scarce causal evidence." These findings advance the hybrid model from a descriptive account of "which sites participate in rivalry" to a predictive framework of "how stimulus properties determine dominant sites," providing new evidence for the neural mechanisms of binocular rivalry.

The causal role of the occipital-right parietal circuit in grating rivalry reveals a collaborative mechanism between early visual competition and the dorsal attention system. Anodal stimulation of the occipital lobe significantly reduced eye dominance strength, which is consistent with classical theories of competition between early monocular neurons [**?**, **?**]. Competition for simple grating stimuli occurs primarily at the level of monocular

neurons in the early visual cortex [**?**]. Anodal stimulation increases cortical excitability, which may alter the competitive balance through two mechanisms: first, by reducing the selectivity of interocular inhibition, allowing neural representations from both eyes to co-activate more frequently; and second, by increasing the noise level of spontaneous neural activity, thereby weakening the stability of monocular dominance. Notably, although cathodal stimulation of the occipital lobe showed a numerical trend toward enhancing eye dominance, it did not reach statistical significance. This asymmetric effect may reflect the nonlinear characteristics of tDCS in modulating cortical excitability: anodal stimulation more effectively enhances spontaneous activity, whereas cathodal stimulation has limited inhibitory effects on established competitive networks. Alternatively, this may reflect the robustness of early competitive networks—interocular inhibition mechanisms may be sensitive to excitatory enhancement but possess compensatory capacities against inhibitory interference. This finding aligns with recent tDCS research suggesting that effects in the early visual cortex are state-dependent [?]. More importantly, the right parietal lobe exhibited a regulatory pattern functionally dissociated from the occipital lobe during grating rivalry: anodal stimulation reduced eye dominance strength, while cathodal stimulation increased the perceptual alternation rate, indicating that the two interventions affected different dimensions. This differentiated effect is consistent with the dual regulatory role of the parietal lobe in binocular rivalry —neuroimaging studies have found significant parietal activation during perceptual switches [?], while TMS studies have confirmed that disrupting parietal function can alter dominance durations [?]. Our causal evidence further reveals that the right parietal lobe, as a key node in the dorsal attention pathway, exerts influence on different aspects of competition through distinct neural mechanisms. Anodal stimulation enhances the flexible allocation of attentional resources, distributing attention more evenly between the representations of the two eyes and thus weakening sustained monocular dominance (reduced eye dominance). In contrast, cathodal stimulation reduces attentional stability, leading to more frequent switching between the two eyes (increased alternation rate) without changing the total amount of attentional resources obtained by each eye (unchanged eye dominance). This dissociation pattern suggests that eye dominance strength and perceptual alternation rates may be regulated by different neural subpopulations within the parietal attentional system. Overall, the occipital-right parietal collaborative pattern supports a dual-layer architecture of "early feature competition + dorsal attentional regulation" [?]: for feature-level stimuli, the brain prioritizes competition at the early sensory level (occipital) while recruiting the spatial attention system (right parietal) for modulation.

In sharp contrast to the grating condition, the prefrontal cortex and left parietal lobe showed selective involvement under face/house stimulus conditions. When stimulus attributes involve object-level representations, the brain shifts to flexibly recruit high-level cognitive control and object integration resources.

As highly complex stimuli, the competition between faces and houses involves not only low-level feature conflicts but also high-level object processing such as object recognition [?]. In binocular rivalry, object information from the suppressed eye can still activate

high-level visual areas (FFA and PPA in the fusiform gyrus), indicating that information at the object representation level is not completely suppressed [?]. The left parietal lobe is located at the intersection of the ventral visual pathway and the dorsal attention pathway, potentially participating in the integration of object information and attentional signals. In Experiment 7, both anodal and cathodal stimulation reduced eye dominance strength. This atypical pattern does not align with the classical "anodal excitation, cathodal inhibition" expectation, and its mechanism remains unclear. One possible explanation is that the left parietal lobe' s involvement in binocular rivalry depends on an optimal state of excitability, where deviation in either direction disrupts its normal function. Another possibility is that tDCS produced nonlinear effects on the complex local circuits or transcallosal connections of this region. It must be emphasized that these explanations are preliminary conjectures based on current results and lack direct neurophysiological evidence. Future research could combine functional neuroimaging or electrophysiological recordings to further elucidate the specific mechanisms of the left parietal lobe in object-level binocular rivalry. Anodal stimulation of the prefrontal cortex also significantly reduced eye dominance strength, consistent with its critical role in perceptual switching —neuroimaging studies show significant prefrontal activation during perceptual transitions in binocular rivalry [**?**],

