Offline transcranial direct current stimulation improves the ability to perceive crowded targets

Guanpeng Chen*  
School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, People’s Republic of China  
IDG/McGovern Institute for Brain Research, Peking University, Beijing, People’s Republic of China  
Peking-Tsinghua Center for Life Sciences, Peking University, Beijing, People’s Republic of China

Ziyun Zhu*  
School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, People’s Republic of China  
IDG/McGovern Institute for Brain Research, Peking University, Beijing, People’s Republic of China  
Peking-Tsinghua Center for Life Sciences, Peking University, Beijing, People’s Republic of China

Qing He  
School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, People’s Republic of China  
IDG/McGovern Institute for Brain Research, Peking University, Beijing, People’s Republic of China  
Peking-Tsinghua Center for Life Sciences, Peking University, Beijing, People’s Republic of China

Fang Fang  
School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, People’s Republic of China  
IDG/McGovern Institute for Brain Research, Peking University, Beijing, People’s Republic of China  
Peking-Tsinghua Center for Life Sciences, Peking University, Beijing, People’s Republic of China

The deleterious effect of nearby flankers on target identification in the periphery is known as visual crowding. Studying visual crowding can advance our understanding of the mechanisms of visual awareness and object recognition. Alleviating visual crowding is one of the major ways to improve peripheral vision. The aim of the current study was to examine whether transcranial direct current stimulation (tDCS) was capable of alleviating visual crowding at different visual eccentricities and with different visual tasks. In the present single-blind sham-controlled study, subjects were instructed to perform an orientation discrimination task or a letter identification task with isolated and crowded targets in the periphery, before and after applying 20 minutes of 2 mA anodal tDCS to visual cortex of the hemisphere contralateral or ipsilateral to visual stimuli. Contralateral tDCS significantly alleviated the orientation crowding effect at two different eccentricities and the letter crowding effect. This alleviation was absent after sham or ipsilateral stimulation and could not be fully explained by the performance improvement with the isolated targets. These findings demonstrated that offline tDCS was effective in alleviating visual crowding across different visual eccentricities and tasks, therefore

Citation: Chen, G., Zhu, Z., He, Q., & Fang, F. (2021). Offline transcranial direct current stimulation improves the ability to perceive crowded targets. *Journal of Vision*, 21(2):1, 1–10. https://doi.org/10.1167/jov.21.2.1.
tDCS can improve peripheral vision in crowded scenes and reduce visual crowding.

We conducted a single-blind sham-controlled study to investigate whether tDCS could alleviate visual crowding at different visual eccentricities and with different visual tasks. Specifically, subjects were instructed to perform an orientation discrimination task or a letter identification task with isolated and crowded targets in the periphery, before and immediately after applying 20 minutes of anodal tDCS to the visual cortex of the hemisphere contralateral or ipsilateral to visual stimuli. In experiment 1, we investigated whether tDCS was able to reduce orientation crowding. Experiment 2 was designed to examine whether the tDCS effect found in experiment 1 (if there was any) could be generalized to a smaller eccentricity. Furthermore, experiment 3 tested whether the tDCS effect could be found with a completely different task – letter identification. We hypothesized that contralateral anodal tDCS was able to improve peripheral vision in crowded scenes and effectively alleviate visual crowding across different visual eccentricities and with different visual tasks.

**Methods**

**Participants**

There were totally 118 subjects in 3 experiments (experiment 1: \( n = 45 \), 23 men, 18 to 32 years old; experiment 2: \( n = 45 \), 21 men, 18 to 26 years old; and experiment 3: \( n = 28 \), 16 men, 18 to 32 years old). In each experiment, subjects were divided into three groups at random - the contralateral group (visual stimuli were presented in the hemifield contralateral to the stimulated hemisphere), the ipsilateral group (visual stimuli were presented in the hemifield ipsilateral to the stimulated hemisphere), and the sham group (subjects received sham electrical stimulation). There were 15 subjects in each group in experiments 1 and 2. In experiment 3, there were 9 subjects in the contralateral group and the ipsilateral group each, and 10 subjects in the sham group. All subjects were right-handed, reported normal or corrected-to-normal vision, and had no known neurological or visual disorders. Exclusion criteria included personal or family history of mental illness or neurological disorders (e.g. epilepsy), drug abuse, pregnancy, and metallic implants. They all gave written, informed consent in accordance with the procedures and protocols approved by the human subject review committee of Peking University. This study adhered to the Declaration of Helsinki.

