Anodal transcranial direct current stimulation reduces collinear lateral inhibition in normal peripheral vision

Rajkumar Nallour Raveendran, Katelyn Tsang, Dilraj Tiwana, Amy Chow, Benjamin Thompson

1 Envision Research Institute, Wichita, Kansas, United States of America, 2 School of Optometry & Vision Science, University of Waterloo, Waterloo, Ontario, Canada

* sachinrajopto@gmail.com

Abstract

Collinear flanking stimuli can reduce the detectability of a Gabor target presented in peripheral vision. This phenomenon is called collinear lateral inhibition and it may contribute to crowding in peripheral vision. Perceptual learning can reduce collinear lateral inhibition in peripheral vision, however intensive training is required. Our aim was to assess whether modulation of collinear lateral inhibition can be achieved within a short time-frame using a single 20-minute session of primary visual cortex anodal transcranial direct current stimulation (a-tDCS). Thirteen observers with normal vision performed a 2AFC contrast detection task with collinear flankers positioned at a distance of 2λ from the target (lateral inhibition) or 6λ (control condition). The stimuli were presented 6˚ to the left of a central cross and fixation was monitored with an infra-red eye tracker. Participants each completed two randomly sequenced, single-masked stimulation sessions; real anodal tDCS and sham tDCS. For the 2λ separation condition, a-tDCS induced a significant reduction in detection threshold (reduced lateral inhibition). Sham stimulation had no effect. No effects of a-tDCS were observed for the 6λ separation condition. This result lays the foundation for future work investigating whether a-tDCS may be useful as a visual rehabilitation tool for individuals with central vision loss who are reliant on peripheral vision.

Introduction

Peripheral vision is susceptible to a phenomenon called crowding, whereby it is difficult to segregate a target object from other objects that are in close proximity.[1–4] Crowding is a particular concern for patients with macular degeneration who lose central vision and are forced to rely on peripheral vision. These patients often develop a preferred retinal locus (PRL), a specific region of the peripheral retina that is used for fixation.[5–7] Crowding impairs spatial vision at the PRL leading to problems with everyday visual activates such as reading.

Crowding in peripheral vision involves cortical mechanisms that can be modulated. For example, perceptual learning can reduce letter crowding in central vision for observers with
amblyopia\[8,9\] and in peripheral vision for observers with macular degeneration\[10–13\]. However, perceptual learning typically requires a large number of training trials \[14\] which may be a barrier for patients. In addition, the learning does not always transfer to non-trained stimuli.\[15–17\] Interventions that can directly modulate mechanisms within visual cortex that may contribute to crowding could complement perceptual learning techniques and enable improved vision in patients with central vision loss.

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique\[18–20\] that has the potential to modulate neural mechanisms that contribute to crowding. tDCS involves passing a weak 1-2mA electrical current through two head-mounted electrodes (the anode and cathode) and can induce regional changes in cortical excitability and neurotransmitter concentration that outlast the duration of stimulation. For example, anodal tDCS (a-tDCS) of the motor cortex increases cortical excitability\[21\] and causes a regional reduction in the concentration of the inhibitory neurotransmitter GABA \[22–24\]. When applied to the primary visual cortex, a-tDCS modulates contrast sensitivity\[25,26\], visually evoked potential amplitude\[25\] and the visual cortex BOLD response\[26\]. Of particular importance for crowding, a-tDCS can immediately improve Vernier acuity and reduce surround suppression within the near-periphery\[27–29\], possibly by modulating inhibition within the visual cortex\[27\].

Lateral masking involves the presentation of a central target Gabor patch between two flanker patches.\[12\] When the patches have collinear orientation, contrast detection thresholds for the target can be increased (collinear inhibition or lateral masking) or reduced (collinear facilitation) depending on target/flanker separation. Collinear inhibition is distinct from crowding, which involves impaired object recognition rather than elevated detection thresholds. However, collinear inhibition represents a well-established psychophysical technique for assessing low-level inhibitory mechanisms that may contribute to crowding. Collinear inhibition and facilitation arise within the primary visual cortex\[30,31\] and are present in central \[8\] and peripheral vision\[12,32\]. Maniglia et al. \[12\] observed that collinear lateral inhibition could be reduced by \(\approx 40\%\) in normal peripheral vision after perceptual learning (20 sessions/week over 8 weeks), indicating that collinear inhibition mechanisms within the periphery are plastic.

