



## Research Report

# Objective neural face recognition neuromodulation within a single transcranial direct current stimulation session



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## ARTICLE INFO

## Article history:

Received 1 October 2025

Revised 12 March 2026

Accepted 18 March 2026

Action editor Nicholas Paul Holmes

Published online 24 March 2026

## Keywords:

Neuromodulation

tDCS

Face recognition

EEG

Fast periodic visual stimulation

## ABSTRACT

Due to considerable technical and methodological challenges, neuromodulatory effects of online and post-stimulation transcranial direct current electrical stimulation (tDCS) on human cognition remain unclear. Here we evaluated these effects of tDCS on a sensitive, objective and reliable neural marker of human face identity recognition. Eighteen participants took part in this combined tDCS-EEG study. Following a sham tDCS period during rapid periodic individuation of pictures of unfamiliar faces (Phase 1), tDCS was applied for 10 min during the same visual stimulation over the right occipito-temporal cortex (Phase 2), followed by a second sham tDCS period (Phase 3). The face individuation neural electroencephalographic (EEG) response confined to small frequency bins (.014 Hz bandwidth) was significantly reduced by 28% during tDCS. After tDCS, a 66% increase compared to during-tDCS level, i.e., ‘rebound’ effect, was observed. These effects were of equal magnitude over occipito-temporal regions of the two hemispheres and only limited to neural face individuation, with general neural responses to the global periodic visual stimuli being unaffected. Overall, these observations demonstrate significant and selective neuromodulation of a key human cognitive brain function using a single tDCS session and only two HD-ring electrodes, highlighting the interest of frequency-tagged electrophysiology to quantify neuromodulation effects.

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<https://doi.org/10.1016/j.cortex.2026.03.013>

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## 1. Introduction

Transcranial direct current electrical stimulation (tDCS) has been used for many years in fundamental and translational research to non-invasively neuromodulate human sensory, motor and cognitive functions (Bastani & Jaberzadeh, 2012; Dedoncker et al., 2016; Hill et al., 2016). tDCS is based on injecting low-intensity (i.e., a few milliamperes) direct currents onto the scalp for several minutes (for recent review see (Antal et al., 2017; Woods et al., 2016)). Since the 2000s, the use of tDCS as an alternative (or complementary) treatment for different neurological, psychiatric, and cognitive disorders has been widely studied (for reviews, see (Ciullo et al., 2021) and (Lefaucheur et al., 2017), which address psychiatric and neurological conditions, respectively).

However, both online and post-stimulation effects of tDCS on human brain function generally remain debated and controversial (Friebs & Frings, 2019; Živanovi et al., 2021). One key issue is that studies of tDCS effects on cognitive brain function often rely on explicit behavioral measures (i.e., accuracy rates, response times) (Begemann et al., 2020), which are influenced by many general factors, such as attention, decision-making, and motor coordination. Thus, low accuracy or slow response times at a face identity recognition (FIR) task for instance may reflect deficits in these general processes rather than in the ability to recognize faces. Furthermore, these tests are limited by their difficulty in capturing essential aspects of real-world face recognition, such as its automaticity and speed, as laboratory tasks with long exposure durations and artificial stimuli promote analytical strategies that do not reflect natural processes (Rossion et al., 2020a; Volfart & Rossion, 2024).

Among human cognitive functions, face identity recognition (FIR) is particularly crucial for human social life and interactions, involving a large (right predominant) occipito-temporal cortical network in our species (Grill-Spector et al., 2017; Haxby et al., 2000; Jonas et al., 2016; Sergent & Signoret, 1992). Several tDCS studies have reported behavioral modulations of FIR (Barbieri et al., 2016; Civile et al., 2018; Civile & McLaren, 2022; Renzi et al., 2015). However, these effects have been relatively weak, and other studies have failed to report congruent effects (Kho et al., 2023; Willis et al., 2019), leading to a lack of clear demonstration of tDCS modulation of human FIR. Some methodological limitations of reported studies may be the tDCS application over non-relevant or suboptimal brain locations such as the dorsolateral prefrontal cortex (DLPFC) (Civile et al., 2018; Civile & McLaren, 2022). For instance, in a series of tDCS studies, Civile et al. (Civile et al., 2018, 2020; Civile & McLaren, 2022) investigated the face inversion effect (i.e., lower FIR performance for inverted compared to upright faces). In the stimulation protocol, anodal tDCS was delivered over the left dorsolateral prefrontal cortex (DLPFC), over area Fp3, while the cathode was placed over the right eyebrow. In subsequent studies, Civile and colleagues found that stimulation over this area decreased the face inversion effect (Civile et al., 2018). With the same neuromodulation protocol, Civile and McLaren (Civile & McLaren, 2022) investigated the face inversion effect for own- or other-race faces. They found that anodal tDCS eliminates the other-

race effect (Meissner & Brigham, 2001; Rossion et al., 2011a) by diminishing the face inversion effect for own-race faces. However, this effect could be due to tDCS affecting the condition associated with the highest performance.

Beyond behavioral measures, an alternative approach is to study the effects of tDCS on implicit measures of brain function using non-invasive electroencephalography (EEG) (Schestatsky et al., 2013; Wunder et al., 2018). For instance, repetition suppression effects to unfamiliar faces on the face-selective N170 event-related potential (Bentin et al., 1996; Rossion et al., 2011b) are modulated by DLPFC stimulation (Lafontaine et al., 2013). Unfortunately, combining tDCS with EEG measures has been seriously limited by the lack of specificity of spontaneous or evoked (i.e., Event-Related Potentials; ERPs) EEG activity, its low signal-to-noise ratio (SNR), and the subjectivity of definition and quantification of responses of interest in the time-domain (peak/window amplitudes and latency measures), especially for individual measurements. Another important challenge concerns the large electrical artifacts generated by the direct current stimulation, which generally prevent the measurement of online effects of tDCS on neural signals recorded with EEG (Faria et al., 2012; Gebodh et al., 2019; Mancini et al., 2015).

Here we circumvent these issues by introducing an original approach to measure the (online) effects of transcranial stimulation on brain function, combining tDCS with EEG recordings during fast periodic (visual) stimulation (FPVS). This latter approach, also known as ‘frequency-tagging’, consists in presenting visual stimuli at a fixed rate, leading to periodic EEG responses that can be expressed in the frequency domain after Fourier Transform (‘Steady-State Evoked Potentials’; (Regan, 1966; Regan, 1989); see (Norcia et al., 2015) for review). It carries considerable advantages in terms of objectivity of definition and quantification of neural responses of interest, which are confined to one or a few frequencies of interest pre-defined by the experimenter. Moreover, signal-to-noise ratio (SNR) is usually very high with this approach, owing to the advantages of presenting numerous stimuli over a relatively short period of time, and the concentration of the signal of interest in small frequency bins that are largely unaffected by broadband EEG noise (Norcia et al., 2015; Regan, 1989).

In the present study, we capitalize on the advantages of this approach to measure FIR before, during and after tDCS as applied directly over the right occipito-temporal cortex.

Specifically, we rely on a face identity oddball paradigm extensively used and validated for a decade (>35 published studies since (Liu-Shuang et al., 2014); see (Rossion et al., 2020b) for a review; more recent studies: e.g. (Hagen et al., 2024; Retter et al., 2021)). In this paradigm, an unfamiliar face identity photograph devoid of external features is repeated with substantial changes of image size at a 6 Hz frequency (i.e., 6 images per second), allowing only one gaze fixation per face stimulus. Every five stimuli, a different unfamiliar face identity is presented (i.e., AAAABAAAACAAAAD ...).

