Neuropsychologia 189 (2023) 108663

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Investigating the role of the fusiform face area and occipital face area using multifocal transcranial direct current stimulation

Siew Kei Kho [a,b,*], David R.T. Keeble [b], Hoo Keat Wong [b], Alejandro J. Estudillo [a,b,**]

[a] Department of Psychology, Bournemouth University, UK
[b] School of Psychology, University of Nottingham, Malaysia

ARTICLE INFO

Keywords:
Transcranial electrical stimulation
Multifocal stimulation
Brain stimulation
Face recognition
Fusiform gyrus

ABSTRACT

The functional role of the occipital face area (OFA) and the fusiform face area (FFA) in face recognition is inconclusive to date. While some research has shown that the OFA and FFA are involved in early (i.e., featural processing) and late (i.e., holistic processing) stages of face recognition respectively, other research suggests that both regions are involved in both early and late stages of face recognition. Thus, the current study aims to further examine the role of the OFA and the FFA using multifocal transcranial direct current stimulation (tDCS). In Experiment 1, we used computer-generated faces. Thirty-five participants completed whole face and facial features (i.e., eyes, nose, mouth) recognition tasks after OFA and FFA stimulation in a within-subject design. No difference was found in recognition performance after either OFA or FFA stimulation. In Experiment 2 with 60 participants, we used real faces, provided stimulation following a between-subjects design and included a sham control group. Results showed that FFA stimulation led to enhanced efficiency of facial features recognition. Additionally, no effect of OFA stimulation was found for either facial feature or whole face recognition. These results suggest the involvement of FFA in the recognition of facial features.

1. Introduction

Faces are thought to be a special category of stimuli as they are recognized differently compared to objects (McKone et al., 2007; Robbins and McKone, 2007, although see alternative reviews, Bukach et al., 2006; Burns et al., 2019; Gauthier and Bukach, 2007). Previous work has also identified several brain areas specialized for face processing which include the fusiform face area (FFA) located in the lateral fusiform gyrus (Kanwisher et al., 1997; McCarthy et al., 1997) and the occipital face area (OFA) located in the lateral inferior occipital gyri (Gauthier et al., 2000). Despite the interactive nature of the FFA and the OFA (Ishai, 2008; Kim et al., 2006), these areas are anatomically and functionally dissociated, as evidenced by patients with OFA lesions who still exhibit FFA activation (Rossion et al., 2003; Steeves et al., 2006). Neuropsychological models of face processing (e.g., Haxby et al., 2000) suggest that the OFA is involved in the early stages of face processing (i.e., representation of independent facial features) whereas the FFA is involved in the late stages of face processing (i.e., representation of facial identity).

In line with this, several studies have demonstrated the involvement of the OFA in the representation of independent facial features and the FFA in the representation of whole faces (Fox et al., 2009; Nichols et al., 2010; Pitcher et al., 2007; Schiltz et al., 2010). For instance, transcranial magnetic stimulation (TMS) of the OFA has been shown to disrupt the discrimination of independent facial features (Pitcher et al., 2007). Additionally, a functional magnetic resonance imaging (fMRI) study has indicated that the OFA presented greater activation for a single feature of the face (e.g., eyes) over a combination of features (e.g., eyes and mouth presented together) (Dachille et al., 2012). Other fMRI studies have also shown that the OFA was responsive to independent facial features (Fox et al., 2009; Nichols et al., 2010) irrespective of whether the features were arranged in a scrambled or normal configuration (Liu et al., 2010).

The FFA, in contrast, was more responsive to features that were arranged in a normal configuration compared to a scrambled configuration (Liu et al., 2010; Zhang et al., 2012). In terms of whole face representation, using measures of holistic face processing such as the face inversion task (Yovel and Kanwisher, 2005) and the composite face task (Schiltz et al., 2010; Schiltz and Rossion, 2006), it has been found that the FFA showed an increased response to holistically intact faces (i.

* Corresponding author. Bournemouth University, UK.
** Corresponding author. Bournemouth University, UK.
E-mail addresses: kkho@bournemouth.ac.uk (S.K. Kho), aestudillo@bournemouth.ac.uk (A.J. Estudillo).

https://doi.org/10.1016/j.neuropsychologia.2023.108663
Received 6 March 2023; Received in revised form 16 August 2023; Accepted 17 August 2023
Available online 22 August 2023

e., upright faces and top-half and bottom-half aligned faces) compared to the OFA (Nichols et al., 2010). Additionally, D. F., a patient with bilateral OFA lesions but intact FFA, showed close-to-normal face categorization performance, suggesting relatively preserved holistic processing (Steeves et al., 2006). Similarly, other patients studies have revealed that damage to the FFA can hinder configural face processing (i.e., spacing between facial features) (Barton et al., 2002). Other than the measures of holistic processing, the FFA was also found to be responsive to changes in identity or expression (Fox et al., 2009), which involve whole face representation.

Conversely, several studies have found opposing findings such as the involvement of the OFA in holistic face processing (Bona et al., 2016; Rhodes et al., 2009; Rivolta et al., 2012) and facial identity processing (Ambrus et al., 2017; Xu and Biederman, 2010) (which both involve whole face representation) and the involvement of the FFA in the perception of individual facial feature (Yovel and Kanwisher, 2004). For example, an fMRI study has shown that both the OFA and the FFA support configural face processing as both regions responded more strongly to faces presented with various spacings between facial features compared to a repeated presentation of the same face (Rhodes et al., 2009). Furthermore, it has been shown that TMS and anodal transcranial direct current stimulation (tDCS) to the OFA disrupts Mooney face detection (Bona et al., 2016; Renzi et al., 2015). Mooney faces are drawings of faces presented in solid black and white which show incomplete representation of faces (Mooney, 1957; Moscovitch et al., 1997). Processing Mooney faces requires perceiving them as wholes because they only contain a partial representation of the faces (Latinus and Taylor, 2005). Hence, the disruption of Mooney face detection after TMS and tDCS to the OFA further supports the involvement of OFA in holistic face processing. TMS over the OFA has also been shown to impair facial identification and semantic processing of facial identity which involve whole face representations (Ambrus et al., 2017, 2019; Eick et al., 2020; Kadosh et al., 2010; Solomon-Harris et al., 2013).

Additionally, an fMRI study has demonstrated that the FFA was not only involved in holistic face processing, but also in facial features perception as it was found that the FFA responded similarly to configural (i.e., spacing among facial features) and featural (i.e., shapes of eyes and mouth in faces) changes of faces (Yovel and Kanwisher, 2004). However, as the featural changes were made in the context of a whole face, the FFA activation could reflect a change of identity, rather than featural processing itself. Overall, these findings suggest that the OFA and the FFA may have overlapping roles in face processing where both regions are involved in the representation of facial features together with whole faces.

The present study aims to further explore the functional role of the OFA and the FFA on face recognition using multifocal tDCS. TDCS is a non-invasive brain stimulation technique where a low-intensity electrical current is delivered between two or more electrodes attached to the scalp in order to modulate neuronal excitability (Reed and Cohen Kadosh, 2018). Previous work has suggested that anodal tDCS could cause neuronal depolarization and lead to an increase in the neurons' firing rate and excitability (Nitsche and Paulus, 2000; Yamada and Sumiyoshi, 2021). Such an increment in the neurons' excitability induced by anodal tDCS usually results in cognitive enhancement (Jacobson et al., 2012). Previous studies have shown that applying tDCS to the occipital region could enhance face processing (see Estudillo et al., 2023; Gonzalez-Perez et al., 2019; Romanska et al., 2015 for similar results with a different stimulation method), including face memory (Barbieri et al., 2016; Brunyé et al., 2017) and holistic face processing (Yang et al., 2014). For example, it has been found that 1.5 mA anodal tDCS administered to the right occipital cortex improved face memory (Barbieri et al., 2016). However, it should be noted that face processing improvements following tDCS has not been consistently reported, as a recent study by Willis et al. (2019) failed to replicate the findings of Barbieri et al. (2016).

Conflicting findings between Barbieri et al. (2016) and Willis et al. (2019) may be attributed to several possible reasons. Firstly, both studies used a traditional two-electrode montage with large sponge electrodes, which could have led to low-focality stimulation of the target area. This may have resulted in current flow spreading towards non-target regions, generating noise in the data. For instance, Barbieri et al. (2016) found that the stimulation effect using the traditional two-electrode montage with large sponge electrodes was not face-specific as it improved both face memory and object memory. Conversely, high-focality stimulation targeting the FFA has been shown to enhance face memory but not object memory (Brunyé et al., 2017). Hence, both Barbieri et al. (2016) and Willis et al. (2019) may have found conflicting findings due to low-focality stimulation of the target area.

Secondly, the effects of tDCS are not always consistent across different measures of performance. For example, a meta-analysis research showed that working memory enhancement was solely shown in reaction time (Brunoni and Vanderhasselt, 2014), whereas another meta-analysis research concluded that working memory enhancement was primarily seen in accuracy (Hill et al., 2016). This discrepancy in results is not unique to working memory research, as similar inconsistencies have been observed in face processing studies: while some research found face processing improvements only in terms of accuracy (Barbieri et al., 2016; Brunyé et al., 2017; Costantino et al., 2017; Renzi et al., 2015), other research found improvements only in reaction times (Willis et al., 2015). These inconclusive findings might reflect potential speed-accuracy trade-offs (Heitz, 2014; Wickelgren, 1977), which can vary within and between participants (Gueugneau et al., 2017; Liesefeld et al., 2015). Such trade-offs could lead to confounding effects and are not uncommon in tDCS research (e.g., Ankri et al., 2020). Finally, the contradictory results between Barbieri et al. (2016) and Willis et al. (2019) may also be attributed to false positive findings (e.g., Horvath et al., 2015; Learmonth et al., 2017). In fact, the presence of non-responders to tDCS (Horvath et al., 2015; López-Alonso et al., 2014) and the inability to replicate the positive effects of tDCS (Learmonth et al., 2017; Willis et al., 2019) have highlighted the inconsistency in the effects of tDCS.

In the current study, we use multifocal tDCS to stimulate our target regions (i.e., the OFA and the FFA) as it provides high focal stimulation and is more effective in increasing cortical excitability compared to the traditional two-electrode tDCS montage (Fischer et al., 2017). The stimulation will be delivered in an offline manner (i.e., stimulation applied before task execution) as previous work has found that offline tDCS improved recognition and memory of faces while online tDCS did not affect task performance (Barbieri et al., 2016). This advantage of applying offline stimulation was also found for working memory (Friehs and Frings, 2019). The effect of applying multifocal tDCS to the OFA and the FFA will be explored at a behavioural level where the accuracy and reaction times for the recognition of whole faces and facial features (eyes, nose, mouth) will be measured.

2. Experiment 1

Experiment 1 investigated the functional role of the OFA and the FFA on whole face and facial feature recognition using multifocal tDCS. Based on previous work which showed involvement of the OFA in the representation of independent facial features and the FFA in the representation of whole faces (Fox et al., 2009; Nichols et al., 2010; Pitcher et al., 2007; Schiltz et al., 2010), we expect enhanced performance for whole face recognition following the FFA stimulation compared to the OFA stimulation. Conversely, enhanced performance is expected for facial feature recognition following the OFA stimulation compared to FFA stimulation. Alternatively, if both regions (i.e., FFA and OFA) have overlapping roles in facial feature and whole face representation as suggested by the mixed findings in the literature (e.g., Bona et al., 2016; Nichols et al., 2010; Yovel and Kanwisher, 2004), there might be no difference in performance for facial feature and whole face recognition between the FFA stimulation and the OFA stimulation. Moreover, given that prior studies have demonstrated that certain facial features may be processed differently (Bukach et al., 2008; DeGutis et al., 2012; Tardif et al., 2019), an exploratory investigation will be carried out to assess whether there are any disparities in the recognition of individual facial features following stimulation of the FFA and the OFA.

3. Methods

3.1. Design

As previous research revealed that variations in biological factors such as head size and scalp thickness could affect the electric field produced by tDCS, a within-subjects design was implemented (Krause and Cohen Kadosh, 2014). The within-subject factors were stimulation type (OFA and FFA) and task type (features and whole face). The order of the stimulation type was counterbalanced, where half of the participants received stimulation targeting the OFA for the first session and the other half received stimulation targeting the FFA for the first session. The presentation order of task type was also counterbalanced within each kind of stimulation. Reaction times and accuracy were used to calculate the rate-correct score (RCS) (Woltz and Was, 2006), a measure of efficiency. RCS is calculated by the number of correct trials divided by the sum of reaction time for correct and incorrect trials, providing thus a measure that combines accuracy and reaction times. The value of RCS indicates the number of correct trials per second, where a higher value of RCS denotes higher efficiency. RCS has been shown to be more efficient in effect detection and accounting for a larger proportion of the variance compared to other integrative measures of speed and accuracy (Vandierendonck, 2017).

3.2. Participants

The sample size was based on past studies (Brunyé et al., 2017; Renzi et al., 2015) that used a similar procedure where participants (24 and 16 participants) were recruited to attend two experimental sessions for a within-subjects tDCS study. Additionally, an a priori power analysis was conducted using G*Power 3.1 (Faul et al., 2009) for a repeated-measures analysis of variance (ANOVA) comparing between two stimulation types (FFA and OFA) and two task types (features and whole faces). The effect size was estimated as a medium effect size, $\eta_p^2 = 0.06$. The effect size estimate was entered into the power analysis with the following parameters: alpha = .05, power = .95. The power analysis suggested that $N = 35$ was required to detect an interaction effect of stimulation type and task type with 95% probability.