**Apparatus**

In all three experiments, visual stimuli were displayed on a Sony Trinitron monitor (refresh rate: 100 Hz;
spatial resolution: $1024 \times 768$; size: 19 inch) with a gray background (luminance: 47.59 cd/m$^2$). Particularly, visual stimuli used in experiment 3 were rendered with a video card with an 8-bit input resolution and a 14-bit output resolution using Cambridge Research System Bits++. The output luminance of the monitor was linearized using a look-up table in conjunction with photometric readings from a colorCAL colorimeter (Cambridge Research System). The viewing distance was 70 cm, and we used a head and chin rest to stabilize subjects’ head position. Subjects were asked to maintain fixation on a black dot at the center of the display and their eye positions were monitored with an Eyelink 1000 Plus eye-tracking system during the experiments. Subjects could maintain their fixation very well across experiments and stimulation conditions.

**Stimuli and design**

All experiments consisted of three phases: pre-stimulation test (Pre), tDCS phase, and post-stimulation test (Post; Figure 1A).

In experiment 1, subjects first received practice, which made sure they well understood the task. During the two test phases, subjects’ orientation discrimination thresholds were measured with two test stimuli: the isolated target (only the target grating appeared) and the crowded target (the target grating and flanker gratings appeared simultaneously; the first column in Figure 1B). In the isolated condition, subjects were required to perform an orientation discrimination task with the target grating (radius: 1.75 degrees; spatial frequency: 2 cycles/degree; Michelson contrast: 1; mean luminance: 47.59 cd/m$^2$; eccentricity: 7.25 degrees) at an orientation of $\theta$ presented in either the upper-left or the upper-right visual quadrant, counterbalanced across subjects. For each subject, the orientation $\theta$ was chosen randomly from two perpendicular orientations (67.5 degrees and 157.5 degrees relative to the horizontal axis) prior to the experiment and was fixed throughout the whole experiment. We used these two orientations because they do not appear in daily life frequently, avoiding any potential ceiling effect. The crowded condition was similar to the isolated condition, except there were two flankers positioned abutting the target in the radial direction with respect to fixation. The flankers were identical to the target but with randomized orientations. The center-to-center distance between the target and flankers was 3.5 degrees. Ten QUEST staircases (Watson & Pelli, 1983) of 40 trials, 5 for each test stimulus, were completed alternately. In each trial, 2 targets with orientations of $\theta$ and $\theta \pm \Delta \theta$ were presented successively for 200 ms each and were separated by a 600-ms blank interval (Figure 1C). The temporal order of these two targets was randomized. Subjects were asked to make a two-alternative forced choice (2-AFC) judgment of the orientation of the second target relative to the first one (clockwise or counterclockwise). The next trial began 800 to 1200 ms after subjects made a key press. The $\Delta \theta$ varied trial by trial and was controlled by the QUEST staircase to estimate subjects’ discrimination thresholds at 75% correct. No feedback was provided during Pre or Post. Each test phase lasted approximately 30 minutes.

The experimental design and visual stimuli in experiment 2 were similar to those in experiment 1 except that both the eccentricity of the target and the radius of the gratings were reduced to 60 percent of those in experiment 1. The target grating was presented at 4.35 degrees eccentricity, and its radius was reduced to 1.05 degrees (the second column in Figure 1B). The target and flankers were still abutting and their center-to-center distance was 2.1 degrees. It was noteworthy that the target spanned 5.5 degrees to 9 degrees eccentricity in the visual field in experiment 1, and 3.3 degrees to 5.4 degrees eccentricity in experiment 2, meaning that there was no spatial overlap between them.

In experiment 3, there were 10 Sloan letters (C, D, H, K, N, O, R, S, V, and Z; 3 degrees × 3 degrees) used as visual stimuli to measure subjects’ letter identification thresholds. The target letter, randomly selected from the above letter set, was presented at 10 degrees eccentricity on the horizontal meridian of either the left or the right visual field, counterbalanced across subjects (the third column in Figure 1B). Similar to experiment 1, during each test phase, 10 QUEST staircases of 40 trials, 5 for each test stimulus (the isolated letter and the crowded letter), were completed alternately. In each trial of the isolated condition, the target letter was presented alone for 250 ms followed by a 500-ms blank interval, and then subjects were instructed to identify the target by making a key press (Figure 1D). The Weber contrast between the target letter and its background, (letter luminance - background luminance) / background luminance, varied trial by trial and was controlled by the QUEST staircase to estimate subjects’ contrast thresholds for letter identification at 55% correct (the 55% correct rate for the 10-alternative forced choice in experiment 3 rendered the task difficulty in experiment 3 equivalent to those in experiments 1 and 2). In the crowded condition, two flankers were positioned abutting the target in the radial direction with respect to fixation and were randomly selected from the above letter set. The Weber contrast between flankers and the background was fixed at 0.33 throughout the experiment. The center-to-center distance between the target and flankers was 3 degrees.