This rapid periodic change of face identities induces an electrophysiological response exactly at the identity change frequency (i.e.,  $6/5 = 1.2$  Hz) predominant over right occipito-temporal regions (Liu-Shuang et al., 2014; Rossion et al., 2020b). This oddball-like paradigm is associated with typical advantages of FPVS-EEG: an implicit direct neural measure

with high objectivity (i.e., frequencies of interest are pre-defined by the experimenters) and sensitivity (high SNR), allowing short experiments of a few minutes. Its validity has been firmly established, showing large reductions of amplitude for the same face stimuli presented upside-down or contrast-reversed (two manipulations known to significantly affect human FIR (Liu-Shuang et al., 2014)), abolished or severely reduced responses in cases of prosopagnosia (Fisher et al., 2020; Liu-Shuang et al., 2016; Volfart et al., 2023) and recruiting typical face-selective regions of the ventral occipito-temporal cortex in intracerebral recordings (Jacques et al., 2020). Hence, this neural measure is particularly well-suited to assess the tDCS effects on human FIR.

The main objective of this study is to quantify the electrophysiological effects of a single tDCS session during face recognition tasks, with the hypothesis that anodal stimulation over the right temporo-occipital region (dominant hemisphere for face recognition) should significantly and specifically increase the face-selective EEG amplitude response.

## 2. Material and methods

### 2.1. Participants

Eighteen participants took part in the study, all of whom provided written informed consent and received financial compensation. The number of participants was determined based on previous studies reporting significant effects (Cohen's  $d \approx .44$ ) with the specific FPVS-EEG paradigm used here (e.g. (Hauk et al., 2021; Zimmermann et al., 2019)). Four participants were excluded due to the presence of muscular artifacts during the EEG recordings. In total, fourteen participants (6 females, 8 males), ranging from 18 to 30 years old, were retained in the study. All of them were right-handed and reported no history of psychiatric, visual, or neurological disorders. This exploratory study was approved by the Lorraine University ethical board and conducted in accordance with the general ethical principles of the Declaration of Helsinki (2013).

### 2.2. Materials

EEG was recorded with a Biosemi® (Biosemi, Amsterdam, Netherlands) system, 64 active electrodes (Ag/AgCl) included in a cap, sampled at 512 Hz, with a 24-bit resolution. Electrodes were positioned according to the international system 10–20 (Seeck et al., 2017), with additional intermediate positions (Jacques, Jonas, et al., 2020; Rossion et al., 2015) in order to increase sampling of occipito-temporal brain regions (Koessler et al., 2009). One electrode was placed at the outer canthi of the right eye to record the horizontal electrooculogram (EOG), while the vertical EOG was measured by positioning two additional electrodes above and below the participant's right eye.

For stimuli presentation, an Ultrasharp 27-inch (model U2715H) Dell monitor was used, featuring LCD technology and LED backlighting. The monitor was positioned at a distance of 80 cm from the participant's eyes. For the experiment, a screen resolution of  $1280 \times 1024$  pixels and a refresh rate of 60 Hz were configured.

### 2.3. Transcranial direct current stimulation

For inducing neuromodulation, we employed a MxN-9 HD (High definition) Soterix device and two HD ring electrodes (12 mm external diameter; Soterix Medical®, New York, NY, USA). Electrodes were inserted in an electrode-holder (24 mm diameter) filled with a conductive gel, creating a  $4.52 \text{ cm}^2$  stimulation area on the scalp for each electrode. Impedances were checked before, during, and after each stimulation and were always inferior or equal to 10 k $\Omega$ . According to the HD electrodes' geometry, current density generated on site was  $.44 \text{ mA cm}^{-2}$  for 2 mA intensity.

The tDCS montage corresponded to an anode placed over the right occipito-temporal cortex (P10 position) and a cathode placed on the left basal fronto-temporal cortex (FT9 position) (Supplementary material S1). This montage was set by considering the highest and robust face-selective and FIR EEG responses observed on P10 electrode obtained in previous studies (Jacques et al., 2019; Liu-Shuang et al., 2014; Rossion et al., 2020b). For the sham stimulations during the pre- and post-tDCS phases, the current was increased from 0 mA to 2 mA within the first 30 sec, followed by a decrease from 2 mA to 0 mA over the subsequent 30 sec. Active tDCS was blinded to the participants, who were instructed to report any discomfort or side effects during the experiment.

### 2.4. Experimental paradigm

The FVPS paradigm has been used as such in numerous previous studies (Dzhelyova et al., 2019; Liu-Shuang et al., 2014). Participants were tested in two conditions: upright and inverted faces. Inverted faces were used as a control condition. Pictures of one unfamiliar neutral face were presented at a general frequency of 6 Hz, with each face stimulus shown every 166.66 ms. This unfamiliar face, either male or female (in different sequences) was randomly selected from a database of 25 faces, and used as the “base” face (Face A, Fig. 2 and all faces in Supplementary material S4). Throughout the FVPS sequence, other unfamiliar faces were introduced at a frequency of 1.2 Hz, also called the oddball frequency. Thus, face identity changes every five faces. As a result, each cycle of visual stimulation consists of presenting a total of five stimuli: four “base” faces and one “oddball” face, with the entire cycle lasting .833 sec. Each cycle was repeated 85 times (i.e., 85 trials), totalling 71 sec for each FPVS sequence. To prevent pixelwise overlap, size of faces varied between 74% and 120% throughout the cycles of stimulation as in previous studies (e.g. (Dzhelyova & Rossion, 2014; Liu-Shuang et al., 2014)). All faces were presented with a sinusoidal modulation of contrast ranging from 0% to 100%. For further details about the FPVS paradigm, please see (Rossion et al., 2020c). In the inverted face condition, face stimuli were flipped vertically.

### 2.5. Procedure

Data collection took place in a quiet and dimly lit room. Visual stimuli were presented at a general frequency of 6 Hz with codes written in Java. Participants were asked to maintain central fixation and attend to the images, responding by pressing a key whenever the fixation point briefly changed

colour from black to red. These changes were presented at irregular intervals, each lasting 200 msec, and occurred on average 8.5 times per minute during the experimental session. The experiment was divided into three phases: P1 (pré), P2 (during tDCS) and P3 (post tDCS) (Fig. 1). In each one, four blocks of stimulus were presented, encompassing the two versions of the FPVS task (upright and inverted) with male and female faces (Fig. 2).

Participants performed the FPVS task for 10 min during each of the three phases of the protocol. In Phase 2 (active), tDCS was delivered for 20 min—10 min before FPVS onset plus 10 min during the FPVS task. Therefore, for the electrophysiological analyses, the same duration of 10-min FPVS blocks in each phase was analysed, ensuring comparable time windows across the three phases.

## 2.6. Data analysis

As in previous EEG-FPVS studies (Rossion et al., 2020c), EEG data were analyzed using the open-source software *Letswave* 6.0 (<https://github.com/NOCIIONS/Letswave6>), running on MATLAB R2023a (MathWorks, USA). Data analysis included the following four different steps.

### 2.6.1. Preprocessing

First, EEG data were filtered using a 4th-order zero-phase Butterworth filter with a high-pass cut-off set at .1 Hz and a low-pass cut-off at 100 Hz. A Fast Fourier Transform (FFT) multi-notch filter was also applied with a width of .5 Hz to remove electrical noise at 50 Hz frequency and 2 harmonics (100 and 150 Hz). After downsampling to 256 Hz to reduce computational load and storage space, the data were segmented by sequence, including 2 sec before and after the sequence (–2 to 75 sec). For four participants (out of 14) with an average blinking rate above .2 times/sec, eyeblink artifacts were corrected using independent component analysis (ICA) (Retter & Rossion, 2016). Channels with excessive noise (above 100  $\mu$ V) in multiple sequences were excluded and interpolated with the adjacent channel values, up to the limit of 5% of the total of channels per participant. Next, data were re-referenced to the average of the 64 electrodes.