Thirty-seven Malaysian Chinese male participants were recruited. Only male participants were recruited as it has been indicated that hormone levels, which fluctuate more in females compared to males due to the menstrual cycle, could be a potential confounding variable as it could affect cortical excitability (Smith et al., 2002). Prior to the experiment, participants completed a screening form regarding the inclusion and exclusion criteria concerning the application of transcranial electrical stimulation (TES) and provided informed consent. Participants were instructed to sleep for at least 6 h at night and avoid consumption of alcohol the day before the experiment session. They were also asked to refrain from caffeine for 1 h before the session and to avoid applying any hair products before each session.

Two participants were excluded from the analysis due to their absence from the second session of the experiment. Participants' age ranged from 18 to 29 years ($M = 20.89$ years, $SD = 2.27$ years) and they were students at the University of Nottingham Malaysia. A remuneration of RM20 or course credits was given for participation. The study has been reviewed and approved by the Science and Engineering Research Ethics Committee (SEREC) at the University of Nottingham Malaysia (approval code: KSK050319).

3.3. Apparatus & materials

PsychoPy was used for stimuli presentation and data collection (Peirce et al., 2019). The transcranial electrical stimulator used was a Starstim 8 (Neuroelectrics, Spain). The stimuli used in the facial recognition task were created using a facial composite software, Faces 4.0 (IQ Biometrics, US). Facial composite software was used as it contains a large variety of facial features (i.e., eyes, nose and mouth) whose appearances are distinct from each other. In total, 80 whole faces, 80 eyes, 80 noses and 80 mouths were used as stimuli. The whole faces had no piercings, glasses or hair. The eyes images were edited to a size of 212 × 69 pixels, nose images were edited to 100 × 133 pixels, mouth images were edited to 130 × 68 pixels and whole face images were edited to 250 × 382 pixels. Whole faces and features were then placed on a 350 × 450 pixels white canvas using Adobe Photoshop CS6. Examples of stimuli are shown below in Fig. 1. The task was administered with an Acer XF240H 24-inch monitor with a resolution of 1920 × 1080 pixels.

3.4. TDCS

TDCS was delivered through Ag/AgCl electrodes with 3.14 cm^2 contact area coated with conductive electrode gel (SignaGel, Parker Laboratories) to ensure good conductivity with the scalp. The electrodes were inserted into a neoprene cap (Starstim, Neuroelectrics, Barcelona, Spain) in accordance to the international 10-10 EEG system. The optimal montages for stimulation of the FFA and the OFA were produced using the Neuroelectrics Stimweaver optimization technique on a realistic head model template (Ruffini et al., 2014). The montage allowed excitation in the target area while limiting the effects in other non-target cortical locations. Only the right FFA and right OFA were selected as target areas as a large body of research has suggested a right hemisphere advantage for face processing (de Heering and Rossion, 2015; Grill-Spector et al., 2018; Rangarajan et al., 2014; Rhodes, 1993).

The standard safety constraint was applied to both parameters where the maximum total injected current was 4 mA and the maximum current allowed for each electrode was 2 mA. During OFA stimulation, seven electrodes were mounted: PO4 (−1455 μA), OZ (−1635 μA), T8 (−317 μA), PO3 (771 μA), P7 (−338 μA), PO8 (1690 μA) and O2 (1284 μA). Seven electrodes were mounted during the FFA stimulation: PO4 (−655 μA), CP6 (−1467 μA), C4 (839 μA), FC6 (−1083 μA), P7 (366 μA), P8 (2000 μA) and CP1 (0 μA). This extra electrode (CP1) was attached during the FFA stimulation with no injected current to ensure that both stimulations had seven electrodes. The model predicted a field intensity of 0.13 V/m at the OFA region and 0.032 V/m at the FFA region (Fig. 2). Both stimulations lasted for 20 min and the current was ramped up and down for the first and last 30s of stimulation respectively.

3.5. Procedure

FFA and OFA stimulation were performed in two sessions separated by at least one week to avoid any carry-over effects from the first session (see Mulquiney et al., 2011; Röhner et al., 2018; Rufener et al., 2019 for a similar procedure). As circadian rhythms could potentially influence cortical excitability (Krause and Cohen Kadosh, 2014), participants received the two sessions of stimulation at the same time of the day (±1 h). The order of stimulation type was counterbalanced among the participants.

At the beginning of the experiment, the participant's head circumference was measured to decide the suitable neoprene cap size. The electrode sites were then cleaned with alcohol prior to stimulation. Next, the gel-filled electrodes were fitted onto the neoprene cap and the electrical reference ear clip was clipped onto the participant's ear lobe. The cables were connected to the electrodes and the impedance level was checked. A cartoon video was presented concurrently with the stimulation. The cartoon video was introduced to reduce inter-

Fig. 1. Examples of stimuli used in the experiment. From right to left: whole face, eyes, nose, mouth (not to scale).

participant variability in visual experience during stimulation period (e.g., Renzi et al., 2015, for a similar procedure). Participants were monitored for any signs of distress at all times for safety purposes.

Participants were seated 80 cm from the screen. After the stimulation, participants completed the face recognition tasks in a counterbalanced order. Whole face images were presented at a visual angle of 13.54°, eyes images at 3.58°, nose images at 7.15° and mouth images at 3.94°. In total, there were 160 trials: 40 trials for whole faces, 40 trials for eyes, 40 trials for nose and 40 trials for mouth. Each stimuli type were presented in different blocks. For each block, participants were instructed to memorize 20 images and 40 images were presented during the test stage. Each block was separated into four sections where in each section, participants had to memorize five images and were tested with ten images.

During the first session, participants were given a brief six practice trials with feedback before the actual task. There were two phases in each task, the study and test phase. A fixation cross was presented at the center of the screen for 0.5s before the presentation of stimuli in each phase. In the study phase, each image was presented for 1s followed by a blank screen for 1s. Participants were instructed to memorize the images. In the test phase, the images that were presented in the study phase were presented along with novel images. Participants were instructed to distinguish which of the images were and were not presented in the study phase. If the image had been presented in the study phase, participants pressed the 'x' key and if the image was novel, the 'm' key was pressed. The images were presented until the participant responded. A different set of images was used for the face recognition tasks in the next session. At the end of each session, participants were asked to complete a questionnaire of sensations related to TES in order to check if there was any difference between the sensation perceived from FFA and OFA stimulation. The experimental session lasted for approximately 1 h for each session.

3.6. Results[1]

All data were analyzed using JASP version 0.16.3 (JASP Team, 2022). An alpha level of 0.05 was used for all statistical tests. A 2 (stimulation type: OFA vs. FFA) × 2 (task type: features vs. whole face) repeated-measures ANOVA was conducted on RCS (Fig. 3). Analysis showed no effect of stimulation type, $F(1, 34) = 0.076$, $p = .785$, $\eta_p^2 = 0.002$. A significant effect of task type was found, $F(1, 34) = 7.608$, $p = .009$, $\eta_p^2 = 0.183$, where efficiency for features ($M = 0.495$, $SD = 0.115$) was higher than whole face ($M = 0.466$, $SD = 0.142$). No interaction effect of stimulation type and task type was found, $F(1, 34) = 0.058$, $p = .811$, $\eta_p^2 = 0.002$.

We also conducted a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA and FFA stimulation. A 2 (stimulation type: OFA vs. FFA) × 3 (feature type: eyes vs. nose vs. mouth) repeated-measures ANOVA was conducted on RCS (Fig. 4). Analysis showed no effect of stimulation type, $F(1, 34) = 0.001$, $p = .998$, $\eta_p^2 = 0.001$. A significant effect of feature type was found, $F(2, 68) = 7.896$, $p < .001$, $\eta_p^2 = 0.188$. A post hoc Holm-Bonferroni test showed that the efficiency for the eyes ($M = 0.470$, $SD = 0.133$) was lower than the nose ($M = 0.507$, $SD = 0.148$), $p = .034$, $d = -0.269$, and the mouth ($M = 0.530$, $SD = 0.128$), $p < .001$, $d = -0.433$. No difference in efficiency was found between the nose and the mouth, $p = .140$, $d = -0.164$. No interaction effect of stimulation type and feature type was found, $F(2, 68) = 1.602$, $p = .209$, $\eta_p^2 = 0.045$.

4. Discussion

Our results showed no difference in efficiency in the face recognition tasks between the FFA and the OFA stimulation. The OFA stimulation did not specifically enhance the performance of facial feature recognition compared to the FFA stimulation. Similarly, the FFA stimulation did not specifically enhance whole face recognition compared to the OFA stimulation. Two potential reasons could explain our results. First, it is possible that neither type of stimulation had an effect on the face recognition tasks as previous work has shown that tDCS may not always lead to an enhancement of face recognition ability (Willis et al., 2019). However, it is also possible that the stimulation was successfully delivered but due to potential overlapping roles of the FFA and the OFA in facial feature and whole face representation, we found no differences across stimulation conditions. However, as the current experiment lacked a control condition (sham stimulation or a control site of stimulation), it is unclear if the FFA stimulation and the OFA stimulation influenced the performance in the face recognition tasks to a similar extent or if neither stimulation type affected face recognition performance.

Additionally, as the stimuli used in this experiment were generated from a facial composite software, they may not be processed in the same way as real human faces (Kätsyri, 2018). Artificial faces are more difficult to remember and less discriminable compared to real human faces as they are treated as out-group members (Balas and Pacella, 2015). This is problematic as in-group members are usually recognized more easily compared to out-group members (Meissner and Brigham, 2001). Moreover, the whole face stimuli in this experiment were made to have the same global shape (jawline and forehead size) and external features (ears). However, past research has shown that the presence of face shape is important to enhance holistic face processing (Retter and Rossion, 2015). Hence, in Experiment 2, we included a control no-stimulation condition (i.e., sham stimulation) and used real faces as stimuli.

[1] Separate analysis for accuracy and reaction times and perceived sensation after the FFA and the OFA stimulation can be found in Appendix 1

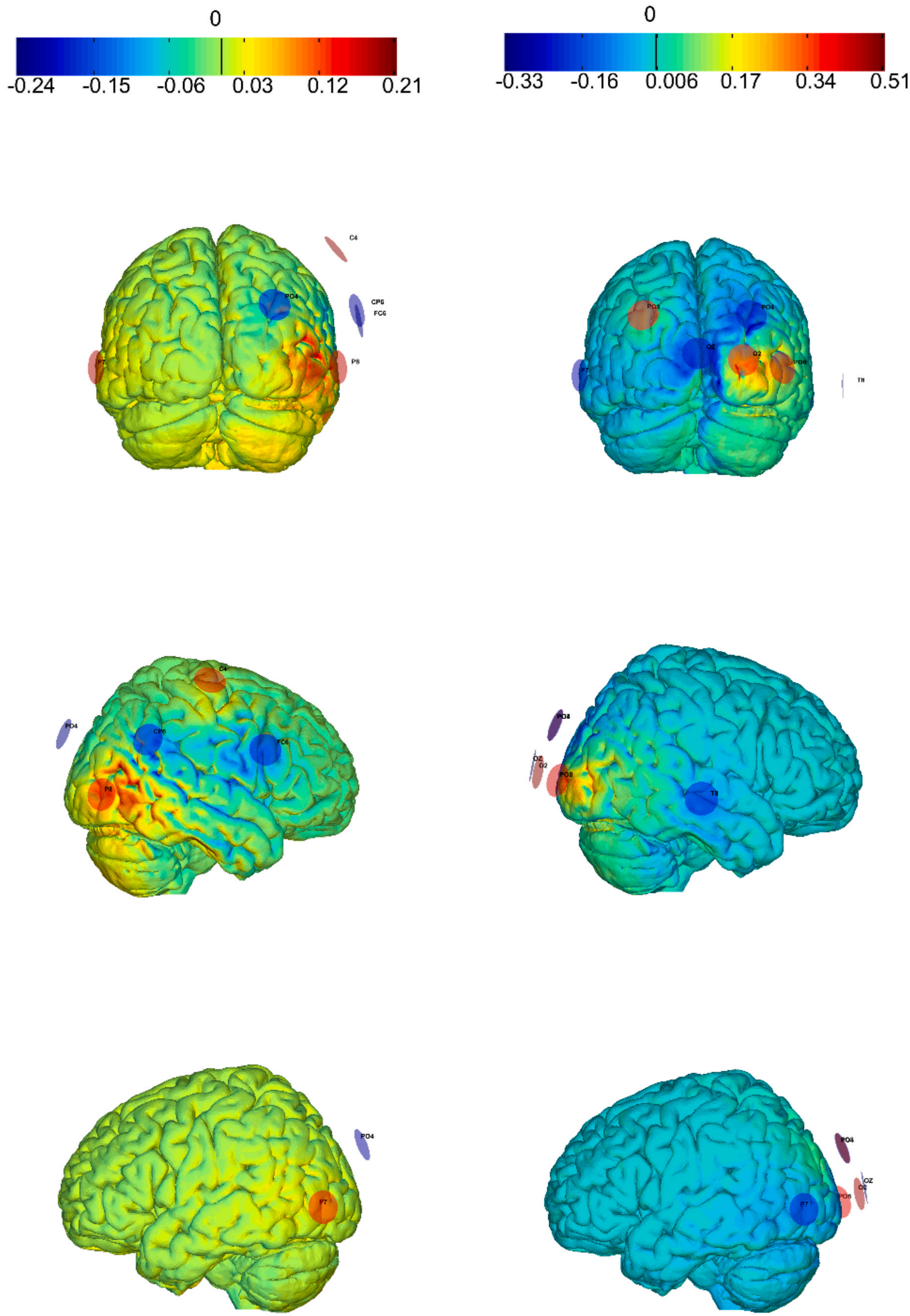

Fig. 2. Visualisation of the normal component of the E-field (V/m) for the FFA stimulation (left) and the OFA stimulation (right) modelled using the Stimweaver algorithm on a standard brain. From top to bottom: back view, right view and left view of the brain. The red circles correspond to the anode and blue circles correspond to the cathode.