In this study, we took a first step towards evaluating whether visual cortex a-tDCS has the potential to reduce crowding in peripheral vision by assessing the acute effects of a single stimulation session on lateral inhibition in participants with normal vision. We observed that 20 min of visual cortex a-tDCS reduced lateral inhibition in the visual periphery of healthy observers by \(\approx 30\%\). This finding paves the way for future studies designed to evaluate the possibility of inducing long-lasting changes in lateral inhibition using a-tDCS and, in the longer term, the potential use of a-tDCS to reduce crowding in individuals with central vision loss.

Materials and methods

Apparatus and visual stimuli

13 participants with best corrected visual acuity of \(\leq 20/20\) agreed to participate in the study. All participants provided written, informed consent. The study was approved by the University of Waterloo research ethics committee. All the procedures involved in this research adhered to the tenets of the Declaration of Helsinki. Participants were instructed to fixate a 0.2˚ central cross and respond to visual stimuli by pressing a key on a keyboard. Visual stimuli were created using PsychoPy\[33,34\] (available for free download: http://www.psychopy.org). The stimuli were presented on a 27” LCD (ASUS - https://www.asus.com/ca-en/Monitors/).
placed at the distance of 50cm from a chinrest. The LCD background luminance was 32 cd/m².

The visual stimuli consisted of a central target, Gabor patch (visible extent size: 1˚, σ: 5, and spatial frequency: 7 cpd) presented 6˚ to the left of the fixation cross. We selected a spatial frequency of 7 cpd because this spatial frequency produced detection thresholds that were measurable with our 8-bit-luminance-contrast stimulus display system. We presented our stimuli at an eccentricity of 6˚ because about 70% of macular degeneration patients have a scotoma size of <5˚ [5] and this experiment was the first step towards investigating the effects of a-tDCS in individuals with macular degeneration. Two flanker Gabor patches (7 cpd, 0.8 contrast) were presented above and below the target. The flanker Gabor patches were positioned at a distance of 2λ (lateral inhibition) or 6λ (control). Throughout the procedure, fixation was monitored in real-time using an infrared video-based eye tracker (EyeLink II, SR Research, Osgoode, Canada, 500 Hz sampling rate).

Psychophysical task
The 2AFC lateral masking task involved the measurement of contrast detection thresholds for the central target Gabor patch. The initial contrast of the central Gabor patch was set at 0.5 and its contrast was altered using a 2 down and 1 up staircase procedure with a fixed step size of 0.05. The staircase was terminated either after 50 trials or 5 reversals. The contrast detection threshold was determined as the mean of the last 4 reversals. Two staircases were completed and averaged for each threshold measurement. The same procedure was followed for both flanker distances of 2λ and 6λ. These particular flanker distances were selected based on a previous study reporting collinear inhibition for 2λ but not for 6λ [12] and our own pilot data supporting this observation. In fact, a 6λ flanker distance may induce facilitation.[32,35] The 2λ separation was our experimental condition and the 6λ condition was a control condition to test for any general effects of a-tDCS on contrast sensitivity for the target stimulus. A training session was provided for all participants prior to data collection. Any trials in which eye position deviated by more than 1˚ from fixation were immediately repeated.

Brain-stimulation (tDCS)
tDCS was delivered by a DC Stimulator MC from NeuroConn gmbh (https://www.rogue-resolutions.com/catalogue/neuro-modulation/dc-stimulator-tes/) using a pair of rubber electrodes (5cm x 5cm) placed inside saline soaked sponges. The electrodes were secured in place by the head strap of the eye tracker over electrode positions Oz (anodal electrode) and Cz (cathodal electrode) identified using the standard 10–20 EEG method (Fig 1). Participants each completed two randomly sequenced stimulation sessions conducted at least 48 hours apart; real 2mA anodal tDCS of the primary visual cortex for 20 minutes and sham tDCS where the current was ramped up and then immediately ramped down with the electrodes kept in place for 20 minutes. Participants were masked to the type of stimulation. During each test session, participants completed a block of four threshold measurements for each flanker distance pre-, during-, 5mins post- and 30mins post-stimulation. The sequence of 2λ and 6λ separation measurements was randomized within each test block.