### 2.6.2. Frequency domain analysis

Fade-in and fade-out phases were excluded, and EEG data was re-segmented into an integer number of 1.2 Hz cycles. Each

epoch was 71 sec long and encompassing 85 complete cycles of stimulation, with each cycle composed of four 'base' faces and one 'oddball' face, lasting .833 sec per cycle. Next, epochs were averaged within participants in the time-domain to improve SNR.

A Fast Fourier Transform (FFT) was applied to these averaged segments, and the amplitude spectra was extracted. EEG evoked responses was then characterized using three methods: 1) Signal-to-noise (SNR) ratio, calculated by dividing the peak amplitude of each frequency in the EEG spectrum by the average of the baseline, usually for visualization purposes, 2) subtraction of the EEG noise (baseline) from the summed harmonics, with responses expressed in microvolts ( $\mu$ V), for response quantification and 3) Z-score spectra, calculated by dividing the difference between peak amplitude of the frequency of interest and the mean amplitude of 22 surrounding bins by the standard deviation of those 22 surrounding bins.

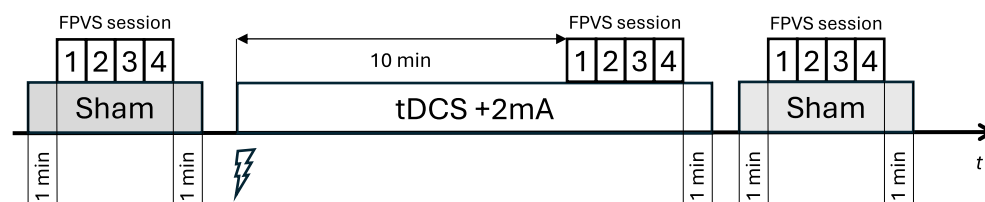
Response amplitudes were quantified considering the sum of baseline-corrected amplitudes of significant harmonics (Retter et al., 2021; Retter & Rossion, 2016) and reported with their standard-deviations. All amplitude values are available in open-access (Mendeley Data: doi: [10.17632/sh76m2vgbc.1](https://doi.org/10.17632/sh76m2vgbc.1)). A significance threshold  $Z > 1.64$  ( $p < .05$ ), one-tailed (signal > noise), was employed to identify the significant EEG responses in the frequency domain.

### 2.6.3. Region of interest analysis

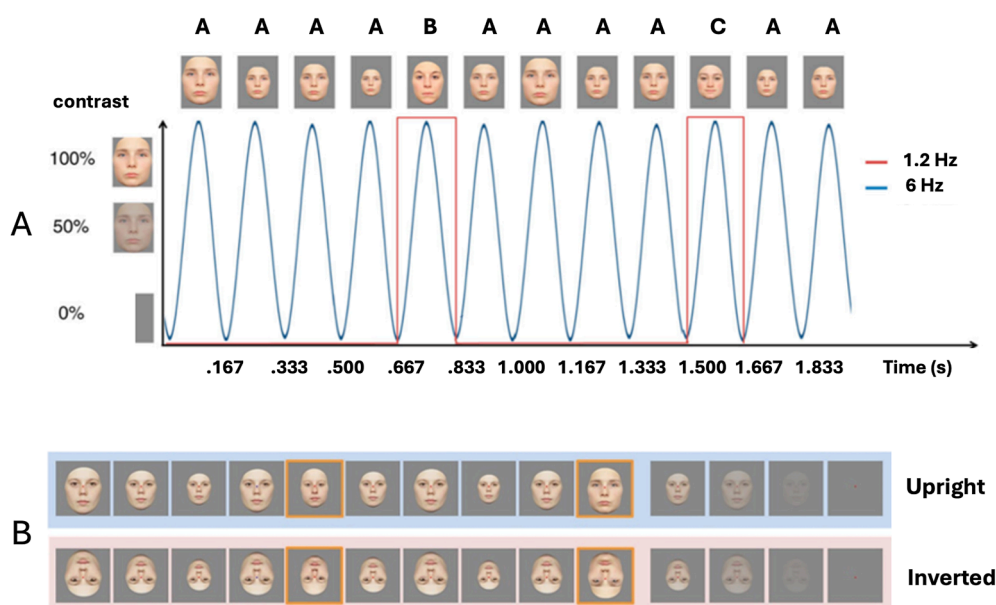
Based on previous scalp EEG studies (Dzhelyova et al., 2019; Rossion et al., 2020c; Vettori et al., 2019), the following regions of interest (ROIs) related to face identification were defined to investigate hemispheric dominance: 1) Right occipital-temporal region (RIGHT OT: electrodes P8/P10/P08); 2) Left occipital-temporal region (LEFT OT: electrodes P7/P9/P07). Additionally, a middle occipital ROI was defined considering the middle posterior channels (Oz/Iz/O1/O2), which are associated with low-level features in visual processing. For the sake of completion, we also present the data average across all electrodes, denoted as ALL ELECTRODES. For each ROI, EEG signals were averaged within each phase (pre-tDCS, during tDCS, and after tDCS).

### 2.6.4. Statistical analysis

Baseline-corrected amplitudes of face selective EEG evoked responses were compared with a three-way repeated measure



**Fig. 1 – Schematic view of the tDCS experiment with three successive phases. In Phase 1 (pre tDCS), participants underwent the sham tDCS stimulation concurrently to the FPVS paradigms. In Phase 2 (during tDCS), participants received 10 min of tDCS stimulation before performing the FPVS tasks during the ongoing stimulation. In Phase 3 (post tDCS), participants underwent an additional sham session with the FPVS tasks.**



**Fig. 2** – The FPVS paradigm measuring unfamiliar face individuation. (A) Faces were presented at a general frequency of 6 Hz, with sinusoidal modulation of contrast. Face identity changes every five images (from Face B to Face C, and so on), so that identity changes occur at a frequency of 1.2 Hz (6 Hz divided by 5). (B) Representation of the paradigm for upright (blue) and inverted faces (red). Adapted from [Dzhelyova et al. \(2019\)](#) and [Liu-Shuang et al. \(2014\)](#).

ANOVA with the factors *Stimulation phases* (pre-tDCS, during tDCS, post-tDCS), *Face orientation* (Upright, Inverted) and *Hemisphere* (Left OT, Right OT). For the general visual response (i.e., 6 Hz and harmonics) two-way repeated measure ANOVAs was used with the factors *Stimulation phases* and *ROI* (Left OT, middle occipital region, right OT). When the assumption of sphericity was violated, Greenhouse–Geisser corrections were applied. In cases of statistically significant effects, post hoc pairwise *t*-tests were performed on the estimated marginal means (EMMs), and *p*-values were adjusted using the Holm correction to control for multiple comparisons. In all cases, a significance level of 5% was used (*p*-value < .05).

### 3. Results

#### 3.1. Significant and selective effect of tDCS on face individuation

Significant EEG responses were observed at 1.2 Hz and its harmonic frequencies for upright faces at all three phases, i.e., before, during and after tDCS (Fig. 3). Z-scores computed on the average of all electrodes revealed different number of significant harmonics between phases. The full set of exact *p*-values for the Z-scores across all harmonics is presented in [Supplementary material S2](#).