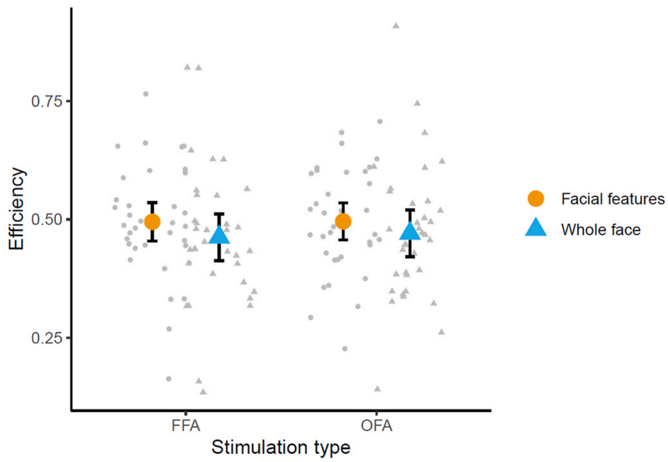

Fig. 3. Measure of efficiency for whole faces and features recognition tasks for OFA and FFA stimulation. Error bars represent 95% confidence interval. No significant differences were observed in facial features and whole face recognition efficiency between stimulation groups.

4.1. Experiment 2

Similar to Experiment 1, Experiment 2 aims to examine the contributions of OFA and FFA stimulation towards performance in the recognition of whole faces and facial features. In Experiment 2, we introduced several changes. First, we used stimuli cropped from real face images as they more accurately reflect the faces, eyes, noses, and mouths encountered in real life. Additionally, the face shape was preserved as it provides relevant cues for holistic face processing (Retter and Rossion, 2015). Second, stimulation was provided following a between-subject design and included a control no-stimulation condition (i.e., sham stimulation condition). We decided to follow a between-subject design for two main reasons. From a practical point of view, a within-subject design including the three stimulation conditions (FFA, OFA, and sham) would require a minimum of 14 days, assuming the recommended minimum gap of seven days between stimulation sessions (see Mulquiney et al., 2011; Röhner et al., 2018; Rufener et al., 2019 for a similar procedure). This could lead to an increase of dropouts, making data collection more difficult. In addition, recent research showed that transcranial electrical stimulation enhances face identification following a between-subject, but not a within-subject design (Penton et al., 2018). However, to avoid the effect of differences across groups, in Experiment 2, participants were tested before and after the stimulation. Finally, in this experiment we also included female participants to improve the representativeness of the sample. To prevent any potential confounding effects resulting from fluctuations in hormone levels caused by the menstrual cycle (Smith et al., 2002), female participants were only recruited during the follicular phase. This phase was chosen as hormone levels during this time are the most comparable to those of males (for a similar procedure, see Barbieri et al., 2016).

If the OFA is involved in facial features representation while the FFA is involved whole face representation (Nichols et al., 2010; Fox et al., 2009; Pitcher et al., 2007; Schiltz et al., 2010), we would expect enhanced performance for whole face recognition following FFA stimulation compared to OFA stimulation and sham stimulation. Conversely, we expect enhanced performance for facial feature recognition following OFA stimulation compared to FFA stimulation and sham stimulation. Alternatively, if both regions (i.e., FFA and OFA) have overlapping roles in facial feature and whole face representation as suggested by the mixed finding in the literature (e.g., Bona et al., 2016; Nichols et al., 2010; Yovel and Kanwisher, 2004), performance for facial feature and whole face recognition should be improved to the same extent after the application of FFA stimulation and OFA stimulation compared to sham stimulation. Similar to Experiment 1, an exploratory analysis will be performed to evaluate whether there are any differences in recognizing specific facial features after stimulation of the FFA and OFA. This is because prior research has demonstrated that certain facial features may undergo distinct processing (Bukach et al., 2008; DeGutis et al., 2012; Tardif et al., 2019).

5. Methods

5.1. Design

A mixed design was used. The within-subject factors were task type (whole face and features) and session (pre-stimulation and post-stimulation). The between-subject factor was the stimulation type (OFA, FFA and sham). Similar to Experiment 1, the dependent variable was efficiency. The presentation order of task type was counterbalanced for all participants.

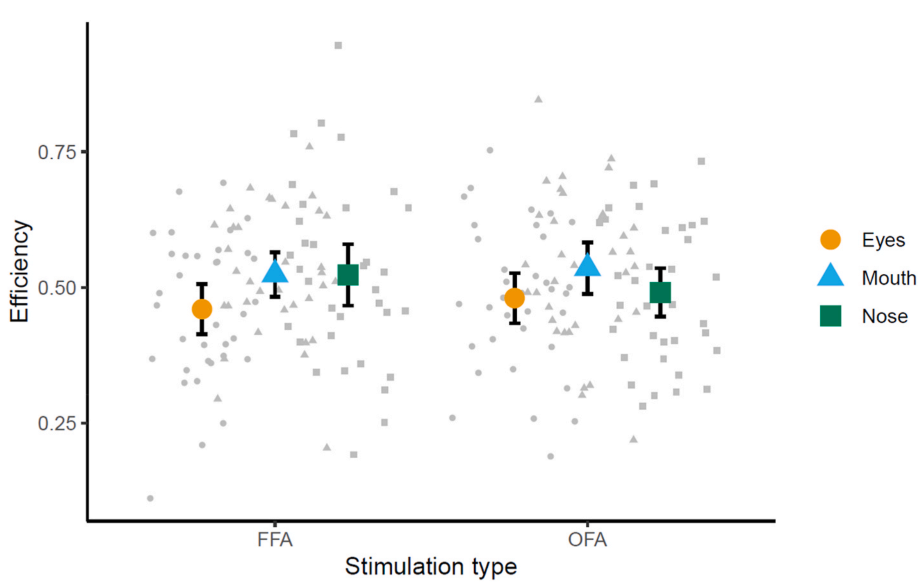

Fig. 4. Measure of efficiency for facial features recognition tasks for OFA and FFA stimulation. Error bars represent 95% confidence interval. No significant differences were observed in facial features (i.e., eyes, nose and mouth) recognition efficiency between stimulation groups.

5.2. Participants

The sample size for this study was based on Barbieri et al. (2016) who used a similar procedure where 48 participants were recruited for a between-subjects tDCS study with three conditions (online a-tDCS, offline a-tDCS and sham stimulation). Additionally, an a priori power analysis was conducted using G*Power 3.1 (Faul et al., 2009) for a mixed ANOVA comparing between three stimulation type (FFA, OFA and sham stimulation), two task type (whole faces and facial features) and two session type (pre-stimulation and post-stimulation). The effect size was estimated as a medium effect size, $\eta_p^2 = 0.06$. The effect size estimate was entered into the power analysis with the following parameters: alpha = .05, power = .95. The power analysis suggested that $N = 24$ was required to detect an interaction effect of stimulation type, task type and session with 95% probability.

Sixty Malaysian Chinese (38 females) participants were recruited. To address the potential influence of ORE in face recognition (Estudillo, 2021; Estudillo et al., 2020; Hayward et al., 2008; Wong et al., 2020), only Malaysian Chinese participants were recruited as the stimuli presented in the experiment were created using only Chinese faces. Past work has also indicated that hormone levels which fluctuate among females due to the menstrual cycle could affect cortical excitability (Smith et al., 2002). Hence, female participants were recruited during the follicular phase of the menstrual cycle as in this phase, the hormone levels are most similar to males (for a similar procedure, see Barbieri et al., 2016).

Prior to the experiment, participants completed a screening form for the inclusion and exclusion criteria concerning the application of TES and provided informed consent. Participants were instructed to sleep for at least 6 h at night and avoid consumption of alcohol the day before the experiment session. They were also asked to refrain from caffeine for 1 h before the session and to avoid applying any hair products before each session. Participants' age ranged between 18 and 29 years ($M = 21.38$ years, $SD = 2.2$ years) and were students at the University of Nottingham Malaysia. Remuneration of RM10 or course credits was given for participation. A one-way ANOVA was conducted to examine if there was any age difference between stimulation groups. No significant age difference was found between stimulation group, $F(2, 57) = 0.346$, $p = .709$. A chi-square test of independence showed that there was no significant relationship between stimulation group and gender, $X^2(2, N = 60) = 0.574$, $p = .750$. The study has been reviewed and approved by the Science and Engineering Research Ethics Committee (SEREC) in the University of Nottingham Malaysia (approval code: KSK050319).

5.2.1. Apparatus and materials

Similar to Experiment 1, PsychoPy (Peirce et al., 2019) and Starstim 8 (Neuroelectrics, Spain) were used. The stimuli used in the recognition tasks were created using the CAS-PEAL face database (Gao et al., 2008). In total, 180 whole faces (90 females and 90 males), 60 eyes (30 females and 30 males), 60 noses (30 females and 30 males) and 60 mouths (30 females and 30 males) were used as stimuli. The whole faces had no piercings, glasses, external hair or facial hair. The stimuli for the features task were cropped from whole faces available in the CAS-PEAL face database. The eyes images were cropped to a size of 550 × 162 pixels, nose images were cropped to 377 × 400 pixels and mouth images were cropped to 450 × 237 pixels. The whole face images were resized to 600 pixels in height and the width was resized according to the original proportion of the whole face. Whole faces and features were then placed on a 800 × 800 pixels black canvas using Adobe Photoshop CS6. Examples of stimuli are as shown below in Fig. 5.

5.3. TDCS

Three types of stimulation were used in this experiment: FFA stimulation, OFA stimulation and sham stimulation. The montage used for stimulation of the right FFA and the right OFA were as in Experiment 1. Sham stimulation used the same montage as either FFA stimulation or OFA stimulation but the current was only delivered during the first and last 30s to evoke the sensation of stimulation, without affecting neuronal excitability (Thair et al., 2017). Half of the participants received sham stimulation using the FFA stimulation montage and the other half using the OFA stimulation montage.

5.4. Procedure

Participants first completed baseline whole face and feature recognition tasks. The baseline task was used to control potential differences across groups. Participants completed the baseline whole face and feature recognition tasks in a counterbalanced order and were seated 80 cm from the screen. Whole face images were presented at a visual angle of 10.36°, eyes images at 3.08°, nose images at 6.94° and mouth images at 4.44°. Participants were given a brief six practice trials session with feedback before the actual trial began. In total, there were 180 trials: 90 trials for whole faces and 90 trials for features (30 trials each for eyes, nose and mouth stimuli). In each recognition task, participants were instructed to memorize 45 images and 90 images were presented during the test stage. Each task was separated into nine blocks where participants had to memorize five images in each block and were then tested with ten images. A self-paced break of at least 20 s was given after every three blocks.

There were two phases in each task, the study phase and the test phase. A fixation cross was presented at the center of the screen for 0.5s before the presentation of stimuli in the study and test phase. In the study phase, each image was presented for 1s followed by a blank screen for 1s. Participants were instructed to memorize the images presented in the study phase. After the study phase, participants had a self-paced rest of at least 10 s before moving on to the test phase. In the test phase, the images that were presented in the study phase were presented intermixed with novel images. The images were presented until the participant responded. Participants were instructed to distinguish which of the images were presented and which were not presented in the study phase. If the image was presented in the study phase, participants pressed the 'x' key and if the image was novel, the 'm' key was pressed.

The procedure for the stimulation session was as in Experiment 1.

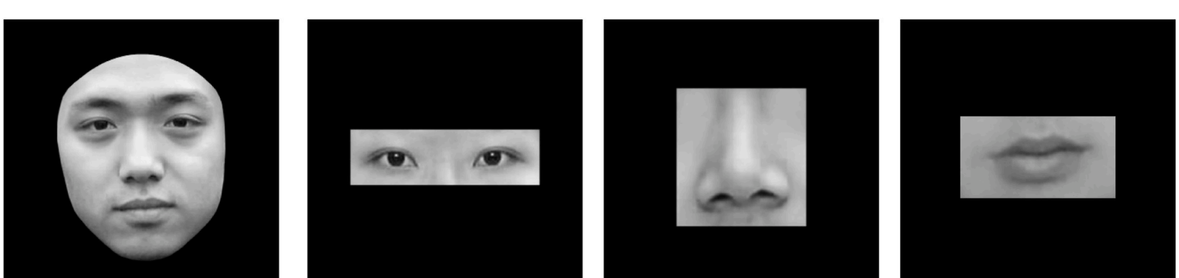

Fig. 5. Examples of stimuli used in the experiment, from right to left: whole face, eyes, nose, mouth (not to scale).

After the stimulation session, participants were asked to complete new versions of the whole face and features recognition tasks that were identical in procedure to the baseline tasks. The versions of the tasks were counterbalanced for pre- and post-stimulation sessions. At the end of the session, participants were asked to complete a questionnaire of sensations related to TES to check if there was any difference between the sensation perceived from FFA, OFA and sham stimulation. The experimental session lasted for approximately 1 h for each session.