Data analysis
Prior to analysis, the standard deviation across reversals was calculated for each individual staircase. Any staircase with a standard deviation of 2 or greater was considered to be unreliable and excluded from analysis. An ANOVA with within-subject factors of stimulation type (anodal vs. sham) and time (pre-, during-, 5 minutes post- and 30 minutes post-stimulation)
was applied to the log contrast thresholds. Post-hoc Tukey HSD was used to compare the log contrast thresholds between different stimulation sessions. Paired t-tests were used to compare session 1 and session 2 baselines to test for task learning. 2λ and 6λ baselines were also compared to ensure that the 2λ separation induced collinear lateral inhibition. A p value of <0.05 was considered statistically significant.

**Results**

One staircase had a SD greater than 2 and was removed from further analysis (see S1 and S2 Tables). Baseline contrast detection thresholds for the central Gabor patch differed significantly between the two flanker separation conditions, with higher thresholds for the 2λ separation than the 6λ separation (mean ± SEM; 2λ 0.36±0.03, 6λ 0.14±0.02, t_{12} = 8.2, p < 0.001). This is consistent with previous observations of collinear inhibition within peripheral vision at a target/flanker separation of 2λ[31,32] but not at a 6λ separation. No significant difference
between the baseline measures for session 1 and session 2 were observed for either the $2\lambda$ (session 1, $0.39\pm0.15$; session 2, $0.34\pm0.16$) ($t_{12} = 1.1$, $p = 0.30$) or $6\lambda$ (session 1, $0.13\pm0.15$; session 2, $0.15\pm0.11$) ($t_{12} = 0.83$, $p = 0.42$) conditions. This indicates the absence of task learning from one session to the next.

Fig 2 shows raw individual participant data for the a-tDCS and sham stimulation sessions for the $2\lambda$ (top row) and $6\lambda$ (bottom row) flanker separation conditions (a table of data with mean contrast threshold and standard deviation of staircase reversals for every individual participant is provided in the supporting material: S1 and S2 Tables). Fig 3 shows baseline-normalized group means. For the $2\lambda$ separation, a-tDCS significantly improved contrast detection thresholds for the central target (reduced collinear inhibition) whereas sham stimulation had no effect. There was a significant interaction between stimulation type [anodal vs. sham] and time [pre, during, post 5 min, post 30 min] ($F_{3, 36} = 3.01$, $p = 0.042$, partial $\eta^2 = 0.21$), with post-hoc Tukey HSD comparisons revealing significantly reduced contrast thresholds relative to baseline for the a-tDCS session during stimulation ($p = 0.001$) and 30 min post stimulation ($p = 0.01$). Thresholds at the 5 min post stimulation timepoint did not differ significantly from baseline ($p = 0.23$). Thresholds within the sham stimulation session did not differ from baseline for any timepoint. For the $6\lambda$ separation, there was no significant interaction between stimulation type and time ($F_{3, 36} = 0.46$, $p = 0.71$, partial $\eta^2 = 0.04$) indicating no difference between a-tDCS and sham on contrast detection thresholds.

Fig 2. Contrast threshold. Log contrast detection thresholds (db) for each participant for the $2\lambda$ (top row) and $6\lambda$ (bottom row) flanker separations during the active (left column) and sham (right column) stimulation sessions.

https://doi.org/10.1371/journal.pone.0232276.g002
The purpose of the study was to test the hypothesis that anodal tDCS would reduce collinear lateral inhibition in peripheral vision of observers with normal vision. The hypothesis was based on previous reports of improved peripheral Vernier acuity, Snellen acuity and contrast sensitivity.

