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Color perception matches selectivity in human early visual cortex

Where and how the color perception formed in the human brain remains one of the most intriguing topics in vision science. Color selective neurons could be found along the visual hierarchy [1,2], but which level contributes directly to color perception and behaviorally correlated processing is still under debate. Lesion [3] and functional magnetic resonance imaging [4,5] studies in human subjects suggested a group of color-selective areas in the ventral occipitotemporal cortex (VOTC), which labeled V4/V4α or V8, might be critical for color percepts. The intracranial electrical brain stimulation (EBS) could induce chromatic phosphenes in human VOTC, which also show color selectivity when activated by visual stimulus [6,7]. These evidence seem to suggest that color perception formed in the high-order visual cortex. Here we systematically examined a case of intracranial electrodes implanted patient who exhibited matched EBS induced color perception and visual stimulus induced color selectivity in her left dorsal V2, a part of the early visual cortex.

The patient was 38-year-old right-handed women with 21 years history of the epileptic seizures secondary to left temporal pole arachnoid cyst. She had a history of conduct arachnoid cyst resection 20 years ago and anterior temporal lobectomy 10 years ago, but it did not effectively inhibit her epileptic seizures. Gradually, the patient's seizure deteriorated with frequency ranging from once to 10 times per month. Oral administration of lamotrigine was ineffective. According to self-reports, the patient's overall cognitive function was normal. Neuropsychological assessments showed that the full intelligence quotient and memory quotient was 123. All the experimental procedures were approved by the Ethics Committee of the Sanbo Hospital of Capital Medical University.

Stereotactic electrodes were intracranially implanted for further epileptic zone evaluation. The stereo-electroencephalogram (sEEG) electrodes were manufactured by Huake Hengsheng Medical Technology Co Ltd, Beijing, China, with a diameter of 0.8 mm and multiple 2 mm long contacts that spaced 1.5 mm apart from each other. The reference electrode was placed on the forehead. On monitoring days, the impedance of all the recording electrode contacts were kept below 50 kΩ, and the contacts with impedances higher than this value were excluded from analyses. Video EEG monitor lasted for 21 days after implantation, and the lamotrigine dosage was gradually reduced during this period.

The positions of each electrode contacts were identified using a post-implantation CT scan co-registered with the pre-implantation T1 image. An early visual area (V1 − V3) atlas was applied to the Freesurfer reconstructed brain anatomy, using the method developed by Benson and colleagues [8].

During the EBS session, the patient was informed to sit at her hospital bed and fixate at a "+" on a 31.5-inches LCD monitor (view distance = 22 cm). Rectangular electrical pulses were delivered to pairs of adjacent contacts (frequency = 50 Hz, pulse width = 0.2 ms, duration = 5 s, amplitude = 1–6 mA). The amplitude was going up with a step of 1 mA until a certain phosphene was reported. The patient was asked to draw her visual percepts on the monitor immediately after the phosphene disappeared. The electrode X1 to X3 was localized on the dorsal part of V2 (Fig. 1A). The patient reported a chromatic phosphene in her right-bottom visual field when the contact pair X1-X2 was stimulated (Fig. 1D, left panels) while an achromatic phosphene with a similar location when the contact pair X2-X3 was stimulated (Fig. 1D, right panels). No phosphene was reported during sham trials randomly intermixed with stimulation trials. These results suggested that the neurons around X1, but not X2, have color preference.