5.5. Results[2]

All data were analyzed using JASP version 0.16.3 (JASP Team, 2022). A mixed 2 (task type: features vs. whole faces) × 2 (session: pre vs. post) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA was conducted on efficiency measured by RCS (Fig. 6). No main effect of stimulation type was found, $F(2, 57) = 0.133$, $p = .876$, $\eta_p^2 = 0.005$. A main effect of session was found, $F(1, 57) = 19.694$, $p < .001$, $\eta_p^2 = 0.257$, where pre-stimulation trials ($M = 0.57$, $SD = 0.152$) had lower efficiency compared to post-stimulation trials ($M = 0.617$, $SD = 0.16$). Analysis revealed a main effect of task type, $F(1, 57) = 45.985$, $p < .001$, $\eta_p^2 = 0.447$, where features task ($M = 0.553$, $SD = 0.149$) had lower efficiency compared to whole faces task ($M = 0.633$, $SD = 0.156$). Analysis also revealed a significant interaction effect of stimulation type and task type, $F(2, 57) = 3.534$, $p = .036$, $\eta_p^2 = 0.11$, and of task type and session, $F(1, 57) = 4.865$, $p = .031$, $\eta_p^2 = 0.079$. No interaction effect of stimulation type and session was found, $F(2, 57) = 0.379$, $p = .687$, $\eta_p^2 = 0.013$.

A three-way interaction effect of stimulation type, task type and session was found, $F(2, 57) = 3.817$, $p = .028$, $\eta_p^2 = 0.118$. To further explore this three-way interaction effect, we calculated the difference in efficiency between post- and pre-stimulation for each variable ($RCS_{Post} - RCS_{Pre}$). A higher value would indicate higher efficiency after stimulation. We analyzed these scores using 2 (task type: features vs. whole faces) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA. Analysis revealed a significant main effect of task type, $F(1, 57) = 4.865$, $p = .031$, $\eta_p^2 = 0.079$, where features task ($M = 0.065$, $SD = 0.115$) had higher efficiency compared to whole face task ($M = 0.028$, $SD = 0.094$). No effect of stimulation type was found, $F(2, 57) = 0.379$, $p = .687$, $\eta_p^2 = 0.013$. A significant interaction effect of task type and stimulation was found, $F(2, 57) = 3.817$, $p = .028$, $\eta_p^2 = 0.118$. Simple main effect analysis showed that features task ($M = 0.106$, $SD = 0.145$) had higher efficiency compared to whole face task ($M = 0.013$, $SD = 0.125$) for FFA stimulation, $F(1, 19) = 7.928$, $p = .011$, $\eta^2 = 0.294$. No difference between features task and whole face task was found for OFA stimulation, $F(1, 19) = 0.716$, $p = .408$, $\eta^2 = 0.036$, and sham stimulation, $F(1, 19) = 1.749$, $p = .202$, $\eta^2 = 0.084$.

We also conducted a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA and FFA stimulation. A mixed 3 (feature type: eyes vs. nose vs. mouth) × 2 (session: pre vs. post) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA was conducted on RCS (Fig. 7). No main effect of stimulation type was found, $F(2, 57) = 0.875$, $p = .423$, $\eta_p^2 = 0.030$. A main effect of session was found, $F(1, 57) = 21.870$, $p < .001$, $\eta_p^2 = 0.277$, where pre-stimulation trials ($M = 0.526$, $SD = 0.159$) had lower efficiency compared to post-stimulation trials ($M = 0.593$, $SD = 0.189$). Analysis revealed a main effect of feature type, $F(2, 114) = 3.206$, $p = .044$, $\eta_p^2 = 0.053$. A post hoc Holm-Bonferroni test revealed no difference in efficiency between the eyes ($M = 0.536$, $SD = 0.161$) and the nose ($M = 0.570$, $SD = 0.182$), $p = .076$, $d = -0.197$, the eyes and the mouth ($M = 0.573$, $SD = 0.187$), $p = .076$, $d = -0.211$, and the nose and the mouth, $p = .880$, $d = -0.014$.

No interaction effect was found between feature type and stimulation type, $F(4, 114) = 0.726$, $p = .576$, $\eta_p^2 = 0.025$, and session and stimulation type, $F(2, 57) = 2.433$, $p = .097$, $\eta_p^2 = 0.079$. A significant interaction effect was found between feature type and session, $F(2, 114) = 2.099$, $p = .127$, $\eta_p^2 = 0.036$. Simple main effect analysis revealed no difference in feature type pre-stimulation, $F(2, 118) = 0.898$, $p = .410$, $\eta_p^2 = 0.015$. A main effect of feature type was found post-stimulation, $F(2, 118) = 4.232$, $p = .017$, $\eta_p^2 = 0.067$. A post hoc Holm-Bonferroni test showed that the eyes ($M = 0.556$, $SD = 0.167$) had lower efficiency compared to the nose ($M = 0.618$, $SD = 0.191$), $p = .019$, $d = -0.330$. No difference was found between the eyes and the mouth ($M = 0.604$, $SD = 0.203$), $p = .071$, $d = -0.252$, and the nose and the mouth, $p = .514$, $d = 0.078$. No three-way interaction was found between feature type, session and stimulation type, $F(4, 114) = 2.258$, $p = .067$, $\eta_p^2 = 0.073$.

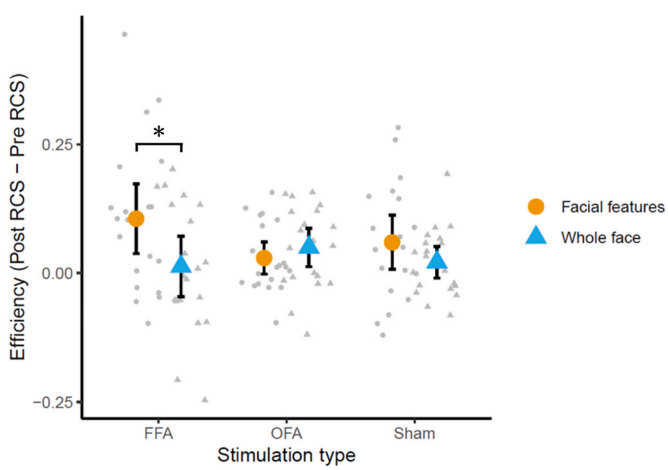

Fig. 6. Post-stimulation minus pre-stimulation scores for efficiency of features and whole face recognition tasks for OFA, FFA and sham stimulation. Error bars represent 95% confidence interval. Statistically significant differences ($p < .05$) are denoted by asterisks.

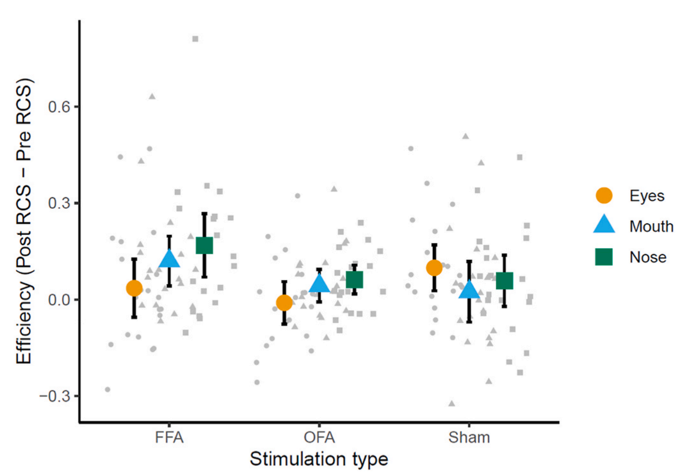

Fig. 7. Post-stimulation minus pre-stimulation scores for efficiency of facial features recognition tasks for OFA, FFA and sham stimulation. Error bars represent 95% confidence interval. No significant differences were observed in facial features (i.e., eyes, nose and mouth) recognition efficiency between stimulation groups.

[2] Analysis of the perceived sensation after the FFA, OFA and sham stimulation, analysis on baseline scores to compare face recognition ability and age between stimulation groups and additional analyses: 2 (task type: features vs. whole faces) × 2 (session: pre vs. post) × 3 (simulation type: FFA vs. OFA vs. sham) mixed ANOVA conducted on accuracy and reaction time could be found in Appendix 2

6. Discussion

Our results showed that the features task had higher efficiency compared to whole face task only for the FFA stimulation, but not for the OFA stimulation and sham stimulation. Contrary to previous work which showed the involvement of the OFA in the representation of facial features and the FFA in the representation of whole faces (Fox et al., 2009; Nichols et al., 2010; Pitcher et al., 2007; Schiltz et al., 2010), our results showed that the FFA stimulation enhanced facial feature recognition whereas OFA stimulation had no effect on both facial feature and whole face recognition. Additionally, no effect of the FFA stimulation was found on whole face recognition. Overall, our findings support the involvement of the FFA in featural recognition.

7. General discussion

This study aimed to investigate the functional role of the FFA and the OFA using multifocal tDCS. In Experiment 1, tDCS over the OFA and the FFA did not produce any change in the efficiency to recognize whole faces and facial features. However, past work has shown that artificial faces may not be processed in the same way as real human faces as they are more difficult to remember and less discriminable compared to real human faces as they are treated as out-group members (Balas and Pacella, 2015; Kätsyri, 2018). Furthermore, in Experiment 1, the whole face stimuli were created with identical global shape (forehead size and jawline). However, previous studies have demonstrated that the presence of face shape is crucial for holistic face processing (Retter and Rossion, 2015).

To avoid these problems, in Experiment 2, we used real faces and found that that the FFA stimulation increased efficiency for feature recognition. Although we used a between-subject design, this result could not be attributed to individual differences in face recognition abilities (i.e., participants in the FFA stimulation group having higher facial feature recognition ability compared to the OFA stimulation group and sham stimulation group) as we have measured baseline performance before the stimulation session and improvements in Experiment 2 were calculated by comparing pre- and post-stimulation scores. Additionally, analysis of pre-stimulation scores showed no difference in face recognition ability between the stimulation groups (Appendix 2). This finding of enhanced feature recognition following the FFA stimulation is in line with past fMRI studies showing the involvement of the FFA in feature recognition (Dachille et al., 2012; Liu et al., 2010). For example, the FFA responded similarly to facial features presented individually and facial features presented in face-like combination (Dachille et al., 2012). Although a different study found that the FFA was more responsive to features that were arranged in a normal configuration compared to a scrambled configuration, this finding showed that the FFA responded to the presence of facial features even in a scrambled configuration (Liu et al., 2010). These studies suggest that the FFA is involved in facial feature representation.

However, despite using real faces our results in Experiment 2 showed no effect of the FFA stimulation on whole face recognition. One possible explanation for the lack of FFA stimulation effect on whole face recognition in Experiment 2 is the difference in task difficulty between facial feature and whole face recognition. Our findings showed that the features task was more difficult (i.e., lower efficiency) compared to the whole face task in Experiment 2. Earlier studies have found that the effect of tDCS are more apparent when the task difficulty is greater, as seen in areas such as arithmetic (Pope and Miall, 2012; Popescu et al., 2016; Rütsche et al., 2015), working memory (Gill et al., 2015; Vergallito et al., 2018) and attention (Nelson et al., 2014; Reteig et al., 2017). Similarly, performance enhancement in video games following tDCS effects were observed only when participants were multitasking, but not when participants were executing a single task (Hsu et al., 2015). Since the feature recognition task was more difficult than the whole face recognition task, the effect of tDCS may only be apparent for facial feature recognition and not whole face recognition.

In contrast to our expectations, we found no difference in efficiency for facial features and whole face recognition after OFA stimulation. One possible reason for this may be that the montage used for the OFA stimulation in this experiment was not effective in eliciting an advantage in the recognition tasks. In other words, our results may not rule out the involvement of OFA in the representation of facial features and whole faces, but that the montage used for OFA stimulation in this experiment was not effective in enhancing performance in the recognition tasks. In fact, based on the Neuroelectrics Stimweaver report, the predicted field intensity for OFA stimulation (0.13 V/m) was much higher compared to the predicted field intensity for FFA stimulation (0.032 V/m), hence, the effect of OFA stimulation should be larger than the FFA stimulation. In contrast to this, participants reported in Experiment 1 that they felt more itching for FFA stimulation compared to OFA stimulation (see Appendix 1). Since there is no direct way of measuring the effect of the stimulation in our experiment, it could be that the real stimulation effect did not replicate the predicted stimulation effect as other factors such as biological differences could affect the application of tDCS (Krause and Cohen Kadosh, 2014). Differences in the biological substrates such as the pre-existing neurotransmitter levels, head size and scalp thickness could contribute to inter-individual differences in the electric field in the brain generated by tDCS causing the stimulation effect to vary across participants (Krause and Cohen Kadosh, 2014; Laakso et al., 2019). As a result, the efficiency of the OFA stimulation might have varied depending on whether the participants received the stimulation in an optimum manner. Another limitation of our study is that the anatomical location of the OFA and FFA was determined using a single realistic head model template. Although this method in conjunction with the Neuroelectrics Stimweaver optimization algorithm has been demonstrated to be a reliable method for localizing the target areas (Ruffini et al., 2014), it should be noted that individual MRI scans would have allowed for a more precise localization.