**Fig 3. Reduction of collinear inhibition.** Reduction of collinear inhibition using anodal-tDCS. Mean change in contrast detection threshold from baseline for the 2λ (red) and 6λ (blue) flanker separations for the anodal (solid line) and sham (dashed line) stimulation conditions. Error bars represent ±1 SEM and asterisk symbols represent statistical significance (p<0.05). DS, during stimulation; PS, post stimulation.

https://doi.org/10.1371/journal.pone.0232276.g003

**Discussion**

The purpose of the study was to test the hypothesis that anodal tDCS would reduce collinear lateral inhibition in peripheral vision of observers with normal vision. The hypothesis was based on previous reports of improved peripheral Vernier acuity, Snellen acuity and contrast sensitivity.
along with reduced center-surround suppression\[27\] following occipital lobe a-tDCS in participants with normal vision. Enhanced contrast sensitivity and modulation of visual cortex activity following a-tDCS have also been observed in patients with amblyopia.\[25,26\] We observed a significant reduction of collinear inhibition during and 30 min after a single 20 min application of a-tDCS to the occipital lobe. The data collected 5 min post active stimulation exhibited that same trend as data collected during active stimulation and 30 min post active stimulation, but they did not differ significantly from baseline or the sham condition. These results could be likely due to noise inherent in both tDCS effects and psychophysical tasks involving peripheral vision. The effects of a single a-tDCS session are transient, but, overall, our results suggest that a-tDCS is able to modulate low-level lateral interactions in early visual cortex that may contribute to crowding in peripheral vision. The reduction of collinear inhibition that we observed for the measurements made offline (after stimulation) is consistent with previous studies reporting stronger offline than online (during stimulation) primary visual cortex a-tDCS effects \[36\]. However, in addition to the offline effect, we also observed a significant reduction of collinear inhibition for the online measurements. This is in agreement with a previous report of primary visual cortex a-tDCS effects on surround suppression. In general, offline effects are likely to be more important for the potential use of a-tDCS to improve vision in people with central vision loss as they indicate a lasting influence of a-tDCS on visual cortex function.

A number of explanations have been proposed for the effects of visual cortex a-tDCS. These include changes in response gain\[29\], stochastic resonance leading to increased signal strength \[37\], and reduced GABA-mediated inhibition\[22,24\]. Our results are most clearly aligned with a reduction in cortical inhibition as we observed an effect for the lateral inhibition condition but not the control condition that would have also benefitted from response gain and stochastic resonance changes. Our results also support previous work indicating that lateral inhibition takes place in V1\[31,38\], the primary target of our stimulation.

Previous studies have observed that collinear lateral inhibition can be reduced using perceptual learning in observers with normal vision\[12\] and observers with macular degeneration \[10\]. Maniglia et al.\[12\] reported an approximately 40% reduction of peripheral collinear lateral inhibition after training in healthy observers (an approximate absolute change in contrast threshold of 0.06). However, in order to achieve this reduction, each participant underwent 160 sessions over the course of 8 weeks (≈ 7600 trials/week). In this study, we observed that a single session of anodal tDCS reduced collinear lateral inhibition by approximately 30% (an absolute change in contrast threshold of 0.13 from baseline to 30 min post active stimulation). This suggests that a-tDCS may enhance the effects of perceptual learning paradigms designed to reduce collinear lateral inhibition. Indeed, a very recent study of healthy adults by Contemori et al. observed that the combination of a different tDCS protocol, transcranial random noise stimulation, and perceptual learning reduced peripheral crowding for trigram stimuli to a greater extent than perceptual learning alone.\[39\] Furthermore, tDCS increased the transfer of learning to other tasks. Taken together, the present results and the results of Contemori et al.\[39\] provide a strong foundation for the future application of non-invasive brain stimulation to the rehabilitation of patients with central vision loss, for whom the limitations of peripheral vision represent a major cause of visual disability \[40\].