while single-neuron recordings show that the activity patterns of prefrontal neurons can predict upcoming perceptual switches [**?**]. Enhancing prefrontal excitability via anodal stimulation may influence competition through two pathways: first, by strengthening top-down cognitive control to promote active inhibition of the dominant percept and active facilitation of the suppressed percept, thereby accelerating state transitions [**?**]; and second, by enhancing sensitivity to monitoring object-level conflicts, allowing the system to detect inconsistencies between binocular representations more quickly and trigger perceptual reorganization. Interestingly, cathodal stimulation of the prefrontal cortex did not reach significance, echoing the pattern observed in the occipital lobe under the grating condition and again demonstrating the stronger regulatory potency of anodal stimulation relative to cathodal stimulation. More importantly, neither the prefrontal cortex nor the right parietal lobe showed significant effects under the face/house condition, despite these regions being effective under the grating condition. This pattern of selective disappearance across stimulus conditions provides critical causal evidence: not all brain regions involved in binocular rivalry function in a stimulus-invariant manner; instead, they are flexibly incorporated into or withdrawn from the competitive network based on the representational hierarchy of the stimuli. Overall, the causal role of the prefrontal-left parietal circuit suggests that when low-level feature differences are insufficient to resolve perceptual conflict (e.g., face vs. house), the brain recruits object recognition (left parietal-ventral pathway connection) and cognitive control (prefrontal) resources, resulting in an upward shift of the competitive site hierarchy.

When interpreting these findings, the boundaries of the conclusions must be carefully defined. First, regarding the interpretation of null effects: Experiments 3 and 4 (left parietal and frontal lobes for gratings) and Experiments 5 and 6 (occipital and right parietal lobes for faces/houses) found no significant tDCS modulation effects, with Bayes Factors ($BF_{10} = 0.13 \sim 0.31$) providing moderate support for the null hypothesis. We interpret these null effects as evidence that these regions are not core neural sites for rivalry involving those specific stimulus types. However, alternative explanations exist: the limited spatial resolution of tDCS may have failed to precisely target key neural circuits; the 1.00 mA stimulation intensity might have been insufficient for certain regions; or compensatory mechanisms within the neural network may have masked the behavioral effects of single-region intervention. Therefore, null effects should be interpreted as "no causal role detected under current parameters." Second, regarding results where Bayes Factors provided only weak evidence: although the effects in Experiment 7 (left parietal-face/house, $BF_{10} = 2.10$) and Experiment 8 (frontal-face/house, $BF_{10} = 2.47$) were statistically significant in frequentist terms, the Bayesian evidence reached only a weak level ($BF_{10} = 1 \sim 3$), requiring independent replication. In contrast, Experiment 1 (occipital-grating, $BF_{10} = 20.54$) and Experiment 2 (right parietal-grating, $BF_{10} = 5.16$) received stronger support, making their conclusions more robust. Furthermore, the perceptual alternation rate reached significance only in Experiment 2 ($BF_{10} = 1.73$) across all eight experiments, which may reflect a weaker regulatory effect of tDCS on this metric or suggest that this metric is

more heavily regulated by subcortical structures. Subsequent validation paths include increasing sample sizes, employing fMRI-guided individualized localization, and using TMS for more precise causal testing.

The core contribution of this study lies in deepening the hybrid model theory of binocular rivalry from a causal perspective. Since its inception, the hybrid model has emphasized that binocular rivalry results from the joint action of excitation and inhibition across multiple neural levels, occurring both at the monocular neuron level in the early visual cortex and at the object representation and cognitive control levels in higher cortices [?, ?, ?]. However, traditional hybrid models have focused more on "which sites participate in rivalry" and less on "how the relative contributions of different sites change with task demands." The "dual discrete sites-stimulus dependent pattern" discovered in this study suggests that the neural mechanism of binocular rivalry is not an immutable fixed network, but a flexible system capable of reconfiguration based on input characteristics. When the visual system encounters simple gratings, competition is primarily resolved at the early feature extraction level; when facing complex objects, competition introduces high-level cognitive resources for object recognition and semantic integration.

This phenomenon of "flexible site configuration" may reflect an optimization strategy of the visual system: allocating neural resources flexibly based on task complexity to avoid over-activating high-level brain regions during simple tasks while ensuring sufficient cognitive support for complex tasks.