8. Conclusion

In sum, our results from Experiment 1 showed no significant change in the efficiency to recognize whole faces and facial features after tDCS application over the OFA and FFA, which may have been influenced by the use of artificial faces. Experiment 2, using real faces, revealed that FFA stimulation increased efficiency for facial feature recognition. However, no effect of FFA stimulation was observed for whole face recognition, possibly due to lower level of task difficulty. OFA stimulation did not show any effect on either whole face or feature recognition, which may be attributed to the ineffectiveness of the stimulation montage. Overall, our findings suggest that the FFA is involved in facial feature representation, with implications for understanding the neural mechanisms underlying face processing.

Authors' contributions

Siew Kei Kho: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualisation and Project administration. David R.T. Keeble: Writing – review & editing and Funding acquisition. Hoo Keat Wong: Writing – review & editing. Alejandro J. Estudillo: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Visualization and Supervision.

Funding

This study was funded by the Fundamental Research Grant Scheme (FRGS) from the Ministry of Education (MOE) Malaysia (Grant number: FRGS/1/2018/SS05/UNIM/02/4).

Declaration of competing interest

None.

Data availability

The datasets generated during the current study are available in the Open Science Framework repository, https://osf.io/3jsqv/?view_only=b881ba78add0442c94ca872180713509.

Appendices.

***Appendix 1**: Perceived sensation after the FFA and the OFA stimulation and analyses of accuracy and reaction times for Experiment 1*

Perceived sensation

A Wilcoxon signed-rank test was conducted on the effect of stimulation type (OFA vs. FFA) on the rating score (0 = none, 1 = mild, 2 = moderate and 3 = strong) for the different sensations perceived (itching, pain, burning, warmth/heat, metallic/iron taste and fatigue/decreased alertness) (Fig. 8). Rating score for itching was higher for FFA stimulation ($M = 1.429$, $SD = 1.065$) compared to OFA stimulation ($M = 0.9429$, $SD = 0.765$), $W = 199$, $p = .013$. No difference was found between FFA stimulation and OFA stimulation on the rating score for pain ($W = 176$, $p = .075$), burning ($W = 62$, $p = .549$), warmth/heat ($W = 38.5$, $p = .627$), metallic/iron taste ($W = 4$, $p = .773$) and fatigue/decreased alertness ($W = 50$, $p = .768$). Wilcoxon signed-rank test was also conducted on the effect of stimulation type (OFA vs. FFA) on the rating score for how much the stimulation affected participant's general state (0 = not at all, 1 = slightly, 2 = considerably, 3 = much and 4 = very much). The stimulation did not produce a statistically significant change in the rating score for general state, $W = 85.5$, $p = 1$. For additional remarks on the sensation of stimulation, refer to Table 1.

The results revealed that the rating score for itching was higher for the FFA stimulation compared to the OFA stimulation. Although participants reported more itching during the FFA stimulation than the OFA stimulation, no difference was reported for participant's rating of their general state after the FFA stimulation and OFA stimulation. Additionally, the stimulation was administered in an offline manner (before task). Hence, the itching sensation should have had minimal to no effect on the performance of the face recognition tasks.

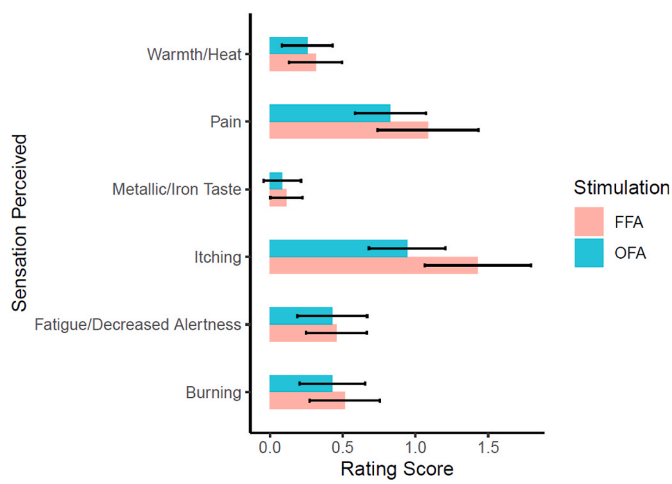

Fig. 8. Rating score of sensations perceived during FFA and OFA stimulation. Error bars represent 95% confidence interval.

Table 1
Additional remarks on the sensation of stimulation for Experiment 1.

Stimulation	Additional remarks
OFA	Felt calmer and more relaxed.
FFA	Cold burn
	Ticklish

Note. Remarks provided by three participants.

Accuracy and median reaction time analysis

A 2 (stimulation type: OFA vs. FFA) × 2 (task type: features vs. whole face) repeated-measures ANOVA was conducted on accuracy calculated by proportion correct (Fig. 9). Analysis showed no effect of stimulation type, $F(1, 34) = 0.611$, $p = .440$, $\eta_p^2 = 0.018$, or task type, $F(1, 34) = 0.065$, $p = .801$, $\eta_p^2 = 0.002$. No interaction effect of stimulation type and task type was found, $F(1, 34) = 0.823$, $p = .371$, $\eta_p^2 = 0.024$.

We also conducted a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA and FFA stimulation. A 2 (stimulation type: OFA vs. FFA) × 3 (feature type: eyes vs. nose vs. mouth) repeated-measures ANOVA was conducted on accuracy (Fig. 10). When Mauchly's test indicated that the assumption of sphericity had been violated, the degrees of freedom was corrected using Greenhouse-Geisser estimates of sphericity. Analysis showed no effect of stimulation type, $F(1, 34) = 2.456$, $p = .126$, $\eta_p^2 = 0.067$, or feature type, $F(2, 68) = 1.033$, $p = .362$, $\eta_p^2 = 0.029$. No interaction effect of stimulation type and feature type was found, $F(1.643, 55.860) = 1.901$, p

$= .166$, $\eta_p^2 = 0.053$.

For the reaction time analysis, median reaction times were used instead of mean reaction times as medians are less influenced by extreme scores. A 2 (stimulation type: OFA vs. FFA) × 2 (task type: features vs. whole face) repeated-measures ANOVA was conducted on the median reaction times for correct responses ((Fig. 9). Analysis showed no effect of stimulation type, $F(1, 34) = 0.098$, $p = .756$, $\eta_p^2 = 0.003$. However, a significant effect of task type was found, $F(1, 34) = 11.548$, $p = .002$, $\eta_p^2 = 0.254$, where reaction time for features ($M = 1.141$s, $SD = 0.268$s) was faster compared to whole faces ($M = 1.260$s, $SD = 0.437$s). No interaction effect of stimulation type and task type was found, $F(1, 34) = 1.576$, $p = .218$, $\eta_p^2 = 0.044$.

Additionally, a 2 (stimulation type: OFA vs. FFA) × 3 (feature type: eyes vs. nose vs. mouth) repeated-measures ANOVA was conducted on median reaction times for correct responses as a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA and FFA stimulation (Fig. 10). When Mauchly's test indicated that the assumption of sphericity had been violated, the degrees of freedom was corrected using Greenhouse-Geisser estimates of sphericity. Analysis showed no effect of stimulation type, $F(1, 34) = 0.954$, $p = .336$, $\eta_p^2 = 0.027$. A significant effect of feature type was found, $F(1.632, 55.502) = 15.932$, $p < .001$, $\eta_p^2 = 0.319$. A post hoc Holm-Bonferroni test demonstrate that the reaction time for the eyes ($M = 1.229$s, $SD = 0.369$s) was longer than the nose ($M = 1.132$s, $SD = 0.282$s), $p < .001$, $d = 0.312$, and the mouth ($M = 1.102$s, $SD = 0.261$s), $p < .001$, $d = 0.409$. No difference in reaction time was found between the nose and the mouth, $p = .205$, $d = 0.097$. No interaction effect of stimulation type and feature type was found, $F(1.533, 52.107) = 0.978$, $p = .363$, $\eta_p^2 = 0.028$.

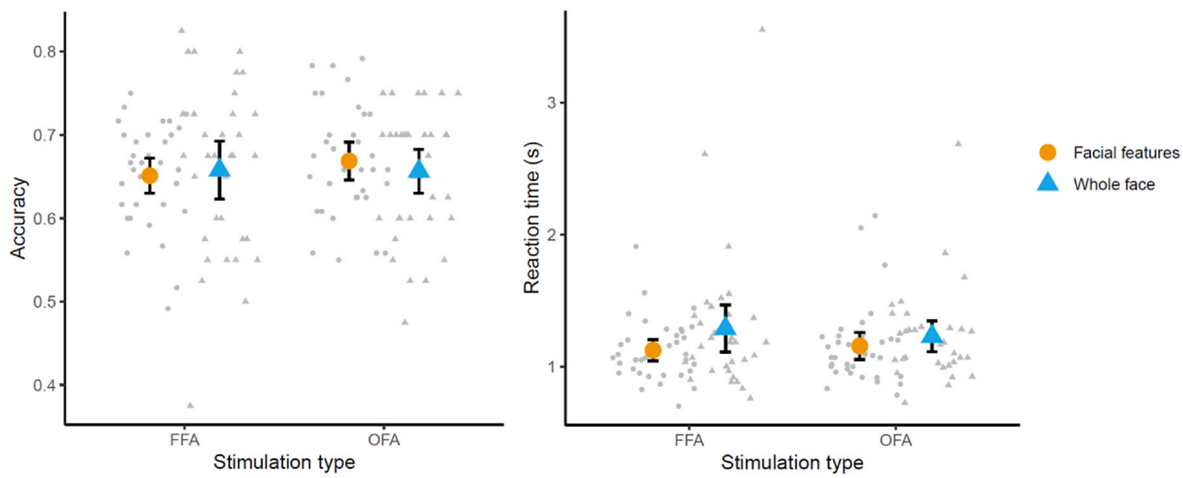

Fig. 9. Measure of accuracy and reaction time for whole faces and features recognition tasks for OFA and FFA stimulation. Error bars represent 95% confidence interval.

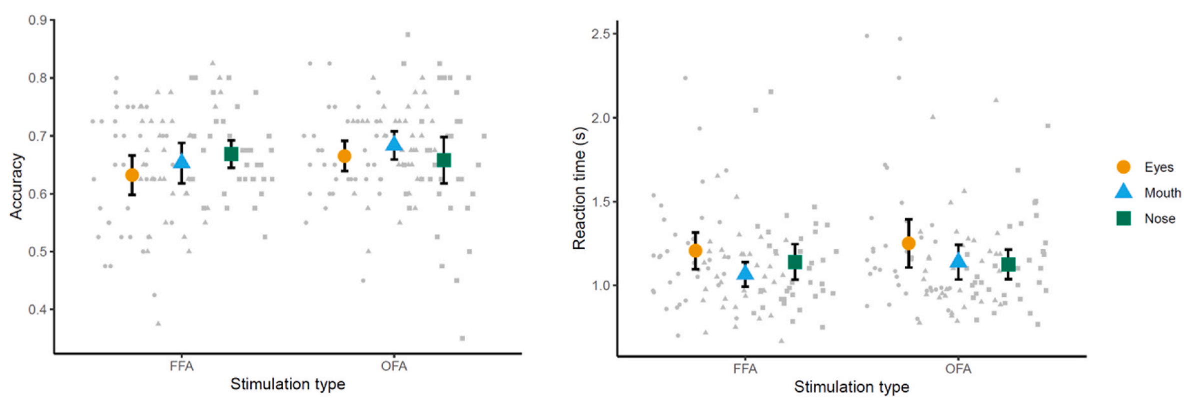

Fig. 10. Measure of accuracy and reaction time for facial features recognition tasks for OFA and FFA stimulation. Error bars represent 95% confidence interval.

***Appendix 2:** Perceived sensation after the FFA, OFA and sham stimulation, analysis on baseline scores to compare face recognition ability between stimulation groups prior to receiving stimulation and analyses of accuracy and reaction times for Experiment 2*

Perceived sensation

Kruskal-Wallis test was conducted on the rating score (0 = none, 1 = mild, 2 = moderate and 3 = strong) of perceived sensation (itching, pain, burning, warmth/heat, metallic/iron taste and fatigue/decreased alertness) of the stimulation type (FFA vs. OFA vs. sham) (Fig. 11). No difference was found for rating score of itching ($H(2) = 3.33$, $p = .19$), pain ($H(2) = 0.05$, $p = .97$), burning ($H(2) = 2.21$, $p = .33$), warmth/heat ($H(2) = 2.32$, $p = .31$), metallic/iron taste ($H(2) = 0.43$, $p = .81$) and fatigue/decreased alertness ($H(2) = 2.53$, $p = .28$) between stimulation type. Kruskal-Wallis test also revealed no difference between stimulation type on the rating score of how much the participant's general state was affected after stimulation (0 = not at all, 1 = slightly, 2 = considerably, 3 = much and 4 = very much), ($H(2) = 1.09$, $p = .58$). For additional remarks on the sensation of stimulation and participant's belief on whether they have received real or placebo stimulation, refer to Tables 2 and 3. Our results showed no difference in sensation perceived between FFA, OFA and sham stimulation.