One limitation of our study is that there is no consensus on whether lateral masking and crowding are associated, although they share similar features such as increasing strength with eccentricity\[41\] and a recent study showed that crowding and lateral masking are related and share similar neural mechanisms.\[42\] In particular, the mechanism of crowding is likely to involve higher visual processing centers.\[41\] Nonetheless, it is plausible that enhancing the early stages of visual processing by reducing collinear inhibition will improve higher-level visual processing of crowded stimuli.\[43,44\] In addition, in this study we used a 6A target
flanker separation distance as a control condition. This separation distance was chosen because it does not induce lateral inhibition, however, flankers at this separation may induce collinear lateral facilitation.[32,35] An alternative control condition could have involved the presentation of orthogonally oriented flankers at a 2λ target-flanker separation.[32,35,45] The fact that we found no effect of a-tDCS for the 6λ separation may suggest that lateral facilitation is not affected by V1 a-tDCS, perhaps because lateral facilitation involves visual areas downstream from V1.[46,47] A study focused directly on lateral facilitation is required to address this interesting possibility. Finally, this study demonstrates only an acute effect of a-tDCS on lateral inhibition. The next stage in the development of this research area will be to study the possibility of long-lasting effects, perhaps by administering multiple a-tDCS sessions[48,49] and/or combining a-tDCS with perceptual learning.[50].

Supporting information

S1 Table. Mean contrast threshold values (db) and SD of reversals for each participant in 2λ condition.
(DOCX)

S2 Table. Mean contrast threshold values (db) and SD of reversals for each participant in 6λ condition.
(DOCX)

Acknowledgments

The authors would like to thank Dr. Andy Silva for his assistance with PsychoPy.

Author Contributions

Conceptualization: Rajkumar Nallour Raveendran, Benjamin Thompson.
Data curation: Rajkumar Nallour Raveendran, Katelyn Tsang, Dilraj Tiwana, Amy Chow.
Formal analysis: Rajkumar Nallour Raveendran, Katelyn Tsang, Dilraj Tiwana, Amy Chow.
Funding acquisition: Rajkumar Nallour Raveendran, Benjamin Thompson.
Investigation: Rajkumar Nallour Raveendran.
Methodology: Rajkumar Nallour Raveendran, Amy Chow, Benjamin Thompson.
Project administration: Rajkumar Nallour Raveendran, Amy Chow.
Resources: Benjamin Thompson.
Supervision: Rajkumar Nallour Raveendran, Benjamin Thompson.
Validation: Rajkumar Nallour Raveendran, Katelyn Tsang, Dilraj Tiwana.
Visualization: Rajkumar Nallour Raveendran.
Writing – original draft: Rajkumar Nallour Raveendran.
Writing – review & editing: Rajkumar Nallour Raveendran, Katelyn Tsang, Dilraj Tiwana, Benjamin Thompson.

References

1. Bouma H. Interaction Effects in Parafoveal Letter Recognition. Nature. Nature Publishing Group; 1970; 226: 177–178. https://doi.org/10.1038/226177a0 PMID: 5437004
2. Levi DM. Visual crowding. Curr Biol. Elsevier; 2011; 21: R678–R679. https://doi.org/10.1016/j.cub.2011.07.025 PMID: 21959149

3. Levi DM. Crowding—an essential bottleneck for object recognition: a mini-review. Vision Res. 2008; 48: 635–54. https://doi.org/10.1016/j.visres.2007.12.009 PMID: 18226828

4. Pelli DG. Crowding: a cortical constraint on object recognition. Curr Opin Neurobiol. Elsevier Current Trends; 2008; 18: 445–451. https://doi.org/10.1016/j.conb.2008.09.008 PMID: 18835355

5. Fletcher DC, Schuchard RA. Preferred retinal loci relationship to macular scotomas in a low-vision population. Ophthalmology. Elsevier; 1997; 104: 632–8. https://doi.org/10.1016/s0161-6420(97)30260-7 PMID: 9111255

6. Timberlake GGT, Sharma MKM, Grose SAS, Gobert DD V, Guach J, Maino JJH, et al. Retinal Location of the Preferred Retinal Locus Relative to the Fovea in Scanning Laser. Optom Vis Sci. 2005; 82: 177–185. Available: http://www.ncbi.nlm.nih.gov/pubmed/15767869 doi: 10.1097/01.opx.0000156311.49058.e8 PMID: 15767869