The day after the EBS session, visual evoked intracranial potentials to both chromatic (green-red, blue-yellow) and achromatic (black-white) stimuli were examined. The locations of the visual stimulus were specially designed to match the locations of electrically evoked phosphene (Fig. 1B). Forty trials for each condition were present, and the duration of a trial was 600 ms (ISI = 400 ms). Visual stimuli were flipped to the opponent color once at 300 ms. As shown in Fig. 1C and E, time-frequency analyses of the evoked potential illustrated a remarkable high-γ amplitude enhancement (100–250 Hz) evoked by the blue-yellow stimulus in X1 but not X2. For each electrode contact, a trial-level independent *t*-test on the averaged high-γ amplitudes between 100 and 800 ms was conducted (with *Bonferroni* adjustments). The results showed that, in X1, the high-γ evoked by blue-yellow stimulus was significantly larger than red-green [$t(74) = 3.321$, $p = 0.001$] and black-white [$t(74) = 2.144$, $p = 0.035$] stimuli (Fig. 1F). No significance was found in X2 (all $p > 0.05$). These results demonstrated color selectivity of X1 that was consistent with the EBS data.

Consistent with the previous literature (Murphey et al., 2008; Schalk et al., 2017), we also found that the electrical stimulation on a contact pair (E2-E3), which location on the ventral occipitotemporal cortex (VOTC), could induce a chromatic phosphene (Supplementary Fig. 1B) ("a multicolor, porridge-like mess" according to the patient). To investigate the conduction direction between V2 and VOTC, cortico-cortical evoked potential (CCEP) were conducted (repetition = 20 times, pulse width = 0.2 ms, amplitude = 2, 4, 6 mA). The evoked responses are transferred to z-scores with respect to baseline in single-trial level. Significant evoked potentials were observed inE 2-E3 after X1-X2 stimulation onsets with a 58 ms averaged P1 latency (Supplementary Fig. 1C). No significant potential was observed in X1-X2 when E2-E3 was stimulated (Supplementary Fig. 1D).

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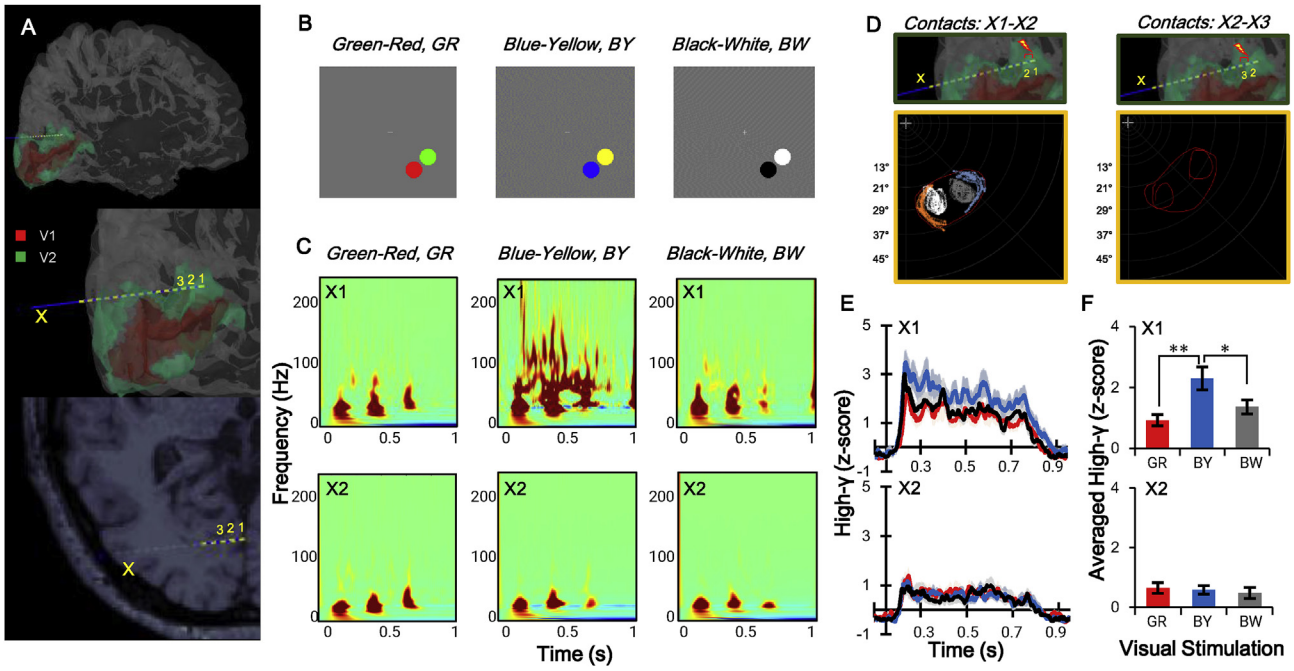