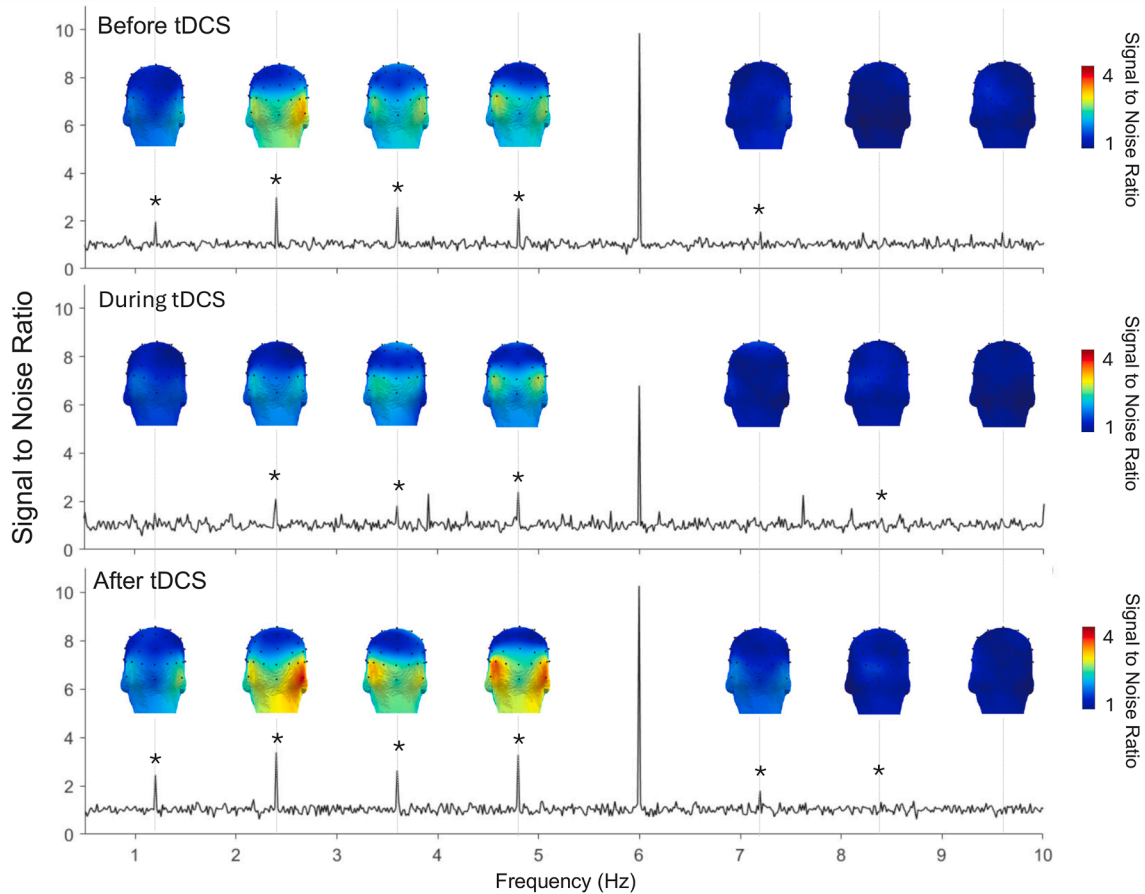
For upright faces, five significant 1.2 Hz harmonics were found before and after tDCS (*before*: 1.2 Hz, 2.4 Hz, 3.6 Hz, 4.8 Hz and 7.2 Hz; *after*: 2.4 Hz, 3.6 Hz, 4.8 Hz, 7.2 Hz and 8.4 Hz;  $Z > 1.64$ ,  $p < .05$ ), whereas only three 1.2 Hz harmonics were significant during tDCS (2.4 Hz, 3.6 Hz and 4.8 Hz,  $Z > 1.64$ ,  $p < .05$ ). For inverted faces, three and two harmonics were

significant before and after tDCS, respectively (*before*: 2.4 Hz, 3.6 Hz and 4.8 Hz,  $Z > 1.64$ ,  $p < .05$ ; *after*: 1.2 Hz, 4.8 Hz,  $Z > 1.64$ ,  $p < .05$ ), whereas only one reached significance during tDCS (4.8 Hz,  $Z > 1.64$ ,  $p < .05$ ).

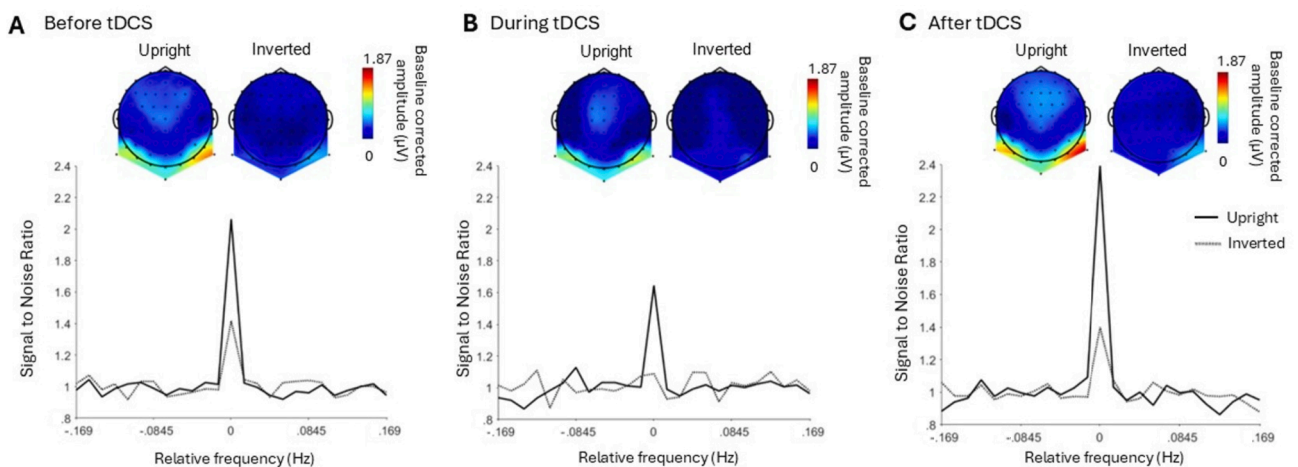
Based on these results, the number of harmonics to consider for the summation was defined according to the highest significant consecutive harmonics across phases and face orientation. Therefore, six consecutive harmonics (except peaks at 6 Hz that were also corresponding to “base” frequency) were summed in all conditions to quantify the face selective amplitude response. This number of harmonics is also in line with the number of harmonics generally considered in this paradigm ([Rossion et al., 2020c](#)).

EEG responses were maximal at OT channels and in all phases, with a right hemisphere dominance before and after tDCS (Figs. 3–5). Over the right OT ROI, the average amplitude for upright faces was  $1.25 \pm .64 \mu\text{V}$  (mean  $\pm$  SD) before tDCS. It dropped to  $.90 \pm 1.14 \mu\text{V}$  during tDCS (i.e.,  $-28\%$ ), then increased after tDCS to  $1.50 \pm .74 \mu\text{V}$  (i.e.,  $+66\%$  compared to during tDCS and  $+20\%$  compared to before tDCS) (Figs. 4 and 5). For SNR values, see [Supplementary material S3](#).