**Transcranial direct current stimulation**

The tDCS was delivered by a battery-powered, constant current stimulator (DC-Stimulator PLUS; neuroConn) and a pair of conductive rubber electrodes
Figure 1. Experimental designs and stimuli. (A) All experiments consisted of three phases: pre-stimulation test (Pre), tDCS phase, and post-stimulation test (Post). (B) Visual stimuli in experiments 1 to 3. Black dots indicate the fixation point. In experiments 1 and 2, oriented gratings were presented in the upper-left or the upper-right (not shown in this figure) quadrant. In experiment 3, letters were presented on the horizontal meridian of either the left or the right (not shown in this figure) visual field. (C) Schematic description of a two-alternative forced choice trial in a QUEST staircase for measuring the orientation discrimination threshold with a crowded grating in experiments 1 and 2. (D) Schematic description of a 10-alternative forced choice trial in a QUEST staircase for measuring the contrast threshold for identifying crowded letters in experiment 3.

(size: 35 cm²). The electrodes were enclosed in saline-soaked sponges and held in place by two elastic bands. The anodal electrode was placed over the visual cortex in either the left or the right hemisphere (P1 or P2 in the international 10–20 electroencephalogram [EEG] system), whereas the cathodal electrode was placed over the cheek ipsilateral to the anodal electrode. The electrical current flowed from the anode to the cathode (i.e. from visual cortex to the ipsilateral cheek). The impedance was kept below 10 kΩ. In the contralateral and the ipsilateral groups, the electrical current was ramped up to 2 mA over 10 seconds, held at 2 mA for 20 minutes, and then ramped down to zero over 10 seconds. In the sham group, the electrical current was ramped up to 2 mA over 10 seconds at the beginning of the 20-minute phase, but held at 2 mA...
for only 15 seconds. The stimulation parameters in our study were adopted from a previous study (Reinhart, Xiao, McClenahan, & Woodman, 2016). Reinhart and colleagues found that 20 minutes of 2.0 mA (but not 1.0 and 1.5 mA) anodal tDCCS could significantly improve spatial vision.

Data analysis

For each test stimulus, subjects’ performance at Pre and Post was quantified as the mean threshold from five QUEST staircases. Subjects’ performance improvement with a test stimulus from Pre to Post was calculated as (pre-stimulation threshold – post-stimulation threshold) / pre-stimulation threshold × 100%.

Repeated-measures ANOVAs, with test (Pre versus Post) as a within-subject factor and group (contralateral versus ipsilateral versus sham) as a between-subject factor, and two-tailed t-tests were used to test whether there was any significant difference in threshold and improvement. It should be pointed out that, in all three experiments, for each test stimulus, no significant threshold difference at Pre was found among the three groups of subjects (1-way ANOVA, all p values > 0.18).

Results

Experiment 1: tDCCS effects on isolated and crowded orientation discrimination at a large eccentricity

In the isolated condition, a repeated-measures ANOVA revealed that neither the main effect of test or group (test: F(1, 42) = 0.07, p = 0.79; group: F(2, 42) = 0.16, p = 0.86), nor the interaction between test and group (F(2, 42) = 0.30, p = 0.74) was significant, suggesting that offline tDCCS had little effect on isolated orientation discrimination (Figure 2A).

In the crowded condition, however, we observed a significant main effect of test (F(1, 42) = 13.42, p = 0.001) and a significant interaction between test and group (F(2, 42) = 13.89, p < 0.001), yet the main effect of group (F(2, 42) = 0.09, p = 0.91) was not significant. A planned t-test showed that in the contralateral group, the orientation discrimination threshold at Post (15.41 ± 0.95 degrees, X ± Y indicates the mean ± SEM) was significantly reduced compared with that at Pre (20.13 ± 1.18 degrees, t(14) = 6.68, p < 0.001; Figure 2B). No such effect was observed in the ipsilateral group or the sham group.