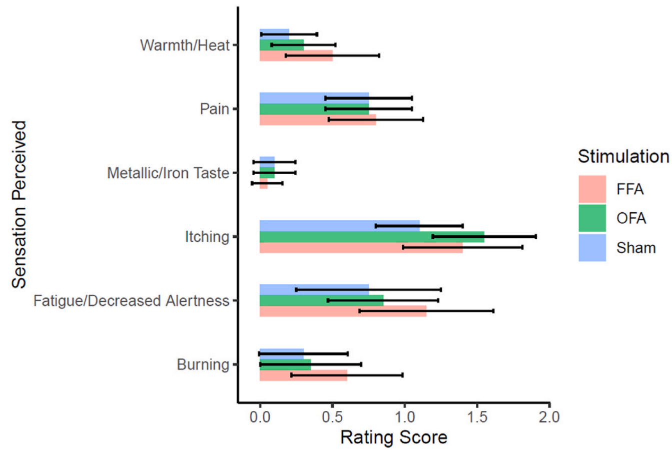

Fig. 11. Rating score of sensations perceived during FFA, OFA and sham stimulation. Error bars represent 95% confidence interval.

Table 2
Additional remarks on the sensation of stimulation for Experiment 2.

Stimulation	Additional remarks
OFA	Decreased alertness and felt tired even when the cartoon video reached the funny part.
FFA	Sleepy
Sham	The tingling sensation started at the beginning of the stimulation very mildly and faded away gradually. The sensation became much more intense in the middle of the stimulation period and persisted until the end until it was stopped.
	I felt sleepier at the second half of the video.
	Really sleepy for some reason but the cartoon kept me alert.
	Felt in the initial minute and final minute of the stimulation period.

Note. Remarks provided by six participants.

Table 3
Participant's belief on whether they have received real or placebo stimulation for Experiment 2.

	Number of participants		
Stimulation	Real	Placebo	Not sure
FFA	12	1	7
OFA	16	1	3
Sham	8	2	10

Note. Each stimulation group had 20 participants.

Baseline (pre-stimulation)

A mixed 2 (task type: features vs. whole faces) × 3 (simulation group: FFA vs. OFA vs. sham) ANOVA was conducted to examine if there were any difference in accuracy between stimulation group prior to stimulation. Accuracy reported is in proportion correct. Analysis revealed no main effect of stimulation group on accuracy, $F(2, 57) = 0.258$, $p = .773$, $\eta_p^2 = 0.009$. A main effect of task type was found, $F(1, 57) = 45.978$, $p < .001$, $\eta_p^2 = 0.446$, where features task ($M = 0.659$, $SD = 0.082$) had lower accuracy compared to whole faces task ($M = 0.732$, $SD = 0.08$). No significant interaction effect was found between stimulation group and task type on accuracy, $F(2, 57) = 0.504$, $p = .607$, $\eta_p^2 = 0.017$.

A second mixed ANOVA was conducted to examine if there was any difference in reaction time for correct trials between stimulation group prior to stimulation. Analysis revealed no main effect of stimulation group, $F(2, 57) = 0.389$, $p = .679$, $\eta_p^2 = 0.013$. A main effect of task type was found, $F(1, 57) = 20.909$, $p < .001$, $\eta_p^2 = 0.268$, where the features task ($M = 1.14$s, $SD = 0.253$s) had longer reaction time for correct trials compared to the whole faces task ($M = 1.05$s, $SD = 0.214$s). No significant interaction effect was found between stimulation group and task type on reaction time for correct trials, $F(2, 57) = 2.403$, $p = .1$, $\eta_p^2 = 0.078$.

Altogether, the results showed no difference in face recognition ability and age between stimulation groups prior to receiving stimulation. However, the features task had lower accuracy and longer reaction time compared to the whole faces task.

Accuracy and median reaction time analysis

A mixed 2 (task type: features vs. whole faces) × 2 (session: pre vs. post) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA was conducted on accuracy calculated by proportion correct (Fig. 12). Analysis revealed no main effect of stimulation type, $F(2, 57) = 0.173$, $p = .842$, $\eta_p^2 = 0.006$, or session, $F(1, 57) = 2.432$, $p = .124$, $\eta_p^2 = 0.041$. A main effect of task type was found, $F(1, 57) = 75.496$, $p < .001$, $\eta_p^2 = 0.570$, where features task ($M = 0.658$, $SD = 0.083$) had lower accuracy compared to whole faces task ($M = 0.722$, $SD = 0.082$). The analysis revealed no interaction effect of stimulation type and task type, $F(2, 57) = 1.189$, $p = .312$, $\eta_p^2 = 0.040$, no interaction effect of stimulation type and session, $F(2, 57) = 0.111$, $p = .895$, $\eta_p^2 = 0.004$, no interaction effect of task type and session, $F(1, 57) = 1.988$, $p = .164$, $\eta_p^2 = 0.034$, and no three-way interaction effect of stimulation type, task type and session, $F(2, 57) = 0.153$, $p = .858$, $\eta_p^2 = 0.005$.

We also conducted a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA, FFA and sham stimulation. A 3 (stimulation type: OFA vs. FFA vs. sham) × 3 (feature type: eyes vs. nose vs. mouth) × 2 (session: pre vs. post) mixed ANOVA was conducted on accuracy (Fig. 13). When Mauchly's test indicated that the assumption of sphericity had been violated, the degrees of freedom was corrected using Greenhouse-Geisser estimates of sphericity. Analysis revealed no main effect of stimulation type, $F(2, 57) = 0.230$, $p = .795$, $\eta_p^2 = 0.008$, session, $F(1, 57) = 0.003$, $p = .955$, $\eta_p^2 = 0.001$ or feature type, $F(1.810, 103.144) = 0.596$, $p = .537$, $\eta_p^2 = 0.010$. The analysis also revealed no interaction effect of stimulation type and feature type, $F(3.619, 103.144) = 0.453$, $p = .751$, $\eta_p^2 = 0.016$, no interaction effect of stimulation type and session, $F(2, 57) = 0.214$, $p = .808$, $\eta_p^2 = 0.007$, no interaction effect of feature type and session, $F(2, 114) = 2.312$, $p = .104$, $\eta_p^2 = 0.039$, and no three-way interaction effect of stimulation type, feature type and session, $F(4, 114) = 1.099$, $p = .361$, $\eta_p^2 = 0.037$.

A mixed 2 (task type: features vs. whole faces) × 2 (session: pre vs. post) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA was conducted on median reaction time for correct trials (Fig. 12). No main effect of stimulation type was found, $F(2, 57) = 0.256$, $p = .775$, $\eta_p^2 = 0.009$. A significant main effect of session was found, $F(1, 57) = 23.764$, $p < .001$, $\eta_p^2 = 0.294$, where pre-stimulation trials ($M = 1.095$s, $SD = 0.238$s) had longer reaction time compared to post-stimulation trials ($M = 1$s, $SD = 0.210$s). Analysis revealed a significant main effect of task type, $F(1, 57) = 30.555$, $p < .001$, $\eta_p^2 = 0.349$, where features task ($M = 1.085$s, $SD = 0.247$s) had longer reaction time compared to whole faces task ($M = 1.011$s, $SD = 0.203$s). Analysis also revealed no interaction effect of stimulation type and task type, $F(2, 57) = 2.346$, $p = .105$, $\eta_p^2 = 0.076$, no interaction effect of stimulation type and session, $F(2, 57) = 0.280$, $p = .757$, $\eta_p^2 = 0.010$, and no interaction effect of task type and session, $F(1, 57) = 2.289$, $p = .136$, $\eta_p^2 = 0.039$.

A three-way interaction effect of stimulation type, task type and session was found, $F(2, 57) = 3.406$, $p = .04$, $\eta_p^2 = 0.107$. To further explore this three-way interaction effect, we calculated the difference in reaction time between pre- and post-stimulation for each variable ($RT_{Pre} - RT_{Post}$). A higher value would indicate improvement in reaction time (shorter reaction time) after stimulation. We analyzed these scores using a 2 (task type: features vs. whole faces) × 3 (simulation type: FFA vs. OFA vs. sham) ANOVA. Analysis revealed no main effect of task type, $F(1, 57) = 2.289$, $p = .136$, $\eta_p^2 = 0.039$, or stimulation type, $F(2, 57) = 0.280$, $p = .757$, $\eta_p^2 = 0.010$. A significant interaction effect of task type and stimulation was found, $F(2, 57) = 3.406$, $p = .04$, $\eta_p^2 = 0.107$. Simple main effect analysis showed that features task ($M = 0.123$s, $SD = 0.167$s) had a larger improvement in reaction time compared to whole face task ($M = 0.036$s, $SD = 0.187$s) after FFA stimulation, $F(1, 19) = 6.35$, $p = .021$, $\eta^2 = 0.25$. No difference between features task and whole face task was found for OFA stimulation, $F(1, 19) = 1.267$, $p = .274$, $\eta^2 = 0.063$, and sham stimulation, $F(1, 19) = 2.207$, $p = .154$, $\eta^2 = 0.104$.

Additionally, a 3 (stimulation type: OFA vs. FFA vs. sham) × 3 (feature type: eyes vs. nose vs. mouth) × 2 (session: pre vs. post) mixed ANOVA was conducted on median reaction times for correct responses as a post-hoc exploratory analysis to investigate whether there were any differences across facial features recognition following the OFA and FFA stimulation (Fig. 13). No main effect of stimulation type, $F(2, 57) = 0.660$, $p = .521$, $\eta_p^2 = 0.023$ and feature type, $F(2, 114) = 0.656$, $p = .521$, $\eta_p^2 = 0.011$ was found. A significant main effect of session was found, $F(1, 57) = 29.837$, $p < .001$, $\eta_p^2 = 0.344$, where pre-stimulation trials ($M = 1.149$s, $SD = 0.282$s) had longer reaction time compared to post-stimulation trials ($M = 1.041$s, $SD = 0.277$s). Analysis also revealed no interaction effect of stimulation type and feature type, $F(4, 114) = 0.920$, $p = .455$, $\eta_p^2 = 0.031$, no interaction effect of stimulation type and session, $F(2, 57) = 0.866$, $p = .426$, $\eta_p^2 = 0.029$, no interaction effect of feature type and session, $F(2, 114) = 2.270$, $p = .108$, $\eta_p^2 = 0.038$ and no three-way interaction effect of stimulation type, feature type and session was found, $F(4, 114) = 0.718$, $p = .581$, $\eta_p^2 = 0.025$.

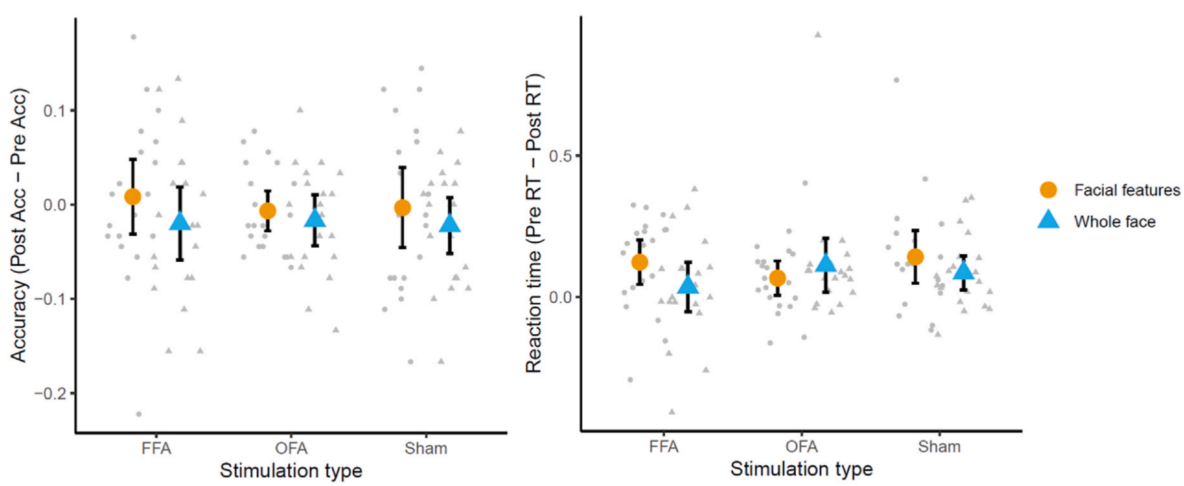

Fig. 12. Accuracy (post-minus pre-stimulation) and reaction time (pre-minus post-stimulation) of features and whole face recognition tasks for OFA, FFA and sham stimulation. Error bars represent 95% confidence interval.

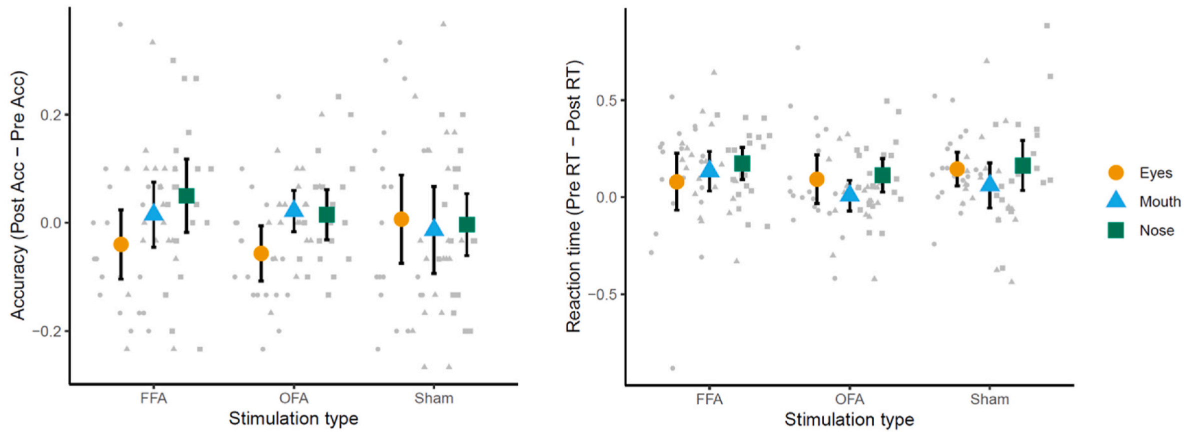

Fig. 13. Accuracy (post-minus pre-stimulation) and reaction time (pre-minus post-stimulation) of facial features recognition tasks for OFA, FFA and sham stimulation. Error bars represent 95% confidence interval.