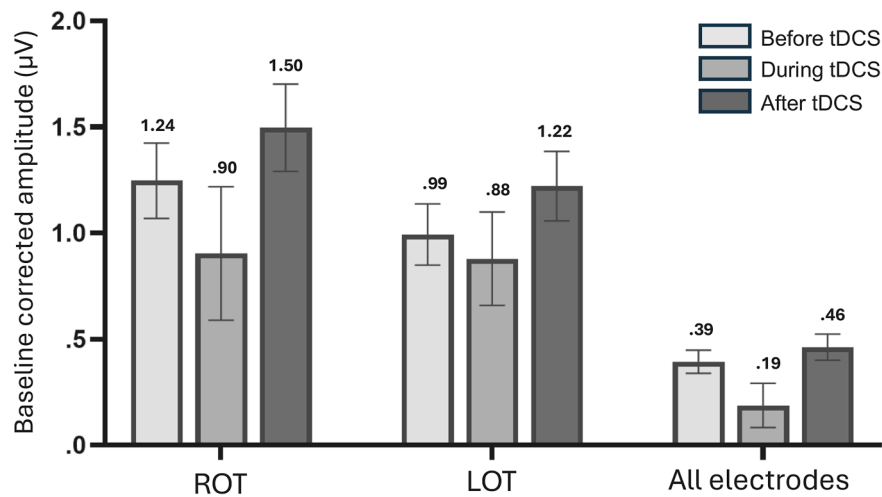
A repeated-measures ANOVA showed a main effect of *Face orientation* ( $F_{1,13} = 33.1$ ,  $p < .001$ ) with a larger amplitude for Upright ( $1.12 \pm .79 \mu\text{V}$ ) than Inverted faces ( $.30 \pm .47 \mu\text{V}$ ). In addition, there was a significant *Stimulation phase* effect ( $F_{1,38,17.89} = 10.84$ ,  $p = .002$ ) with post-hoc *t*-tests revealing a significant amplitude decrease of the response between before and during tDCS ( $t_{13} = 3.11$ ,  $p = .017$ ), a significant increase between during and after tDCS ( $t_{13} = 3.63$ ,  $p = .009$ ), and a significant increase after compared to before tDCS ( $t_{13} = 2.19$ ,  $p = .048$ ). No significant effect of *Hemisphere* was observed ( $F_{1,13} = 2.12$ ,  $p = .17$ ), and no significant two-way interaction



**Fig. 3** – Grand-average SNR FFT spectra at right OT region for each stimulation phases for upright faces. Black stars indicate significant 1.2 Hz and harmonics response ( $Z > 1.64$ ,  $p < .05$ ). Scalp EEG topographies of the SNR are presented at 1.2 Hz and its harmonics (2.4, 3.6, 4.8, 7.2, 8.4 and 9.6 Hz; except for 6 Hz that also correspond to base frequency stimulation). Note the large reduction of SNR during tDCS, with fewer peaks of smaller ratios, followed by a significant ‘rebound’ effect, with higher peaks after tDCS.



**Fig. 4** – Grand average SNR of the sum of the six first 1.2 Hz harmonics quantified at bilateral OT, in black solid line for upright faces and in dotted grey line for inverted faces (A) before tDCS, (B) during tDCS and (C) after tDCS. The spectrum is centred on the frequency bin of interest. Above are presented the scalp mal topographies of the 1.2 Hz and harmonics baseline corrected amplitude response.



**Fig. 5 – Histogram of corrected amplitude response at the sum of 1.2 Hz and harmonics across the different ROIs and stimulation phases of upright faces. Bars represent standard mean errors, and the mean is reported on top of each bar. ROT: right occipito-temporal region, LOT: left occipito-temporal region.**

between *Hemisphere* and *Face orientation* ( $F_{1,13} = .38, p = .55$ ), *Face orientation* and *Stimulation phase* ( $F_{2,26} = 1.29, p = .29$ ), *Stimulation phase* and *Hemisphere* ( $F_{1,33,17,25} = 3.10, p = .09$ ) or three-way interactions were found ( $F_{1,31,17,06} = .20, p = .72$ ).

Additionally, to evaluate consistency across individuals, as recommended in the literature on interindividual variability in tDCS (Bergmann and Hartwigsen, 2021), we conducted a two-step analysis. Given the absence of a main effect of *Hemisphere* and of interactions with the other experimental factors (*Stimulation Phase* and *Face Orientation*), EEG responses from the left and right occipitotemporal regions of interest (Left OT and Right OT) were collapsed across hemispheres for the following analyses.

First, we quantified the proportion of participants showing effects in the expected direction for each pairwise phase contrast: P2–P1, 8/14 (57.1%) negative; P3–P2, 12/14 (85.7%) positive; and P3–P1, 12/14 (85.7%) positive, indicating a consistent group-level trend in the post-intervention phases. Second, we applied interquartile-range (IQR) outlier detection, defining extreme values as those outside  $[Q1 - 1.5 \times IQR; Q3 + 1.5 \times IQR]$ . No statistical outliers were detected in any of the three contrasts.

Taken together, these findings indicate that, despite expected interindividual variability in tDCS, the effects are consistent in most participants and are not driven by a small number of extreme responders, reinforcing the group-level pattern across the evaluated phases.

### 3.2. No tDCS effect on general visual EEG responses (base frequency)

A significant response was observed for upright faces for all phases at the general visual base frequency (i.e., 6 Hz), also up to five harmonics (i.e., 12 Hz, 18 Hz, 24 Hz, 30 Hz and 36 Hz,  $Z > 1.64, p < .05$ ) on the average of all electrodes (Fig. 6A). Quantification of the EEG responses was therefore computed

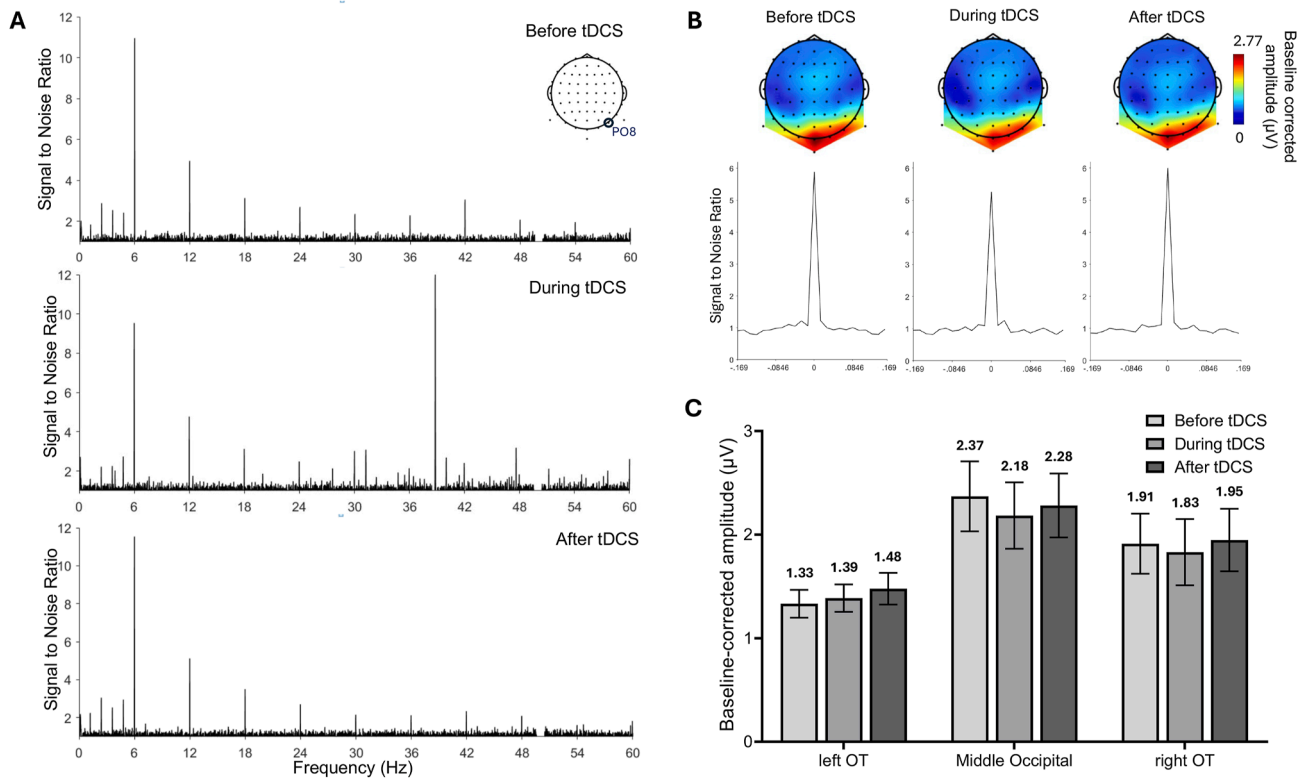
with the sum of these six first harmonics. The base rate response was localized primarily over the middle occipital ROI, extending to the right OT region (Fig. 6B). Scalp EEG amplitude maps displayed consistent topographies across the three phases of the experiment (Fig. 6C).