Fig. 1. (A) Location of the implanted electrode in the dorsal V2. (B) Illustrations of three conditions of visual stimulation which matched the electrical induced receptive fields. (C) Time-frequency analyses of visual evoked response. (D) Electrical stimulation of the electrode pair X1-X2 induces a chromatic phosphene, while stimulation of the pair X2-X3 induces an achromatic phosphene. Bottom subpanels show the phosphene drew by the patient. Red solid lines represent the receptive field boundaries. (E) Time course of the high-gamma responses (100–250 Hz) for each visual stimulation. The evoked responses are transferred to z-scores with respect to baseline in single-trial level. The translucent area around each line represents the standard error. (F) Comparison of the averaged high-gamma activity (50–800 ms) across three visual simulation conditions. *GR: green-red; BY: blue-yellow; BW: black-white.* *, $p < 0.05$; **, $p < 0.01$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Discussions

Although two previous studies have already suggested that EBS on human early visual cortex could effectively induce color perceptual [9,10], the current study has systematically measured the color preference in local neuron ensembles using both EBS and visual evoked potential within the same RF. On the other hand, as shown in Fig. 1D, the color preference in X1 was spatially organized in the local RF, which is consistent with the hue map in non-human primates' V2 [1]. Moreover, the unidirectional connectivity from V2 to VOTC may play a critical role in color awareness.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brs.2019.09.002.

References

[1] Xiao Y, Wang Y, Felleman DJ. A spatially organized representation of colour in macaque cortical area v2. Nature 2003;421(6922):535–9.
[2] Conway BR, Tsao DY. Color-tuned neurons are spatially clustered according to color preference within alert macaque posterior inferior temporal cortex. Proc Natl Acad Sci 2009;106(42):18034–9.
[3] Damasio A, Yamada T, Damasio H, Corbett J, Mckee J. Central achromatopsia: Behavioral, anatomic, and physiologic aspects. Neurology 1980;31(7):920–1.
[4] Zeki S, Bartels A. The clinical and functional measurement of cortical (in) activity in the visual brain, with special reference to the two subdivisions (v4 and v4α) of the human colour centre. Philosophical Transactions Biological Sciences 1999;354(1387):1371–82.
[5] Hadjikhani N, Liu AK, Dale AM, Cavanagh P, Tootell RBH. Retinotopy and color sensitivity in human visual cortical area V8. Nat Neurosci 1998;1(3):235–41.
[6] Murphey DK, Yoshor D, Beauchamp M. Perception matches selectivity in the human anterior color center. Curr Biol 2008;18(3):216–20.
[7] Schalk G, Kapeller C, Guger C, Ogawa H, Hiroshima S, Lafersousa R, et al. Face-phenes and rainbows: causal evidence for functional and anatomical specificity of face and color processing in the human brain. Proc Natl Acad Sci 2017;114(46):201713447.
[8] Benson NC, Butt OH, Brainard DH, Aguirre GK. Correction of distortion in flattened representations of the cortical surface allows prediction of v1-v3 functional organization from anatomy. PLoS Comput Biol 2014;10(3):e1003538.
[9] Murphey DK, Maunsell J, Yoshor D, Beauchamp MS. Perceiving electrical stimulation of identified human visual areas. Proc Natl Acad Sci 2009;47:5389–93.
[10] Lee HW, Hong SB, Seo DW, Tae WS, Hong SC. Mapping of functional organization in human visual cortex: electrical cortical stimulation. Neurology 2000;54(4):849–54.

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