References

Ambrus, G.G., Amado, C., Krohn, L., Kovács, G., 2019. TMS of the occipital face area modulates cross-domain identity priming. Brain Struct. Funct. 224 (1), 149–157. https://doi.org/10.1007/s00429-018-1768-0.

Ambrus, G.G., Windel, F., Burton, A.M., Kovács, G., 2017. Causal evidence of the involvement of the right occipital face area in face-identity acquisition. Neuroimage 148, 212–218. https://doi.org/10.1016/j.neuroimage.2017.01.043.

Ankri, Y.L.E., Braw, Y., Luboshits, G., Meiron, O., 2020. The effects of stress and transcranial direct current stimulation (tDCS) on working memory: a randomized controlled trial. Cognit. Affect Behav. Neurosci. 20 (1), 103–114. https://doi.org/10.3758/s13415-019-00755-7.

Balas, B., Pacella, J., 2015. Artificial faces are harder to remember. Comput. Hum. Behav. 52, 331–337. https://doi.org/10.1016/j.chb.2015.06.018.

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. https://doi.org/10.1016/j.neuropsychologia.2015.12.030.

Barton, J.J.S., Press, D.Z., Keenan, J.P., O'Connor, M., 2002. Lesions of the fusiform face area impair perception of facial configuration in prosopagnosia. Neurology 58, 71–78. https://doi.org/10.1212/WNL.58.1.71.

Bona, S., Cattaneo, Z., Silvanto, J., 2016. Investigating the causal role of rOFA in holistic detection of Mooney faces and objects: an fMRI-guided TMS study. Brain Stimul. 9 (4), 594–600. https://doi.org/10.1016/j.brs.2016.04.003.

Brunoni, A.R., Vanderhasselt, M.A., 2014. Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: a systematic review and meta-analysis. Brain Cognit. 86, 1–9. https://doi.org/10.1016/j.bandc.2014.01.008.

Brunyé, T.T., Moran, J.M., Holmes, A., Mahoney, C.R., Taylor, H.A., 2017. Non-invasive brain stimulation targeting the right fusiform gyrus selectively increases working memory for faces. Brain Cognit. 113, 32–39. https://doi.org/10.1016/j.bandc.2017.01.006.

Bukach, C.M., Bub, D.N., Gauthier, I., Tarr, M.J., 2006. Perceptual expertise effects are not all or none: spatially limited perceptual expertise for faces in a case of prosopagnosia. J. Cognit. Neurosci. 18 (1), 48–63. https://doi.org/10.1162/089892906775250094.

Bukach, C.M., Le Grand, R., Kaiser, M.D., Bub, D.N., Tanaka, J.W., 2008. Preservation of mouth region processing in two cases of prosopagnosia. J. Neuropsychol. 2 (Pt 1), 227–244. https://doi.org/10.1348/174866407X231010.

Burns, E.J., Arnold, T., Bukach, C.M., 2019. P-curving the fusiform face area: meta-analyses support the expertise hypothesis. Neurosci. Biobehav. Rev. 104 (July), 209–221. https://doi.org/10.1016/j.neubiorev.2019.07.003.

Costantino, A.I., Titoni, M., Bossi, F., Premoli, I., Nitsche, M.A., Rivolta, D., 2017. Preliminary evidence of "other-race effect"-like behavior induced by cathodal-tDCS over the right occipital cortex, in the absence of overall effects on face/object processing. Front. Neurosci. 11, 661. https://doi.org/10.3389/fnins.2017.00661.

Dachille, L.R., Gold, J.M., James, T.W., 2012. The response of face-selective cortex with single face parts and part combinations. Neuropsychologia 50 (10), 2454–2459. https://doi.org/10.1016/j.neuropsychologia.2012.06.016.

de Heering, A., Rossion, B., 2015. Rapid categorization of natural face images in the infant right hemisphere. Elife 4, e06564. https://doi.org/10.7554/eLife.06564.

DeGutis, J., Cohan, S., Mercado, R.J., Wilmer, J., Nakayama, K., 2012. Holistic processing of the mouth but not the eyes in developmental prosopagnosia. Cogn. Neuropsychol. 29 (5–6), 419–446. https://doi.org/10.1080/02643294.2012.754745.

Eick, C.M., Kovács, G., Rostalski, S.M., Röhrig, L., Ambrus, G.G., 2020. The occipital face area is causally involved in identity-related visual-semantic associations. Brain Struct. Funct. 225 (5), 1483–1493. https://doi.org/10.1007/s00429-020-02068-9.

Estudillo, A.J., 2021. Self-reported face recognition abilities for own and other-race faces. J. Crim. Psychol. 11 (2), 105–115. https://doi.org/10.1108/JCP-06-2020-0025.

Estudillo, A.J., Lee, J.K.W., Mennie, N., Burns, E., 2020. No evidence of other-race effect for Chinese faces in Malaysian non-Chinese population. Appl. Cognit. Psychol. 34 (1), 270–276. https://doi.org/10.1002/acp.3609.

Estudillo, A.J., Lee, Y.J., Álvarez-Montesinos, J.A., García-Orza, J., 2023. High-frequency transcranial random noise stimulation enhances unfamiliar face matching of high resolution and pixelated faces. Brain Cognit. 165, 105937 https://doi.org/10.1016/j.bandc.2022.105937.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.G., 2009. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav. Res. Methods 41 (4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149.

Fischer, D.B., Fried, P.J., Ruffini, G., Ripolles, O., Salvador, R., Banus, J., Ketchabaw, W. T., Santarnecchi, E., Pascual-Leone, A., Fox, M.D., 2017. Multifocal tDCS targeting the resting state motor network increases cortical excitability beyond traditional tDCS targeting unilateral motor cortex. Neuroimage 157, 34–44. https://doi.org/10.1016/j.neuroimage.2017.05.060.

Fox, C.J., Moon, S., Iaria, G., Barton, J.S., 2009. The correlates of subjective perception of identity and expression in the face network: an fMRI adaptation study. Neuroimage 44 (2), 569–580. https://doi.org/10.1016/j.neuroimage.2008.09.011.

Friehs, M.A., Frings, C., 2019. Offline beats online. NeuroReport 30 (12), 795–799. https://doi.org/10.1097/WNR.0000000000001272.

Gao, W., Cao, B., Shan, S., Chen, X., Zhou, D., Zhang, X., Zhao, D., 2008. The CAS-PEAL large-scale Chinese face database and baseline evaluations. IEEE Trans. Syst. Man Cybern. Syst. Hum. 38 (1), 149–161. https://doi.org/10.1109/TSMCA.2007.909557.

Gauthier, I., Bukach, C., 2007. Should we reject the expertise hypothesis? Cognition 103 (2), 322–330. https://doi.org/10.1016/j.cognition.2006.05.003.

Gauthier, I., Tarr, M.J., Moylan, J., Skudlarski, P., Gore, J.C., Anderson, A.W., 2000. The fusiform "face area" is part of a network that processes faces at the individual level. J. Cognit. Neurosci. 12 (3), 495–504. https://doi.org/10.1162/089892900562165.

Gill, J., Shah-Basak, P.P., Hamilton, R., 2015. It's the thought that counts: examining the task-dependent effects of transcranial direct current stimulation on executive function. Brain Stimul. 8 (2), 253–259. https://doi.org/10.1016/j.brs.2014.10.018.

Gonzalez-Perez, M., Wakui, E., Thoma, V., Nitsche, M.A., Rivolta, D., 2019. Transcranial alternating current stimulation (tACS) at 40 Hz enhances face and object perception. Neuropsychologia 135, 107237. https://doi.org/10.1016/j.neuropsychologia.2019.107237.

Grill-Spector, K., Weiner, K.S., Gomez, J., Stigliani, A., Natu, V.S., 2018. The functional neuroanatomy of face perception: from brain measurements to deep neural networks. Interface Focus 8, 20180013. https://doi.org/10.1098/rsfs.2018.0013.

Gueugneau, N., Pozzo, T., Darlot, C., Papaxanthis, C., 2017. Daily modulation of the speed–accuracy trade-off. Neuroscience 356, 142–150. https://doi.org/10.1016/j.neuroscience.2017.04.043.

Haxby, J.V., Hoffman, E. a, Gobbini, M.I., 2000. The distributed human neural system for face perception. Trends Cognit. Sci. 4 (6), 223–233. https://doi.org/10.1016/S1364-6613(00)01482-0.

Hayward, W.G., Rhodes, G., Schwaninger, A., 2008. An own-race advantage for components as well as configurations in face recognition. Cognition 106 (2), 1017–1027. https://doi.org/10.1016/j.cognition.2007.04.002.

Heitz, R.P., 2014. The speed-accuracy tradeoff: history, physiology, methodology, and behavior. Front. Neurosci. 8, 150. https://doi.org/10.3389/fnins.2014.00150.

Hill, A.T., Fitzgerald, P.B., Hoy, K.E., 2016. Effects of anodal transcranial direct current stimulation on working memory: a systematic review and meta-analysis of findings from healthy and neuropsychiatric populations. Brain Stimul. 9 (2), 197–208. https://doi.org/10.1016/j.brs.2015.10.006.

Horvath, J.C., Vogrin, S.J., Carter, O., Cook, M.J., Forte, J.D., 2015. Effects of transcranial direct current stimulation on motor evoked potential amplitude are