Then, subjects’ performance improvements in orientation discrimination from Pre to Post were analyzed (Figure 2C). In the contralateral group, the improvement with the crowded gratings (22.60 ± 3.34%) was significant (t(14) = 6.76, p < 0.01), but not with the isolated gratings (−0.46 ± 6.79%, t(14) = −0.07, p = 0.95). And the improvement with the crowded gratings was greater than that with the isolated gratings (t(14) = 3.415, p = 0.004). There was no significant improvement with the isolated or crowded gratings in the ipsilateral group or the sham group (all t-values < 0.77, p values > 0.46). Notably, in the crowded condition, the improvement in the contralateral group was significantly larger than those in the ipsilateral and the sham groups (contralateral > ipsilateral, t(28) = 3.38, p < 0.001; contralateral > sham, t(28) = 3.81, p < 0.001).

The findings in experiment 1 revealed that offline tDCCS contralateral to the visual stimuli could improve subjects’ orientation discrimination performance with the crowded gratings, but not with the isolated gratings. No significant improvement was observed in the ipsilateral group or the sham group.

Experiment 2: tDCCS effects on isolated and crowded orientation discrimination at a small eccentricity

In the isolated condition, a repeated-measures ANOVA revealed a significant interaction between test
and group \(F(2, 42) = 4.69, p = 0.01\), but the main effect of test \(F(1, 42) = 1.28, p = 0.26\) or group \(F(2, 42) = 0.59, p = 0.56\) was not significant. A planned \(t\)-test showed that the orientation discrimination threshold (8.64 ± 0.58 degrees) at Post was significantly lower than that at Pre (10.16 ± 0.75 degrees) in the contralateral group \((t(14) = 3.05, p < 0.01; \text{Figure 3A}).\)

In the crowded condition, a similar ANOVA revealed a significant main effect of test \(F(1, 42) = 19.34, p < 0.001\), and a significant interaction between test and group \(F(2, 42) = 6.83, p < 0.01\). However, the main effect of group was not significant \(F(2, 42) = 0.36, p = 0.70\). A planned \(t\)-test showed that in the contralateral group, the orientation discrimination threshold at Post (13.70 ± 1.42 degrees) was significantly lower than that at Pre (18.72 ± 1.32 degrees) \((t(14) = 7.23, p < 0.001; \text{Figure 3B}).\)

Regarding performance improvement, in the contralateral group, the improvements with the isolated (12.97 ± 3.82%) and crowded (25.90 ± 2.51%) gratings were both statistically significant (isolated: \(t(14) = 3.40, p < 0.01\); crowded: \(t(14) = 10.32, p < 0.001\)), and the improvement with the crowded gratings was greater than that with the isolated gratings \((t(14) = 2.75, p = 0.016; \text{Figure 3C}).\)

Nevertheless, no significant improvement with the isolated or crowded gratings was found in the ipsilateral group or the sham group (all \(t\)-values < 1.78, \(p\) values > 0.10). We also found in both the isolated and crowded conditions, the improvements in the contralateral group were significantly larger than those in the ipsilateral and the sham groups (isolated: contralateral > ipsilateral, \(t(28) = 2.47, p = 0.02\); contralateral > sham, \(t(28) = 3.00, p = 0.006\); crowded: contralateral > ipsilateral, \(t(28) = 3.12, p = 0.004\); contralateral > sham, \(t(28) = 3.68, p < 0.001\)).

The results in experiment 2 were similar to those in experiment 1, demonstrating the ability of tDCS to alleviate the crowding effect across different visual eccentricities. Additionally, the contralateral tDCS could also improve orientation discrimination performance with the isolated targets. But the improvement with the crowded gratings was greater than that with the isolated gratings, suggesting that tDCS had a more prominent effect on promoting subjects’ performance with the crowded targets.

**Experiment 3: tDCS effects on isolated and crowded letter identification**

In the isolated condition, a repeated-measures ANOVA on contrast threshold for letter identification, showed that neither the main effect of test or group (test: \(F(1, 25) = 1.25, p = 0.27\); group: \(F(2, 25) = 2.26, p = 0.03\), nor the interaction between test and group \((F(2, 25) = 0.484, p = 0.622)\) was significant, suggesting that tDCS had little effect on isolated letter identification (Figure 4A).