7. Cheung S-H, Legge GE. Functional and cortical adaptations to central vision loss. Vis Neurosci. 2005; 22: 187–201. https://doi.org/10.1017/S0952523805222071 PMID: 15935111

8. Polat U, Ma-Naim T, Belkin M, Sagi D. Improving vision in adult amblyopia by perceptual learning. Proc Natl Acad Sci U S A. National Academy of Sciences; 2004; 101: 6692–7. https://doi.org/10.1073/pnas.0401200101 PMID: 15096608

9. Levi DM, Li RW. Perceptual learning as a potential treatment for amblyopia: a mini-review. Vision Res. NIH Public Access; 2009; 49: 2535–49. https://doi.org/10.1016/j.visres.2009.02.010 PMID: 19250947

10. Maniglia M, Soler V, Cottereau B, Trotter Y. Spontaneous and training-induced cortical plasticity in MD patients: Hints from lateral masking. Sci Rep. Nature Publishing Group; 2018; 8: 90. https://doi.org/10.1038/s41598-017-18261-6 PMID: 29311565

11. Maniglia M, Pavan A, Sato G, Contemorini G, Montermino S, Battaglini L, et al. Perceptual learning leads to long lasting visual improvement in patients with central vision loss. Restor Neurol Neurosci. 2016; 34: 697–720. https://doi.org/10.3233/RNN-150575 PMID: 27567754

12. Maniglia M, Pavan A, Cuturi LF, Campagna G, Sato G, Casco C. Reducing Crowding by Weakening Inhibitory Lateral Interactions in the Periphery with Perceptual Learning. Goldreich D, editor. PLoS One. Public Library of Science; 2011; 6: 1–9. https://doi.org/10.1371/journal.pone.0025568 PMID: 22065990

13. Chung STL, Li RW, Levi DM. Crowding between first- and second-order letter stimuli in normal foveal and peripheral vision. J Vis. NIH Public Access; 2007; 7: 10.1–13. https://doi.org/10.1167/7.2.10 PMID: 18217825

14. Chung STL. Learning to identify crowded letters: Does it improve reading speed? Vision Res. Pergamon; 2007; 47: 3150–3159. https://doi.org/10.1016/j.visres.2007.08.017 PMID: 17928026

15. Lu-Z, Dosher BA. Mechanisms of perceptual learning. Learn Percept. NIH Public Access; 2009; 1: 19–36. https://doi.org/10.1556/LP.1.2009.1.3 PMID: 20445764

16. Maniglia M, Seitz AR. Towards a whole brain model of Perceptual Learning [Internet]. Current Opinion in Behavioral Sciences. Elsevier; 2018. pp. 47–55. https://doi.org/10.1016/j.cobeha.2017.10.004 PMID: 29457054

17. Fahle M. Perceptual learning: specificity versus generalization. Curr Opin Neurobiol. 2005; 15: 154–160. https://doi.org/10.1016/j.conb.2005.03.010 PMID: 15831396

18. Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, et al. Transcranial direct current stimulation: State of the art 2008. Brain Stimul. 2008; 1: 206–223. https://doi.org/10.1016/j.brs.2008.06.004 PMID: 20633386

19. Reinhart RMG, Cosman JD, Fukuda K, Woodman GF. Using transcranial direct-current stimulation (tDCS) to understand cognitive processing. Attention, Perception, Psychophys. Springer US; 2017; 79: 3–23. https://doi.org/10.3758/s13414-016-1224-2 PMID: 27804033

20. Woods AJ, Antal A, Bikson M, Boggio PS, Brunoni AR, Celnik P, et al. A technical guide to tDCS, and related non-invasive brain stimulation tools. Clin Neuropsychol. NIH Public Access; 2016; 127: 1031–1048. https://doi.org/10.1016/j.clinph.2015.11.012 PMID: 26652115

21. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J Physiol. Wiley-Blackwell; 2000; 527 Pt 3: 633–9. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x PMID: 10990547