The repeated measure ANOVA showed a main effect of ROI ( $F_{2,26} = 4.63, p = .02$ ) with post hoc tests demonstrating a significant difference between left OT and middle occipital ROI (left OT:  $1.38 \pm .47 \mu\text{V}$ , middle occipital ROI:  $2.27 \pm 1.17 \mu\text{V}$ ,  $t_{13} = 3.04, p = .03$ ), but not between left OT and right OT (right OT:  $1.90 \pm 1.09 \mu\text{V}$ ,  $t_{13} = 2.14, p = .10$ ) and not between middle occipital ROI and right OT ( $t_{13} = 1.11, p = .29$ ) (Fig. 4C). No significant effect of *Stimulation phase* (before:  $1.88 \pm 1.05 \mu\text{V}$ , during:  $1.78 \pm 1.05 \mu\text{V}$ , after:  $1.90 \pm .98 \mu\text{V}$ ,  $F_{1,43,18,63} = 2.59, p = .11$ ) and no interaction between the two factors ( $F_{4,52} = 1.26, p = .30$ ) were found.

## 4. Discussion

We explored the neuromodulatory effects of tDCS on face identity recognition by means of concurrent tDCS-FPVS-EEG. While the analysis of scalp EEG during tDCS is usually hindered by artifacts caused by electrical stimulation (Gebodh et al., 2019), presenting stimuli periodically for relatively long stimulation sequences provide electrophysiological responses confined to small frequency bins (frequency resolution:  $1/71\text{sec} = .014 \text{ Hz}$ ) in the EEG frequency domain that are almost immune from broadband EEG noise (Regan, 1989). Moreover, EEG amplitude can be objectively identified and quantified at predefined frequency bins.

Our participants underwent a well-validated FPVS paradigm consisting of the presentation of faces at three experimental phases: before, during, and after tDCS application. TDCS induced distinct EEG response patterns for the base and oddball frequency rates. Responses to the base frequency and



**Fig. 6 – (A) Grand average SNR FFT spectrum of the EEG responses at PO8 electrode for upright faces across the three stimulation phases. High SNR peaks are observed at the base frequency. (B) Grand average SNR of the sum of the six first 6 Hz harmonics at PO8 electrode for the three stimulation phases. Scalp map topographies of the baseline corrected EEG response at 6 Hz and harmonics are presented above. (C) Histogram of the baseline-corrected amplitude for each ROI and each stimulation phases. Bars represent standard mean errors and the mean is reported on top of each bar. OT: occipito-temporal.**

its harmonics, which reflect the general visual response to the flickering face stimuli (a mixture of low- and high-level visual processes) remained relatively stable (no neuromodulation) across all three experimental phases (before, during, and after tDCS), with stronger responses found over the middle occipital region, as expected (Liu-Shuang et al., 2014; Rossion et al., 2020c). In contrast, and most interestingly, significant neuromodulations due to tDCS were found at the oddball frequency and its harmonics, reflecting FIR. Specifically, there was substantial reduction of amplitude during tDCS, followed by subsequent post-tDCS increase.

These large effects found over the typically most sensitive right occipito-temporal region can be attributed to the tDCS montage i.e., the placement of the anode next to the right occipito-temporal cortex, in particular the inferior occipital gyrus, holding face-selective populations of neurons ('Occipital Face Area', OFA) (Jacques et al., 2019, 2020b; Pitcher et al., 2011), might have facilitated the current flow, thereby inducing a high electric field in this region (Louviot et al., 2022). Transcranial magnetic stimulation (TMS) applied over this right OFA region leads to modest but consistent behavioral decreases in performance in FIR tasks (Pitcher et al., 2007, 2011; Solomon-Harris et al., 2013). However, and particularly interestingly, here the neuromodulation effects were found both over the right (where tDCS was applied) and the left

homologous occipito-temporal region, without any significant difference across hemispheres. Thus, tDCS appears to have (transiently) affected the bilateral cortical face network involved in FIR, strongly suggesting that additional downstream regions of the ventral occipito-temporal cortex such as the fusiform face area (Kanwisher et al., 1997), which is key for FIR (Jacques et al., 2020), may have also been significantly neuromodulated (see (Angelini et al., 2024; Solomon-Harris et al., 2016) for evidence of remote effects of TMS and direct electrical stimulation, respectively, within the cortical face network). Whether application of tDCS over the left hemisphere, typically more weakly involved in face (identity) recognition, would lead to same neuromodulation over right homologous region is an outstanding question that could be addressed in future studies with the same approach introduced here.

Several studies have demonstrated that the tDCS elicits changes in cortical excitability, depending on electrodes polarity (Nitsche & Paulus, 2000; Purpura & McMurtry, 1965). With opposite post-effects, anodal tDCS increases cortical excitability, while cathodal tDCS promotes cortical inhibition, leading to secondary changes in cortical activity (Schestatsky et al., 2013; Tabikh et al., 2025). Since anodal DCS triggers vasodilation and enhances perfusion during the stimulation, specifically within a subset of cortical vessels (Gellner et al.,

2023; Vernieri et al., 2010), vascular changes could also account for decreases in amplitude during tDCS. That is, an increased amount of blood would flow to this part of the brain, which may in turn reduce blood flow in neighboring regions, such as more anterior regions of the occipito-temporal cortex involved in FIR (posterior to anterior fusiform gyrus (Jacques et al., 2020)).

Following tDCS, a significant increase in amplitude of the neural FIR response was observed, even surpassing the level of activity pre-tDCS. This ‘rebound’ effect, which is substantial here, might be explained by different neurophysiological mechanisms. First, tDCS can increase neuronal excitability by causing sustained depolarization of neurons, particularly with anodal stimulation (Stagg et al., 2018). In this case, stimulation can induce long-lasting changes in synaptic strength, known as long-term potentiation (LTP) (Polaný et al., 2018), enhancing the responsiveness of neuronal circuits involved in specific tasks such as FIR. Besides that, changes in neurovascular coupling induced by tDCS can also be considered. Gellner et al. (2023), in their in vivo study, demonstrated that anodal DCS increased the permeability of cortical vessels and perivascular microglia mobility after it ended. Thus, the observed increase in amplitudes related to FIR post-stimulation may result from changes in cortical permeability induced by the prior application of tDCS. These combined factors may explain the increased response amplitude observed after tDCS, resulting in a rebound effect that could potentially enhance FIR performance.