In the crowded condition, however, a similar ANOVA showed a significant main effect of test \((F(1, 25) = 12.70, p < 0.01)\) and a significant interaction between test and group \((F(2, 25) = 4.80, p = 0.02)\), but the main effect of group \((F(2, 25) = 3.17, p = 0.06)\) was not significant. A planned \(t\)-test showed that the contrast threshold for letter identification at Post (4.79 ± 0.35%) was lower than that at Pre (6.24 ± 0.31%) in the contralateral group \((t(8) = 5.00, p < 0.001; \text{Figure 4B}).\) However, not in the ipsilateral group or the sham group.

Regarding performance improvement, in the contralateral group, we found a significant improvement with the crowded letters \((23.03 ± 4.70\%, t(8) = 4.90, p = 0.001)\), but not with the isolated letters \((5.25 ± 4.94\%, t(8) = 1.06, p = 0.32).\) The improvement with the crowded letters was significantly larger than that with the isolated letters \((t(8) = 3.567, p = 0.007; \text{Figure 4C}).\)

In the ipsilateral and the sham groups, there was no significant improvement with the isolated or crowded letters (all \(t\)-values < 1.01, \(p\) values > 0.35). Furthermore, we found that in the crowded condition, the improvement in the contralateral group was significantly larger than those in the ipsilateral and

---

**Figure 3. Results of experiment 2. Orientation discrimination threshold with the isolated (A) and crowded (B) gratings at Pre and Post. (C) Percent of improvements in discrimination performance with the isolated and crowded gratings from Pre to Post. \(*p < 0.05, **p < 0.01, ***p < 0.001; \text{error bars denote 1 SEM across subjects.}\)**
the sham groups (contralateral > ipsilateral, \( t(16) = 3.61, p = 0.002 \); contralateral > sham, \( t(17) = 2.54, p = 0.02 \)).

These findings demonstrated that the contralateral tDCS could also improve performance in the crowded letter identification task and suggested that the ability of tDCS to reduce visual crowding might apply similarly to various visual tasks.

**Discussion**

In the current study, we conducted three experiments to investigate whether tDCS was capable of alleviating visual crowding. We found that 20 minutes of anodal tDCS to the visual cortex of the hemisphere contralateral to the visual stimuli improved peripheral vision in crowded scenes and particularly alleviated the crowding effect, regardless of different visual eccentricities and tasks. To our knowledge, this is the first study substantiating that tDCS can effectively alleviate visual crowding.

Our study reveals that, compared with perceptual learning, tDCS has pronounced advantages in alleviating visual crowding (i.e. higher efficiency and lower attentional engagement), which can meet the demands for clinical application (Herpich et al., 2019). In a typical perceptual learning protocol, both intensive training and sustained attentional engagement are required to obtain considerable improvement in discriminating crowded targets (Zhu, Fan, & Fang, 2016; He, Wang, & Fang, 2019), whereas subjects just passively received electrical stimulation during the tDCS phase in our study. Therefore, our study demonstrated that tDCS is an effective and rapid way to alleviate visual crowding.

To optimize the modulatory effect of tDCS on visual crowding, we had carefully considered the stimulation protocol in our study. First, although the effects of tDCS on visual function are mixed in previous studies (Costa et al., 2015; Reinhart, Xiao, McClenahan, & Woodman, 2016; He, Lin, Zhao et al., 2019), anodal tDCS was found to be more effective when applied before task execution than applied during task execution (Pirulli, Fertonani, & Miniussi, 2013; Barbieri, Negrini, Nitsche, & Rivolta, 2016). Therefore, offline tDCS was adopted. Second, regarding the stimulation site, we chose to stimulate visual cortex because it plays a key role in visual crowding (Bi, Cai, Zhou, & Fang, 2009; Chen et al., 2014; Millin, Arman, Chung, & Tjan, 2014; He, Wang, & Fang, 2019). For example, the C1 component, the earliest event-related potential (ERP) component, was found to be associated with the magnitude of the crowding effect, and the largest C1 amplitudes were observed at posterior electrodes, including P1 and P2 (Chen et al., 2014). In addition, it was also shown that tDCS at P1 and P2 could significantly modulates spatial vision in the parafoveal visual field (Reinhart et al., 2016). Therefore, we chose to deliver tDCS at P1 or P2 in the current study.