22. Stagg CJ, Best JG, Stephenson MC, O’Shea J, Wylezinska M, Kincaid ZT, et al. Polarity-sensitive modulation of cortical neurotransmitters by transcranial stimulation. J Neurosci. 2009; 29: 5202–6. https://doi.org/10.1523/JNEUROSCI.4432-08.2009 PMID: 19396916

23. Kim S, Stephenson MC, Morris PG, Jackson SR. tDCS-induced alterations in GABA concentration within primary motor cortex predict motor learning and motor memory: a 7 T magnetic resonance
spectroscopy study. Neuroimage. Elsevier; 2014; 99: 237–43. https://doi.org/10.1016/j.neuroimage.2014.05.070 PMID: 24904994

24. Antonenko D, Schubert F, Bohn F, Ittermann B, Aydin S, Hayek D, et al. tDCS-Induced Modulation of GABA Levels and Resting-State Functional Connectivity in Older Adults. J Neurosci. 2017; 37: 4065–4073. https://doi.org/10.1523/JNEUROSCI.0079-17.2017 PMID: 28314813

25. Ding Z, Li J, Spiegel DP, Chen Z, Chan L, Luo G, et al. The effect of transcranial direct current stimulation on contrast sensitivity and visual evoked potential amplitude in adults with amblyopia. Sci Rep. Nature Publishing Group; 2016; 6: 19280. https://doi.org/10.1038/srep19280 PMID: 26763954

26. Spiegel DP, Byblow WD, Hess RF, Thompson B. Anodal transcranial direct current stimulation transiently improves contrast sensitivity and normalizes visual cortex activation in individuals with amblyopia. Neurorehabil Neural Repair. 2013; 27: 760–9. https://doi.org/10.1177/1545968313491006 PMID: 23774122

27. Spiegel DP, Hansen BC, Byblow WD, Thompson B. Anodal Transcranial Direct Current Stimulation Reduces Psychophysically Measured Surround Suppression in the Human Visual Cortex. de Beeck HO p., editor. PLoS One. Public Library of Science; 2012; 7: e36220. https://doi.org/10.1371/journal.pone.0036220 PMID: 22563485

28. Bonder T, Gopher D, Yeshurun Y. The Joint Effects of Spatial Cueing and Transcranial Direct Current Stimulation on Visual Acuity. Front Psychol. Frontiers Media SA; 2018; 9: 159. https://doi.org/10.3389/fpsyg.2018.00159 PMID: 29515484

29. Polat U, Mizobe K, Pettet MW, Kasamatsu T, Norcia AM. Collinear stimuli regulate visual responses depending on cell’s contrast threshold. Nature. Nature Publishing Group; 1998; 391: 580–584. https://doi.org/10.1038/35372 PMID: 9468134

30. Polat U, Norcia AM. Neurophysiological Evidence for Contrast Dependent Long-range Facilitation and Suppression in the Human Visual Cortex. Vision Res. Pergamon; 1996; 36: 2099–2109. https://doi.org/10.1016/0042-6989(95)00281-2 PMID: 8776476

31. Lev M, Polat U. Collinear facilitation and suppression at the periphery. Vision Res. Pergamon; 2011; 51: 2488–2498. https://doi.org/10.1016/j.visres.2011.10.008 PMID: 22037360

32. Peirce JW. Generating stimuli for neuroscience using PsychoPy. Front Neuroinform. Frontiers; 2008; 2: 10. https://doi.org/10.3389/neuro.11.010.2008 PMID: 19198666

33. Peirce JW. PsychoPy—Psychophysics software in Python. J Neurosci Methods. Elsevier; 2007; 162: 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017 PMID: 17254636

34. Maniglia M, Pavan A, Aedo-Jury F, Trotter Y. The spatial range of peripheral collinear facilitation. Sci Rep. Nature Publishing Group; 2015; 5: 1–14. https://doi.org/10.1038/srep15530 PMID: 26502834

35. Pirulli C, Fertonani A, Minnissi C. The role of timing in the induction of neuromodulation in perceptual learning by transcranial electric stimulation. Brain Stimul. Elsevier Ltd; 2013; 6: 683–689. https://doi.org/10.1016/j.brs.2012.12.005 PMID: 23369505