neither reliable nor significant within individuals over 9 separate testing sessions. Brain Stimul. 8, 310–325. https://doi.org/10.1016/j.brs.2015.01.033.
Hsu, W.Y., Zanto, T.P., Anguera, J.A., Lin, Y.Y., Gazzaley, A., 2015. Delayed enhancement of multitasking performance: effects of anodal transcranial direct current stimulation on the prefrontal cortex. Cortex 69, 175–185. https://doi.org/10.1016/j.cortex.2015.05.014.
Ishai, A., 2008. Let's face it: it's a cortical network. Neuroimage 40 (2), 415–419. https://doi.org/10.1016/j.neuroimage.2007.10.040.
Jacobson, L., Koslowsky, M., Lavidor, M., 2012. TDCS polarity effects in motor and cognitive domains: a meta-analytical review. Exp. Brain Res. 216, 1–10. https://doi.org/10.1007/s00221-011-2891-9.
JASP Team, 2022. JASP. Computer software, Version 0.16.3. https://jasp-stats.org/.
Kadosh, K.C., Walsh, V., Kadosh, R.C., 2010. Investigating face-property specific processing in the right OFA. Soc. Cognit. Affect Neurosci. 6, 58–65. https://doi.org/10.1093/scan/nsq015.
Kanwisher, N., McDermott, J., Chun, M.M., 1997. The fusiform face area: a module in human extrastriate cortex specialized for face perception. J. Neurosci. 17 (11), 4302–4311. https://doi.org/10.1523/JNEUROSCI.17-11-04302.1997.
Kätsyri, J., 2018. Those virtual people all look the same to me: computer-rendered faces elicit a higher false alarm rate than real human faces in a recognition memory task. Front. Psychol. 9, 1362. https://doi.org/10.3389/fpsyg.2018.01362.
Kim, M., Ducros, M., Carlson, T., Ronen, I., He, S., Ugurbil, K., Kim, D.S., 2006. Anatomical correlates of the functional organization in the human occipitotemporal cortex. Magn. Reson. Imag. 24 (5), 583–590. https://doi.org/10.1016/j.mri.2005.12.005.
Krause, B., Cohen Kadosh, R., 2014. Not all brains are created equal: the relevance of individual differences in responsiveness to transcranial electrical stimulation. Front. Syst. Neurosci. 8, 25. https://doi.org/10.3389/fnsys.2014.00025.
Laakso, I., Mikkonen, M., Koyama, S., Hirata, A., Tanaka, S., 2019. Can electric fields explain inter-individual variability in transcranial direct current stimulation of the motor cortex? Sci. Rep. 9, 626. https://doi.org/10.1038/s41598-018-37226-x.
Latinus, M., Taylor, M.J., 2005. Holistic processing of faces: learning effects with Mooney faces. J. Cognit. Neurosci. 17 (8), 1316–1327. https://doi.org/10.1162/0898929055002490.
Learmonth, G., Felisatti, F., Siriwardena, N., Checketts, M., Benwell, C.S.Y., Märker, G., Thut, G., Harvey, M., 2017. No interaction between tDCS current strength and baseline performance: a conceptual replication. Front. Neurosci. 11 https://doi.org/10.3389/fnins.2017.00664.
Liesefeld, H.R., Fu, X., Zimmer, H.D., 2015. Fast and careless or careful and slow? Apparent holistic processing in mental rotation is explained by speed-accuracy trade-offs. J. Exp. Psychol. Learn. Mem. Cognit. 41 (4), 1140–1151. https://doi.org/10.1037/xlm0000081.
Liu, J., Harris, A., Kanwisher, N., 2010. Perception of face parts and face configurations: an fMRI study. J. Cognit. Neurosci. 22 (1), 203–211. https://doi.org/10.1162/jocn.2009.21203.
López-Alonso, V., Cheeran, B., Río-Rodríguez, D., Fernández-Del-Olmo, M., 2014. Inter-individual variability in response to non-invasive brain stimulation paradigms. Brain Stimul. 7 (3), 372–380. https://doi.org/10.1016/j.brs.2014.02.004.
McCarthy, G., Puce, A., Gore, J.C., Allison, T., 1997. Face-specific processing in the human fusiform gyrus. J. Cognit. Neurosci. 9 (5), 605–610. https://doi.org/10.1162/jocn.1997.9.5.605.
McKone, E., Kanwisher, N., Duchaine, B.C., 2007. Can generic expertise explain special processing for faces? Trends Cognit. Sci. 11 (1), 8–15. https://doi.org/10.1016/j.tics.2006.11.002.
Meissner, C.A., Brigham, J.C., 2001. Thirty years of investigating the own-race bias in memory for faces: a meta-analytic review. Psychol. Publ. Pol. Law 7 (1), 3–35. https://doi.org/10.1037/1076-8971.7.1.3.
Mooney, C.M., 1957. Age in the development of closure ability in children. Can. J. Psychol. 11 (4), 219–226. https://doi.org/10.1037/h0083717.
Moscovitch, M., Winocur, G., Behrmann, M., 1997. What is special about face recognition? Nineteen experiments on a person with visual object agnosia and dyslexia but normal face recognition. J. Cognit. Neurosci. 9 (5), 555–604. https://doi.org/10.1162/jocn.1997.9.5.555.
Mulquiney, P.G., Hoy, K.E., Daskalakis, Z.J., Fitzgerald, P.B., 2011. Improving working memory: exploring the effect of transcranial random noise stimulation and transcranial direct current stimulation on the dorsolateral prefrontal cortex. Clin. Neurophysiol. 122 (12), 2384–2389. https://doi.org/10.1016/j.clinph.2011.05.009.
Nelson, J.T., McKinley, R.A., Golob, E.J., Warm, J.S., Parasuraman, R., 2014. Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). Neuroimage 85, 909–917. https://doi.org/10.1016/j.neuroimage.2012.11.061.
Nichols, D.F., Betts, L.R., Wilson, H.R., 2010. Decoding of faces and face components in face-sensitive human visual cortex. Front. Psychol. 1 https://doi.org/10.3389/fpsyg.2010.00028.
Nitsche, M.A., Paulus, W., 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J. Physiol. 527 (3), 633–639. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x.
Peirce, J., Gray, J.R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J.K., 2019. PsychoPy2: experiments in behavior made easy. Behav. Res. Methods 51 (1), 195–203. https://doi.org/10.3758/s13428-018-01193-y.
Penton, T., Bate, S., Dalrymple, K.A., Reed, T., Kelly, M., Godovich, S., Tamm, M., Duchaine, B., Banissy, M.J., 2018. Using high frequency transcranial random noise stimulation to modulate face memory performance in younger and older adults: lessons learnt from mixed findings. Front. Neurosci. 12, 863. https://doi.org/10.3389/fnins.2018.00863.
Pitcher, D., Walsh, V., Yovel, G., Duchaine, B., 2007. TMS evidence for the involvement of the right occipital face area in early face processing. Curr. Biol. 17 (18), 1568–1573. https://doi.org/10.1016/j.cub.2007.07.063.
Pope, P.A., Miall, R.C., 2012. Task-specific facilitation of cognition by cathodal transcranial direct current stimulation of the cerebellum. Brain Stimul. 5 (2), 84–94. https://doi.org/10.1016/j.brs.2012.03.006.
Popescu, T., Krause, B., Terhune, D.B., Twose, O., Page, T., Humphreys, G., Cohen Kadosh, R., 2016. Transcranial random noise stimulation mitigates increased difficulty in an arithmetic learning task. Neuropsychologia 81, 255–264. https://doi.org/10.1016/j.neuropsychologia.2015.12.028.
Rangarajan, V., Hermes, D., Foster, B.L., Weiner, K.S., Jacques, X.C., Grill-Spector, K., Parvizi, J., 2014. Electrical stimulation of the left and right human fusiform gyrus causes different effects in conscious face perception. J. Neurosci. 34 (38), 12828–12836. https://doi.org/10.1523/JNEUROSCI.0527-14.2014.
Reed, T., Cohen Kadosh, R., 2018. Transcranial electrical stimulation (tES) mechanisms and its effects on cortical excitability and connectivity. J. Inherit. Metab. Dis. 41 (6), 1123–1130. https://doi.org/10.1007/s10545-018-0181-4.
Renzi, C., Ferrari, C., Schiavi, S., Pisoni, A., Papagno, C., Vecchi, T., Antal, A., Cattaneo, Z., 2015. The role of the occipital face area in holistic processing involved in face detection and discrimination: a tDCS study. Neuropsychology 29 (3), 409–416. https://doi.org/10.1037/neu0000127.
Reteig, L.C., Talsma, L.J., van Schouwenburg, M.R., Slagter, H.A., 2017. Transcranial electrical stimulation as a tool to enhance attention. Journal of Cognitive Enhancement 1, 10–25. https://doi.org/10.1007/s41465-017-0010-y.
Retter, T.L., Rossion, B., 2015. Global shape information increases but color information decreases the composite face effect. Perception 44 (5), 511–528. https://doi.org/10.1068/p7826.
Rhodes, G., 1993. Configural coding, expertise, and the right hemisphere advantage for face recognition. Brain Cognit. 22 (1), 19–41. https://doi.org/10.1006/brcg.1993.1022.
Rhodes, G., Michie, P.T., Hughes, M.E., Byatt, G., 2009. The fusiform face area and occipital face area show sensitivity to spatial relations in faces. Eur. J. Neurosci. 30 (4), 721–733. https://doi.org/10.1111/j.1460-9568.2009.06861.x.
Rivolta, D., Palermo, R., Schmalzl, L., Williams, M.A., 2012. Investigating the features of the M170 in congenital prosopagnosia. Front. Hum. Neurosci. 6, 45. https://doi.org/10.3389/fnhum.2012.00045.
Robbins, R., McKone, E., 2007. No face-like processing for objects-of-expertise in three behavioural tasks. Cognition 103, 34–79. https://doi.org/10.1016/j.cognition.2006.02.008.
Röhner, F., Breitling, C., Rufener, K.S., Heinze, H.-J., Hinrichs, H., Krauel, K., Sweeney-Reed, C.M., 2018. Modulation of working memory using transcranial electrical stimulation: a direct comparison between TACS and TDCS. Front. Neurosci. 12, 761. https://doi.org/10.3389/fnins.2018.00761.
Romanska, A., Rezlescu, C., Susilo, T., Duchaine, B., Banissy, M.J., 2015. High-frequency transcranial random noise stimulation enhances perception of facial identity. Cerebr. Cortex 25 (11), 4334–4340. https://doi.org/10.1093/cercor/bhv016.
Rossion, B., Caldara, R., Seghier, M., Schuller, A.M., Lazeyras, F., Mayer, E., 2003. A network of occipito-temporal face-sensitive areas besides the right middle fusiform gyrus is necessary for normal face processing. Brain 126 (11), 2381–2395. https://doi.org/10.1093/brain/awg241.
Rufener, K.S., Krauel, K., Meyer, M., Heinze, H.J., Zaehle, T., 2019. Transcranial electrical stimulation improves phoneme processing in developmental dyslexia. Brain Stimul. 12 (4), 930–937. https://doi.org/10.1016/j.brs.2019.02.007.
Ruffini, G., Fox, M.D., Ripolles, O., Miranda, P.C., Pascual-Leone, A., 2014. Optimization of multifocal transcranial current stimulation for weighted cortical pattern targeting from realistic modeling of electric fields. Neuroimage 89, 216–225. https://doi.org/10.1016/j.neuroimage.2013.12.002.
Rütsche, B., Hauser, T.U., Jäncke, L., Grabner, R.H., 2015. When problem size matters: differential effects of brain stimulation on arithmetic problem solving and neural oscillations. PLoS One 10 (3), e0120665. https://doi.org/10.1371/journal.pone.0120665.
Schiltz, C., Dricot, L., Goebel, R., Rossion, B., 2010. Holistic perception of individual faces in the right middle fusiform gyrus as evidenced by the composite face illusion. J. Vis. 10 (2), 1–16. https://doi.org/10.1167/10.2.25.
Schiltz, C., Rossion, B., 2006. Faces are represented holistically in the human occipito-temporal cortex. Neuroimage 32 (3), 1385–1394. https://doi.org/10.1016/j.neuroimage.2006.05.037.
Smith, M.J., Adams, L.F., Schmidt, P.J., Rubinow, D.R., Wassermann, E.M., 2002. Effects of ovarian hormones on human cortical excitability. Ann. Neurol. 51 (5), 599–603. https://doi.org/10.1002/ana.10180.
Solomon-Harris, L.M., Mullin, C.R., Steeves, J.K.E., 2013. TMS to the "occipital face area" affects recognition but not categorization of faces. Brain Cognit. 83 (3), 245–251. https://doi.org/10.1016/j.bandc.2013.08.007.
Steeves, J.K.E., Culham, J.C., Duchaine, B.C., Pratesi, C.C., Valyear, K.F., Schindler, I., Humphrey, G.K., Milner, A.D., Goodale, M.A., 2006. The fusiform face area is not sufficient for face recognition: evidence from a patient with dense prosopagnosia and no occipital face area. Neuropsychologia 44 (4), 594–609. https://doi.org/10.1016/j.neuropsychologia.2005.06.013.
Tardif, J., Morin Duchesne, X., Cohan, S., Royer, J., Blais, C., Fiset, D., Duchaine, B., Gosselin, F., 2019. Use of face information varies systematically from developmental prosopagnosics to super-recognizers. Psychol. Sci. 30 (2), 300–308. https://doi.org/10.1177/0956797618811338.
Thair, H., Holloway, A.L., Newport, R., Smith, A.D., 2017. Transcranial direct current stimulation (tDCS): a beginner's guide for design and implementation. Front. Neurosci. 11, 641. https://doi.org/10.3389/fnins.2017.00641.

Vandierendonck, A., 2017. A comparison of methods to combine speed and accuracy measures of performance: a rejoinder on the binning procedure. Behav. Res. Methods 49 (2), 653–673. https://doi.org/10.3758/s13428-016-0721-5.

Vergallito, A., Romero Lauro, L.J., Bonandrini, R., Zapparoli, L., Danelli, L., Berlingeri, M., 2018. What is difficult for you can be easy for me. Effects of increasing individual task demand on prefrontal lateralization: a tDCS study. Neuropsychologia 109 (2018), 283–294. https://doi.org/10.1016/j.neuropsychologia.2017.12.038.

Wickelgren, W.A., 1977. Speed-accuracy tradeoff and information processing dynamics. Acta Psychol. 41 (1), 67–85. https://doi.org/10.1016/0001-6918(77)90012-9.

Willis, M.L., Costantino, A.I., Nitsche, M.A., Palermo, R., Rivolta, D., 2019. Anodal tDCS and high-frequency tRNS targeting the occipitotemporal cortex do not always enhance face perception. Front. Neurosci. 13, 78. https://doi.org/10.3389/fnins.2019.00078.

Willis, M.L., Murphy, J.M., Ridley, N.J., Vercammen, A., 2015. Anodal tDCS targeting the right orbitofrontal cortex enhances facial expression recognition. Soc. Cognit. Affect Neurosci. 10 (12), 1677–1683. https://doi.org/10.1093/scan/nsv057.

Woltz, D.J., Was, C.A., 2006. Availability of related long-term memory during and after attention focus in working memory. Mem. Cognit. 34 (3), 668–684. https://doi.org/10.3758/BF03193587.

Wong, H.K., Stephen, I.D., Keeble, D.R.T., 2020. The own-race bias for face recognition in a multiracial society. Front. Psychol. 11, 208. https://doi.org/10.3389/fpsyg.2020.00208.

Xu, X., Biederman, I., 2010. Loci of the release from fMRI adaptation for changes in facial expression, identity, and viewpoint. J. Vis. 10 (14), 1–13. https://doi.org/10.1167/10.14.1.

Yamada, Y., Sumiyoshi, T., 2021. Neurobiological mechanisms of transcranial direct current stimulation for psychiatric disorders; neurophysiological, chemical, and anatomical considerations. Front. Hum. Neurosci. 15, 631838 https://doi.org/10.3389/fnhum.2021.631838.

Yang, L.Z., Zhang, W., Shi, B., Yang, Z., Wei, Z., Gu, F., Zhang, J., Cui, G., Liu, Y., Zhou, Y., Zhang, X., Rao, H., 2014. Electrical stimulation over bilateral occipito-temporal regions reduces N170 in the right hemisphere and the composite face effect. PLoS One 9 (12), e115772. https://doi.org/10.1371/journal.pone.0115772.

Yovel, G., Kanwisher, N., 2004. Face perception: domain specific, not process specific. Neuron 44 (5), 889–898. https://doi.org/10.1016/j.neuron.2004.11.018.

Yovel, G., Kanwisher, N., 2005. The neural basis of the behavioral face-inversion effect. Curr. Biol. 15 (24), 2256–2262. https://doi.org/10.1016/j.cub.2005.10.072.

Zhang, J., Li, X., Song, Y., Liu, J., 2012. The fusiform face area is engaged in holistic, not parts-based, representation of faces. PLoS One 7 (7), e40390. https://doi.org/10.1371/journal.pone.0040390.