Thus, this study not only validates the multi-site framework of the hybrid model but also reveals a new organizational principle: the mechanism of flexible configuration of competitive sites. This mechanism provides a unified explanatory framework for the contradictory findings in different studies regarding "key brain regions" —it is not that experimental results are mutually exclusive, but rather that different stimuli lead to the recruitment of different neural networks.

The mechanism of flexible configuration of competitive sites has implications for broader theoretical fields. First, regarding the general theory of multistable perception, our findings suggest a need to distinguish between different types of multistable mechanisms based on stimulus characteristics. Traditional research often treats binocular rivalry, ambiguous figures, and motion-induced blindness as the same class of multistable processes, assuming they share the same neural basis. However, if competitive sites within binocular rivalry itself vary with stimulus type, then different forms of multistability are even more likely to depend on distinct neural networks [**?**, **?**]. This view echoes recent research on the universal characteristics of multistable perception—although different phenomena follow similar statistical laws (such as the contrast dependence described by "Levelt' s Propositions"), their neural implementations may be fundamentally different [**?**]. Second, regarding neural theories of consciousness, this study supports the view of "content-specific networks" rather than a "fixed consciousness network." Global Workspace Theory emphasizes the prefrontal-parietal network as the core of conscious experience [**?**], but our findings indicate that the degree of involvement of this network depends on the features of the conscious content. Conscious experience of simple stimuli may primarily rely on early visual-attentional networks [**?**], while complex stimuli require deeper involvement of the prefrontal-parietal network [**?**]. This implies that the neural basis of consciousness is not a fixed "consciousness core" but a distributed network flexibly configured according to representational content [**?**]. This perspective aligns with the claim of Integrated Information Theory that "consciousness depends on the pattern of information integration" and provides an empirical basis for understanding how different conscious contents correspond to different neural states.

Although this study is the first to provide causal evidence for the flexible configuration of competitive sites, three limitations remain to be addressed in future research. First, the coverage of stimulus types was limited—we only tested two extremes of complexity (simple oriented gratings vs. complex faces/houses), lacking systematic testing of intermediate complexity gradients. For example, the competitive sites for

complex gratings (e.g., plaid patterns) or simple objects (e.g., geometric shapes) remain unclear. Future research should design stimulus sequences with continuously varying complexity to explore whether flexible site configuration is a discrete step-like change or a continuous progressive process. Second, the coverage of brain regions was not comprehensive—we only intervened in four sites (occipital, bilateral parietal, and prefrontal), lacking direct testing of key regions in the ventral visual pathway (such as the fusiform gyrus). Given that complex stimulus competition involves processing at the object representation level, and the core role of the fusiform gyrus in face and house recognition has been widely confirmed [**?**], future studies should combine high-spatial-resolution fMRI localization to precisely identify individual functional regions (such as the face-selective area FFA and the place-selective area PPA) before conducting causal tests with high-precision intervention techniques.

5 结论

This study employed a transcranial direct current stimulation (tDCS) system to intervene in four candidate brain regions (the occipital lobe, the left and right parietal lobes, and the prefrontal cortex) to reveal the stimulus-dependent patterns of neural loci involved in binocular rivalry.

The results indicate that when rivalry occurs at the feature-level hierarchy (using grating stimuli), the brain preferentially recruits the occipital lobe and the right parietal lobe to resolve perceptual conflict. Specifically, both anodal stimulation of the occipital lobe and anodal stimulation of the right parietal lobe reduced the magnitude of eye dominance, while cathodal stimulation of the right parietal lobe accelerated the rate of perceptual alternation. Conversely, when the rivalry involves object-level representations (using face/house stimuli), neural resources are instead allocated to the prefrontal cortex and the left parietal lobe. In this condition, anodal stimulation of both regions, as well as cathodal stimulation of the left parietal lobe, reduced eye dominance. This causal evidence demonstrates that binocular rivalry is not supported by a fixed neural network; rather, the brain flexibly recruits different neural resources based on the representational hierarchy of the stimuli.