36. Schwarzkopf DS, Silvanto J, Rees G. Stochastic resonance effects reveal the neural mechanisms of transcranial magnetic stimulation. J Neurosci. Europe PMC Funders; 2011; 31: 3143–7. https://doi.org/10.1523/JNEUROSCI.4863-10.2011 PMID: 21368025

37. Chen J, He Y, Zhu Z, Zhou T, Peng Y, Zhang X, et al. Attention-Dependent Early Cortical Suppression Contributes to Crowding. J Neurosci. Society for Neuroscience; 2014; 34: 10465–10474. https://doi.org/10.1523/JNEUROSCI.1140-14.2014 PMID: 25100582

38. Contemori G, Trotter Y, Cottereau BR, Maniglia M. tRNS boosts perceptual learning in peripheral vision. Neuropsychologia. Pergamon; 2019; 125: 129–136. https://doi.org/10.1016/j.neuropsychologia.2019.02.001 PMID: 30721741

39. Wallace JM, Chung STL, Tjan BS. Object crowding in age-related macular degeneration. J Vis. The Association for Research in Vision and Ophthalmology; 2017; 17: 33. https://doi.org/10.1167/17.1.33 PMID: 28129416

40. Pelli DG, Palomares M, Majaj NJ. Crowding is unlike ordinary masking: Distinguishing feature integration from detection. J Vis. The Association for Research in Vision and Ophthalmology; 2004; 4: 12. https://doi.org/10.1167/4.12.12 PMID: 15669917

41. Lev M, Polat U. Space and time in masking and crowding. J Vis. The Association for Research in Vision and Ophthalmology; 2015; 15:10. https://doi.org/10.1167/15.13.10 PMID: 26381841

42. Levi DM. Visual Processing in Amblyopia: Human Studies. Strabismus. Taylor & Francis; 2006; 14: 11–19. https://doi.org/10.1080/09273970700536243 PMID: 16513566
44. Kiorpes L. Visual Processing in Amblyopia: Animal Studies. Strabismus. 2006; 14: 3–10. https://doi.org/10.1080/09273970500536193 PMID: 16513565

45. Shani R, Sagi D. Eccentricity effects on lateral interactions. Vision Res. Pergamon; 2005; 45: 2009–2024. https://doi.org/10.1016/j.visres.2005.01.024 PMID: 15820518

46. Maniglia M, Trotter Y, Aedo-Jury F. TMS reveals inhibitory extrastriate cortico-cortical feedback modulation of V1 activity in humans. Brain Struct Funct. Springer; 2019; 224: 3399–3408. https://doi.org/10.1007/s00429-019-01964-z PMID: 31624907

47. Freeman E, Sagi D, Driver J. Lateral interactions between targets and flankers in low-level vision depend on attention to the flankers. Nat Neurosci. Nature Publishing Group; 2001; 4: 1032–1036. https://doi.org/10.1038/nn728 PMID: 11559851

48. Rushmore RJ, Desimone C, Valero-Cabrè A. Multiple sessions of transcranial direct current stimulation to the intact hemisphere improves visual function after unilateral ablation of visual cortex. Eur J Neurosci. NIH Public Access; 2013; 38: 3799–3807. https://doi.org/10.1111/ejn.12373 PMID: 24118563

49. Behrens JR, Kraft A, Irlbacher K, Gerhardt H, Olma MC, Brandt SA. Long-Lasting Enhancement of Visual Perception with Repetitive Noninvasive Transcranial Direct Current Stimulation. Front Cell Neurosci. Frontiers Media S.A.; 2017; 11: 238. https://doi.org/10.3389/fncel.2017.00238 PMID: 28860969

50. Spiegel DP, Li J, Hess RF, Byblow WD, Deng D, Yu M, et al. Transcranial direct current stimulation enhances recovery of stereopsis in adults with amblyopia. Neurotherapeutics. 2013; 10: 831–9. https://doi.org/10.1007/s13311-013-0200-y PMID: 23857313