We propose two possible explanations for the tDCS effect on visual crowding. One is that anodal tDCS may alleviate visual crowding by reducing the concentration of GABA (\( \gamma \)-aminobutyric acid), a primary inhibitory neurotransmitter in the brain (Stagg et al., 2009). The GABA concentration reduction has been shown to be associated with reduced latent inhibitory connections in human cortex (Barron et al., 2016) and an improved ability to detect targets from a clutter (Frangou, Correia, & Kourtzi, 2018). Here, anodal tDCS may reduce inhibitory interactions between neuronal populations responding to the target and flankers, therefore alleviating visual crowding.

A second explanation is that tDCS may alleviate visual crowding by activating the attentional network and improving the spatial resolution of attention. Given that the size of electrodes we used here was relatively large, it was possible that other sites adjacent
to our target brain region were also stimulated (e.g. posterior parietal cortex [PPC], a core brain area of the attentional network; Okamoto et al., 2004; Roe et al., 2016; Falcone, Wada, Parasuraman, & Callan, 2018). Therefore, the tDSC effect found in this study might also result from the activation of the attentional network, which could improve the attention resolution and therefore alleviate visual crowding (He, Cavanagh, & Intriligator, 1996; Chen et al., 2014; Herzog, Sayim, Chicherov, & Manassi, 2015; He, Wang, & Fang, 2019). It might be argued that the alleviation of visual crowding can be simply explained by some test-retest effects (i.e. practice at Pre and Post). However, such alleviation was not observed in the ipsilateral group or the sham group, which rules out this explanation.

In the current study, tDSC not only alleviated visual crowding across three experiments, but also improved the performance in the isolated orientation discrimination task at a small eccentricity in experiment 2. As mentioned before, in experiment 2, the target spanned 3.3 degrees to 5.4 degrees in the visual field. In those studies showing that transcranial electrical stimulation was able to boost task performance in (isolated) orientation discrimination tasks (Fertonani, Pirulli, & Miniussi, 2011; Pirulli, Fertonani, & Miniussi, 2013; Sczesny-Kaiser et al., 2016), visual stimuli were presented within 4 degrees to 5 degrees eccentricity in the visual field, which fell into the eccentricity range of the target in experiment 2. Therefore, our finding in experiment 2 is in line with previous studies (Pirulli, Fertonani, & Miniussi, 2013; Sczesny-Kaiser et al., 2016).

Recent studies showed that transcranial alternating current stimulation (tACS) and transcranial random noise stimulation (tRNS) could also alleviate visual crowding (Contemori, Trotter, Cottereau, & Maniglia, 2019; Battaglini, Ghiani, Casco, & Ronconi, 2020). However, the neural mechanism of the tDSC effect on visual crowding might be different from other transcranial electrical stimulation techniques, which should be explored in the future. In our study, only anodal stimulation was applied to visual cortex. It would be useful to include a cathodal stimulation condition, although meta-analysis studies have shown that the effects of cathodal tDSC on cognitive functions are nonsignificant compared with sham stimulation (Dedoncker, Brunoni, Baeken & Vanderhasselt, 2016a; Dedoncker, Brunoni, Baeken & Vanderhasselt, 2016b; Salehinejad, Wischnewski, Nejati, Vicario, & Nitsche, 2019). Making comparison between anodal and cathodal stimulations will provide a more comprehensive understanding of both tDSC and visual crowding.

In addition to exploring the neural mechanisms of the effect of tDSC on visual crowding, it is also important to apply our current findings to clinical practice. Previous studies found that tDSC could improve visual functions of patients with amblyopia, such as visual acuity (Bocci et al., 2018) and contrast sensitivity (Ding et al., 2016). We speculate that tDSC with proper parameters and design might be able to alleviate visual crowding in patients with amblyopia as well. Therefore, our findings might provide a promising neurorehabilitation way for patients with visual impairments or deficits.

**Conclusions**

We found that tDSC was effective in alleviating visual crowding across different visual eccentricities and tasks. These findings provide not only a promising way to alleviate visual crowding rapidly, but also a guide to clinical neurorehabilitation for patients with visual impairments or deficits.

**Keywords:** visual crowding, transcranial direct current stimulation (tDSC), visual cortex, brain stimulation, cortical plasticity

**Acknowledgments**

Supported by the National Natural Science Foundation of China (31930053, 31671168, and 31421003), Beijing Municipal Science and Technology Commission (Z181100001518002), and Beijing Academy of Artificial Intelligence (BAAI).