In line with this observation, here we conjecture that the increased amplitudes found over occipito-temporal region following tDCS stimulation could improve efficacy in recognizing face identities, not only well beyond limited and spurious effects found for DLPFC stimulation (e.g., Yang et al., 2018) but also specifically for this function. If this is the case, then our findings would hold clinical relevance for neuropsychological conditions involving FIR deficits such as prosopagnosia (Barton, 2024; Bodamer, 1947; Rossion, 2022; Volfart & Rossion, 2024) or developmental difficulties at FIR (prosopagnosia, e.g., Nørkæ et al., 2024; Rossion, 2018), in line with the potential therapeutic effects of tDCS in various neurological disorders, such as migraines, fibromyalgia, drug-resistant major depressive episodes, and addiction/craving (Lefaucheur et al., 2017).

Besides, we observed a robust main effect of Orientation, with larger face-selective amplitudes for upright than inverted faces (upright:  $1.12 \pm .79 \mu\text{V}$ ; inverted:  $.30 \pm .47 \mu\text{V}$ ), consistent with the face inversion literature and a right-lateralized distribution. Crucially, no interactions involving Stimulation phase and Orientation were observed, indicating that tDCS modulated the face-selective response similarly for both orientations. Thus, the observed effects are face-related in that they selectively affect the neural response indexing individual face discrimination, but they are not orientation-specific. This interpretation is further supported by the absence of any modulation of the general visual response at the base frequency.

To the best of our knowledge, the present study represents the first instance of concurrent combination of EEG recording with tDCS targeting regions supporting human face (identity) recognition. During ongoing stimulation, EEG amplitude over the occipito-temporal region marking face identity recognition

was substantially and specifically reduced, followed by increased amplitude after tDCS, well above and beyond the initial response. This latter result suggests that a single-session of tDCS may have potential clinical significance for addressing pathologies marked by deficiencies in face identity recognition and that the combination of FPVS-EEG represents a valuable approach to quantify neural tDCS effects.

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## CRedit authorship contribution statement

**Nelson Torro-Alves:** Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Justine David:** Writing – original draft, Formal analysis. **Mireille Tabikh:** Writing – original draft, Formal analysis. **Yanis Menzer:** Resources, Investigation. **Bruno Rossion:** Writing – review & editing, Validation, Conceptualization. **Laurent Koessler:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

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## Funding

This work was supported by CAPES-COFECUB grant (Me 1018/24, N° Campus France: 50672WE), CAPES process number: 88881.878930/2023–01), CAPES-PrInt-UFPB program (88887.512370/2020–00), and CNPq (443437/2023–8) and ANR eTECH\_Neuro (ANR-24-CE19-7262-01).

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## Declaration of competing interest

The authors have no conflicts of interest to declare in relation to this study.

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## Acknowledgments

We express our deepest gratitude to the healthy subjects for their involvement in the study.

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## Scientific transparency statement

DATA: Some raw and processed data supporting this research are publicly available, while some are subject to restrictions: <https://data.mendeley.com/datasets/sh76m2vgbc/1>.

CODE: All analysis code supporting this research is publicly available: [https://letswave.cn/gs\\_download\\_and\\_installation#download](https://letswave.cn/gs_download_and_installation#download).

MATERIALS: All study materials supporting this research are publicly available: <http://psychtoolbox.org>. Materials are contained in the manuscript or supplemental files.

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior

to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

## Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cortex.2026.03.013>.

## REFERENCES

- Angelini, L., Jacques, C., Maillard, L., Colnat-Coulbois, S., Rossion, B., & Jonas, J. (2024). Bidirectional and cross-hemispheric modulations of face-selective neural activity induced by electrical stimulation within the human cortical face network. *Brain Science*, 14, 906. <https://doi.org/10.3390/brainsci14090906>
- Antal, A., Bjekić, J., Ganho-Ávila, A., Alekseichuk, I., Asseondi, S., Bergmann, TO., ... Fitzgerald, PB., et al. (2017). Low intensity transcranial electric stimulation: Safety, ethical, legal regulatory and application guidelines. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 128, 1774–1809. <https://doi.org/10.1016/j.clinph.2017.06.001>
- 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. (2024). The 2024 Richardson lecture: Prosopagnosia – A classic neurologic deficit meets the modern era. *The Canadian Journal of Neurological Sciences. Le Journal Canadien Des Sciences Neurologiques*, 1–9. <https://doi.org/10.1017/cjn.2024.295>
- Bastani, A., & Jaberzadeh, S. (2012). Does anodal transcranial direct current stimulation enhance excitability of the motor cortex and motor function in healthy individuals and subjects with stroke: A systematic review and meta-analysis. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 123, 644–657. <https://doi.org/10.1016/j.clinph.2011.08.029>
- Begemann, M. J., Brand, B. A., Ćurčić-Blake, B., Aleman, A., & Sommer, I. E. (2020). Efficacy of non-invasive brain stimulation on cognitive functioning in brain disorders: A meta-analysis. *Psychological Medicine*, 50, 2465–2486. <https://doi.org/10.1017/S0033291720003670>
- Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience*, 8, 551–565. <https://doi.org/10.1162/jocn.1996.8.6.551>
- Bodamer, J. (1947). Die Prosop-Agnosie. *Arch Für Psychiatr Nervenkrankh*, 179, 6–53. <https://doi.org/10.1007/BF00352849>
- Ciullo, V., Spalletta, G., Caltagirone, C., Banaj, N., Vecchio, D., Piras, F., & Piras, F. (2021). Transcranial direct current stimulation and cognition in neuropsychiatric disorders: Systematic review of the evidence and future directions. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, 27, 285–309. <https://doi.org/10.1177/1073858420936167>
- Civile, C., & McLaren, I. P. L. (2022). Transcranial direct current stimulation (tDCS) eliminates the other-race effect (ORE) indexed by the face inversion effect for own versus other-race faces. *Scientific Reports*, 12, Article 12958. <https://doi.org/10.1038/s41598-022-17294-w>
- Civile, C., McLaren, R., & McLaren, I. P. L. (2018). How we can change your mind: Anodal tDCS to Fp3 alters human stimulus representation and learning. *Neuropsychologia*, 119, 241–246. <https://doi.org/10.1016/j.neuropsychologia.2018.08.019>
- Civile, C., Waguri, E., Quaglia, S., Wooster, B., Curtis, A., McLaren, R., Lavric, A., McLaren, IPL, et al. (2020a). Testing the effects of transcranial direct current stimulation (tDCS) on the face inversion effect and the N170 event-related potentials (ERPs) component. *Neuropsychologia*, 143, Article 107470. <https://doi.org/10.1016/j.neuropsychologia.2020.107470>
- Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M.-A. (2016). A systematic review and meta-analysis of the effects of transcranial direct current stimulation (tDCS) over the dorsolateral prefrontal cortex in healthy and neuropsychiatric samples: Influence of stimulation parameters. *Brain Stimulation*, 9, 501–517. <https://doi.org/10.1016/j.brs.2016.04.006>
- Dzhelyova, M., Jacques, C., Dormal, G., Michel, C., Schiltz, C., & Rossion, B. (2019). High test-retest reliability of a neural index of rapid automatic discrimination of unfamiliar individual faces. *Visual Cognition*, 27, 127–141. <https://doi.org/10.1080/13506285.2019.1616639>
- Dzhelyova, M., & Rossion, B. (2014). The effect of parametric stimulus size variation on individual face discrimination indexed by fast periodic visual stimulation. *BMC Neuroscience*, 15, 87. <https://doi.org/10.1186/1471-2202-15-87>
- Faria, P., Fregni, F., Sebastião, F., Dias, A. I., & Leal, A. (2012). Feasibility of focal transcranial DC polarization with simultaneous EEG recording: Preliminary assessment in healthy subjects and human epilepsy. *Epilepsy & Behavior: E&B*, 25, 417–425. <https://doi.org/10.1016/j.yebeh.2012.06.027>
- Fisher, K., Towler, J., Rossion, B., & Eimer, M. (2020). Neural responses in a fast periodic visual stimulation paradigm reveal domain-general visual discrimination deficits in developmental prosopagnosia. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 133, 76–102. <https://doi.org/10.1016/j.cortex.2020.09.008>
- Friehs, M. A., & Frings, C. (2019). Offline beats online: Transcranial direct current stimulation timing influences on working memory. *Neuroreport*, 30, 795–799. <https://doi.org/10.1097/WNR.0000000000001272>
- Gebodh, N., Esmailpour, Z., Adair, D., Chelette, K., Dmochowski, J., Woods, A. J., ... Bikson, M. (2019). Inherent physiological artifacts in EEG during tDCS. *Neuroimage*, 185, 408–424. <https://doi.org/10.1016/j.neuroimage.2018.10.025>
- Gellner, A., Frase, S., Reis, J., & Fritsch, B. (2023). Direct current stimulation increases blood flow and permeability of cortical microvasculature in vivo. *European Journal of Neurology: The Official Journal of the European Federation of Neurological Societies*, 30, 362–371. <https://doi.org/10.1111/ene.15616>
- Grill-Spector, K., Weiner, K. S., Kay, K., & Gomez, J. (2017). The functional neuroanatomy of human face perception. *Annual Review of Vision Science*, 3, 167–196. <https://doi.org/10.1146/annurev-vision-102016-061214>
- Hagen, S., Laguesse, R., & Rossion, B. (2024). Extensive visual training in adulthood reduces an implicit neural marker of the face inversion effect. *Brain Science*, 14, 146. <https://doi.org/10.3390/brainsci14020146>
- Hauk, O., Rice, G. E., Volfart, A., Magnabosco, F., Ralph, M. A. L., & Rossion, B. (2021). Face-selective responses in combined EEG/MEG recordings with fast periodic visual stimulation (FPVS). *Neuroimage*, 242, Article 118460. <https://doi.org/10.1016/j.neuroimage.2021.118460>
- Haxby, J. V., Hoffman, E. A., & Gobbini, M. I. (2000). The distributed human neural system for face perception. *Trends in Cognitive Sciences*, 4, 223–233. [https://doi.org/10.1016/S1364-6613\(00\)01482-0](https://doi.org/10.1016/S1364-6613(00)01482-0)