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Stimulus Dependence of Neural Sites in Binocular Rivalry DONG Bo1,2,3, XIA Zuyu1, ZHANG Ming1,2,4 (1 Department of Psychology, Suzhou University of Science and Technology; 2 Research Center for Psychology and Behavioral Sciences, Key Research Base of Humanities and Social Sciences in Jiangsu Higher Education Institutions; 3 Think Tank for Urban Development, Key Research Base of Humanities and Social Sciences in Jiangsu Higher Education Institutions, Suzhou 215009, China) (4 School of Psychology, Northeast Normal University, Changchun 130024, China)

Abstract

Binocular rivalry is a phenomenon wherein the two eyes receive conflicting visual images, resulting in alternating perceptual dominance rather than image fusion. It offers a unique insight into the neural basis of visual consciousness, as the visual input remains constant despite fluctuations in subjective awareness. A fundamental question in binocular rivalry research concerns identifying the visual pathway along which the competition occurs. According to early theories, rivalry primarily involves monocular neurons in the primary visual cortex (V1) or the lateral geniculate nucleus via interocular inhibition mechanisms. However, electrophysiological studies in monkeys showed stronger correlations between neural activity in higher visual areas, e.g., the inferotemporal cortex, and perceptual states, indicating competition at object-level representations. Since rivalry occurs across multiple hierarchical levels through reciprocal interactions, the hybrid model sought to reconcile these findings. Nevertheless, a critical question remains unaddressed: How might different visual conditions alter the sites at which rivalry competition is most prevalent? Although neuroimaging studies hint at this possibility, there is currently no systematic causal evidence, and this prevents us from understanding whether the brain flexibly recruits different neural resources based on stimulus characteristics.

This study employed transcranial direct current stimulation (tDCS) to systematically examine the causal roles of four candidate brain regions, namely, the occipital cortex, the right parietal cortex, the left parietal cortex, and the prefrontal cortex, across two stimulus types representing

different representational levels. Eight independent experiments were conducted based on a 2 × 4 design: two stimulus types (orthogonal gratings as local-feature stimuli vs. face/house images as object-level stimuli) × four brain regions. Each experiment used a within-subjects design with three tDCS conditions, namely, anodal stimulation, cathodal stimulation, and sham stimulation. A total of 160 participants were recruited across experiments (18~22 per experiment; mean age = 20.8 years; all right-handed with normal or corrected-to-normal vision). We used high-definition tDCS with a 4 × 1 electrode montage—comprising one central electrode and four return electrodes—positioned over target regions based on the international 10-10 system. Stimulation intensity (maximum 1.0 mA) was applied for 20 min during each session. Participants completed binocular rivalry tasks using a mirror stereoscope while continuously reporting their perceptual states via key presses. Two dependent variables were measured: eye dominance strength (reflecting competitive bias and relative gain) and perceptual alternation rate (reflecting destabilization and switching frequency).

The results revealed a robust stimulus-dependent pattern of regional involvement. For grating stimuli (Experiments 1~4), occipital tDCS significantly changed eye dominance strength, F(2, 38) = 7.64, p = 0.002,

$= 0.28$, $1 - \beta > 0.99$. Right parietal tDCS also changed eye dominance,

F(2, 38) = 5.36, p = 0.009,   38) = 3.71, p = 0.034,

$= 0.22$, $1 - \beta = 0.99$, and influenced the alternation rate, F(2,

$= 0.16$, $1 - \beta = 0.99$. Neither left parietal nor prefrontal tDCS

affected grating rivalry. In marked contrast, for face/house stimuli (Experiments 5~8), left parietal tDCS significantly changed eye dominance, F(2, 38) = 3.97, p = 0.027,

0.99. Prefrontal tDCS also altered eye dominance, F(2, 38) = 4.06, p = 0.025,

$= 0.17$, $1 - \beta =$

$= 0.18$, $1 -$

$\beta = 0.99$. Notably, neither occipital nor right parietal stimulation affected face/house rivalry. This double dissociation indicates that simple grating rivalry primarily engages the occipital cortex (early interocular competition) and the right parietal cortex (spatial attention modulation), whereas object-level rivalry recruits the prefrontal cortex (cognitive control) and the left parietal cortex (object feature integration).

This study provides causal evidence for a stimulus-dependent, flexible configuration of rivalry sites. Instead of employing a fixed neural network, the brain flexibly allocates hierarchical neural resources based on the stimulus representational level. These findings advance the hybrid model from a descriptive multi-site framework to a predictive theory that specifies how stimulus properties determine the dominant competitive loci, thereby offering new insights into the flexible neural architecture underlying visual consciousness.

Keywords

Binocular rivalry, Neural sites, tDCS, Stimulus-dependent patterns, Flexible configuration

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