Commercial relationships: none.
Corresponding author: Fang Fang.
Email: ffang@pku.edu.cn.
Address: School of Psychological and Cognitive Sciences, Peking University, Beijing, People’s Republic of China.

*GC and ZZ contributed equally to this work.

**References**

Antal, A., Nitsche, M. A., & Paulus, W. (2001). External modulation of visual perception in humans. *NeuroReport, 12*(16), 3553–3555.

Barbieri, M., Negrini, M., Nitsche, M. A., & Rivolta, D. (2016). Anodal-tDCS over the human right occipital cortex enhances the perception and memory of both faces and objects. *Neuropsychologia, 81*, 238–244.

Barron, H. C., Vogels, T. P., Emir, U. E., Makin, T. R., O’Shea, J., & Clare, S. et al. (2016). Unmasking
latent inhibitory connections in human cortex to reveal dormant cortical memories. *Neuron*, 90, 191–203.

Battaglini, L., Noventa, S., & Casco, C. (2017). Anodal and cathodal electrical stimulation over V5 improves motion perception by signal enhancement and noise reduction. *Brain Stimulation*, 10(4), 773–779.

Battaglini, L., Ghiani, A., Casco, C., & Ronconi, L. (2020). Parietal tACS at beta frequency improves vision in a crowding regime. *NeuroImage*, 208, 116451.

Bi, T., Cai, P., Zhou, T., & Fang, F. (2009). The effect of crowding on orientation-selective adaptation in human early visual cortex. *Journal of Vision*, 9(11):13, 1–10.

Bocci, T., Nasini, F., Caleo, M., Restani, L., Barlascio, D., & Ardolino, G. et al. (2018). Unilateral application of cathodal tDCS reduces transcallosal inhibition and improves visual acuity in amblyopic patients. *Frontiers in Behavioral Neuroscience*, 12, 109.

Chen, J., He, Y., Zhu, Z., Zhou, T., Peng, Y., Zhang, X., … Fang, F. (2014). Attention-dependent early cortical suppression contributes to crowding. *Journal of Neuroscience*, 34(32), 10465–10474.

Chung, S. T. L. (2007). Learning to identify crowded letters: Does it improve reading speed? *Vision Research*, 47(25), 3150–3159.

Contemori, G., Trotter, Y., Cottereau, B. R., & Maniglia, M. (2019). tRNS boosts perceptual learning in peripheral vision. *Neuropsychologia*, 125, 129–136.

Costa, T. L., Hamer, R. D., Nagy, B. V., Barboni, M. T. S., Gualtieri, M., Boggio, P. S., … Ventura, D. F. (2015). Transcranial direct current stimulation can selectively affect different processing channels in human visual cortex. *Experimental Brain Research*, 233(4), 1213–1223.

Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M. A. (2016a). The effect of the interval-between-sessions on prefrontal transcranial direct current stimulation (tDCS) on cognitive outcomes: a systematic review and meta-analysis. *Journal of Neural Transmission*, 123(10), 1159–1172.

Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M.A. (2016b). A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex in healthy and neuropsychiatric samples; Influence of stimulation parameters. *Brain Stimulation*, 9(4), 501–517.

Ding, Z., Li, J., Spiegel, D. P., Chen, Z., Chan, L., & Luo, G. et al. (2016). The effect of transcranial direct current stimulation on contrast sensitivity and visual evoked potential amplitude in adults with amblyopia. *Scientific Reports*, 6, 19280.

Falcone, B., Wada, A., Parasuraman, R., & Callan, D. E. (2018). Individual differences in learning correlate with modulation of brain activity induced by transcranial direct current stimulation. *PLoS One*, 13(5), e0197192.

Fertonani, A., Pirulli, C., & Miniussi, C. (2011). Random noise stimulation improves neuroplasticity in perceptual learning. *Journal of Neuroscience*, 31(43), 15416–15423.

Frangou, P., Correia, M., & Kourtzi, Z. (2018). GABA, not BOLD, reveals dissociable learning-dependent plasticity mechanisms in the human brain. *eLife*, 7, e35854.

He, D., Wang, Y., & Fang, F. (2019). The critical role of V2 population receptive fields in visual orientation crowding. *Current Biology*, 29(13), 2229–2236.

He, Q., Lin, B. R., Zhao, J., Shi, Y. Z., Yan, F. F., & Huang, C. B. (2019). No effects of anodal transcranial direct current stimulation on contrast sensitivity function. *Restorative Neurology and Neuroscience*, 37(2), 109–118.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, 383, 334–337.

Herzog, M. H., Sayim, B., Chicherov, V., & Manassi, M. (2015). Crowding, grouping, and object recognition: A matter of appearance. *Journal of Vision*, 15(6):5, 1–18.

Herpich, F., Melnick, M. D., Agosta, S., Huxlin, K. R., Tadin, D., & Battelli, L. (2019). Boosting learning efficacy with noninvasive brain stimulation in intact and brain-damaged humans. *Journal of Neuroscience*, 39(28), 5551–5561.

Huckauf, A., & Nazir, T. A. (2007). How odgcrnwi becomes crowding: Stimulus-specific learning reduces crowding. *Journal of Vision*, 7(2):18, 1–12.

Hussain, Z., Webb, B. S., Astle, A. T., & McGraw, P. V. (2012). Perceptual learning reduces crowding in amblyopia and in the normal periphery. *Journal of Neuroscience*, 32(2), 474–480.

Le Dantec, C. C., Melton, E. E., & Seitz, A. R. (2012). A triple dissociation between learning of target, distractors, and spatial contexts. *Journal of Vision*, 12(2):5, 1–12.

Levi, D. M. (2008). Crowding-An essential bottleneck for object recognition: A mini-review. *Vision Research*, 48(5), 635–654.

Millin, R., Arman, A. C., Chung, S. T. L., & Tjan, B. S. (2014). Visual crowding in V1. *Cerebral Cortex*, 24(12), 3107–3115.
Nitsche, M., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology, 527*(3), 633–639.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., ... & Dan, I. (2004). Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10-20 system oriented for transcranial functional brain mapping. *NeuroImage, 21*(1), 99–111.

Paulus, W. (2011). Transcranial electrical stimulation (tES - tDCS; tRNS, tACS) methods. *Neuropsychological Rehabilitation, 21*(5), 602–617.

Pirulli, C., Fertonani, A., & Miniussi, C. (2013). The role of timing in the induction of neuromodulation in perceptual learning by transcranial electric stimulation. *Brain Stimulation, 6*(4), 683–689.

Raveendran, R. N., Tsang, K., Tiwana, D., Chow, A., & Thompson, B. (2020). Anodal transcranial direct current stimulation reduces collinear lateral inhibition in normal peripheral vision. *PLoS One, 15*(5), e0232276.

Reinhart, R. M. G., Xiao, W., McLenahan, L. J., & Woodman, G. F. (2016). Electrical stimulation of visual cortex can immediately improve spatial vision. *Current Biology, 26*(14), 1867–1872.

Roe, J. M., Nesheim, M., Mathiesen, N. C., Moberget, T., Alnæs, D., & Sneve, M. H. (2016). The effects of tDCS upon sustained visual attention are dependent on cognitive load. *Neuropsychologia, 80*, 1–8.

Salehinejad, M. A., Wischnerwski, M., Nejati, V., Vicario, C. M., & Nitsche, M. A. (2019). Transcranial direct current stimulation in attention-deficit hyperactivity disorder: A meta-analysis of neuropsychological deficits. *PLoS One, 14*(4), e0215095.

Sczesny-Kaiser, M., Beckhaus, K., Dinse, H. R., Schwenkreis, P., Tegenthoff, M., & Höffken, O. (2016). Repetitive transcranial direct current stimulation induced excitability changes of primary visual cortex and visual learning effects—A pilot study. *Frontiers in Behavioral Neuroscience, 10*, 106.

Spiegel, D. P., Hansen, B. C., Byblow, W. D., & Thompson, B. (2012). Anodal transcranial direct current stimulation reduces psychophysically measured surround suppression in the human visual cortex. *PLoS One, 7*(5), e36220.

Stagg, C. J., Best, J. G., Stephenson, M. C., O'Shea, J., Wylezinska, M., Kineses, Z. T., ... & Johansen-Berg, H. (2009). Polarity-sensitive modulation of cortical neurotransmitters by transcranial stimulation. *Journal of Neuroscience, 29*(16): 5202–5206.

Watson, A. B., & Pelli, D. G. (1983). Quest: A Bayesian adaptive psychometric method. *Perception & Psychophysics, 33*(2), 113–120.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences, 15*(4), 160–168.

Zhu, Z., Fan, Z., & Fang, F. (2016). Two-stage perceptual learning to break visual crowding. *Journal of Vision, 16*(6), 16.