- 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 Stimulation*, 9, 197–208. <https://doi.org/10.1016/j.brs.2015.10.006>
- Jacques, C., Jonas, J., Maillard, L., Colnat-Coulbois, S., Rossion, B., & Koessler, L. (2020). Fast periodic visual stimulation to highlight the relationship between human intracerebral recordings and scalp electroencephalography. *Human Brain Mapping*, 41, 2373–2388. <https://doi.org/10.1002/hbm.24952>
- Jacques, C., Jonas, J., Maillard, L., Colnat-Coulbois, S., Koessler, L., & Rossion, B. (2019). The inferior occipital gyrus is a major cortical source of the face-evoked N170: Evidence from simultaneous scalp and intracerebral human recordings. *Human Brain Mapping*, 40, 1403–1418. <https://doi.org/10.1002/hbm.24455>
- Jacques, C., Rossion, B., Volfart, A., Brissart, H., Colnat-Coulbois, S., Maillard, L., & Jonas, J. (2020). The neural basis of rapid unfamiliar face individuation with human intracerebral recordings. *Neuroimage*, 221, 117174. <https://doi.org/10.1016/j.neuroimage.2020.117174>
- Jonas, J., Jacques, C., Liu-Shuang, J., Brissart, H., Colnat-Coulbois, S., Maillard, L., & Rossion, B. (2016). A face-selective ventral occipito-temporal map of the human brain with intracerebral potentials. *Proceedings of National Academy of Sciences of the United States of America*, 113, E4088–E4097. <https://doi.org/10.1073/pnas.1522033113>
- Kanwisher, N., McDermott, J., & Chun, M. M. (1997). The fusiform face area: A module in human extrastriate cortex specialized for face perception. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 17, 4302–4311.
- Kho, S. K., Keeble, D., Wong, H. K., & Estudillo, A. J. (2023). Null effect of anodal and cathodal transcranial direct current stimulation (tDCS) on own- and other-race face recognition. *Social Neuroscience*, 18, 393–406. <https://doi.org/10.1080/17470919.2023.2263924>
- Koessler, L., Maillard, L., Benhadid, A., Vignal, J. P., Felblinger, J., Vespignani, H., & Braun, M. (2009). Automated cortical projection of EEG sensors: Anatomical correlation via the international 10-10 system. *Neuroimage*, 46, 64–72. <https://doi.org/10.1016/j.neuroimage.2009.02.006>
- Lafontaine, M. P., Théoret, H., Gosselin, F., & Lippé, S. (2013). Transcranial direct current stimulation of the dorsolateral prefrontal cortex modulates repetition suppression to unfamiliar faces: An ERP study. *PLoS One*, 8, Article e81721. <https://doi.org/10.1371/journal.pone.0081721>
- Lefacheur, JP., Antal, A., Ayache, SS., Benninger, DH., Brunelin, J., Cogiamanian, F., ... Priori, A., et al. (2017). Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 128, 56–92. <https://doi.org/10.1016/j.clinph.2016.10.087>
- Liu-Shuang, J., Norcia, A. M., & Rossion, B. (2014). An objective index of individual face discrimination in the right occipito-temporal cortex by means of fast periodic oddball stimulation. *Neuropsychologia*, 52, 57–72. <https://doi.org/10.1016/j.neuropsychologia.2013.10.022>
- Liu-Shuang, J., Torfs, K., & Rossion, B. (2016). An objective electrophysiological marker of face individualisation impairment in acquired prosopagnosia with fast periodic visual stimulation. *Neuropsychologia*, 83, 100–113. <https://doi.org/10.1016/j.neuropsychologia.2015.08.023>
- Louviot, S., Tyvaert, L., Maillard, L. G., Colnat-Coulbois, S., Dmochowski, J., & Koessler, L. (2022). Transcranial electrical stimulation generates electric fields in deep human brain structures. *Brain Stimulation*, 15, 1–12. <https://doi.org/10.1016/j.brs.2021.11.001>
- Mancini, M., Pellicciari, M. C., Brignani, D., Mauri, P., De Marchis, C., Miniussi, C., & Conforto, S. (2015). Automatic artifact suppression in simultaneous tDCS-EEG using adaptive filtering. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 2729–2732). <https://doi.org/10.1109/EMBC.2015.7318956>
- Meissner, C. A., & Brigham, J. C. (2001). Thirty years of investigating the own-race bias in memory for faces: A meta-analytic review. *Psychology, Public Policy, and Law*, 7, 3–35. <https://doi.org/10.1037/1076-8971.7.1.3>
- Nørkær, E., Gobbo, S., Roald, T., & Starrfelt, R. (2024). Disentangling developmental prosopagnosia: A scoping review of terms, tools and topics. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 176, 161–193. <https://doi.org/10.1016/j.cortex.2024.04.011>
- Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *Journal of Physiology*, 527, 633–639. <https://doi.org/10.1111/j.1469-7793.2000.t011-1-00633.x>
- Norcia, A. M., Appelbaum, L. G., Ales, J. M., Cottareau, B. R., & Rossion, B. (2015). The steady-state visual evoked potential in vision research: A review. *J Vis*, 15, 4. <https://doi.org/10.1167/15.6.4>
- Pitcher, D., Walsh, V., & Duchaine, B. (2011). The role of the occipital face area in the cortical face perception network. *Experimental Brain Research*, 209, 481–493. <https://doi.org/10.1007/s00221-011-2579-1>
- Pitcher, D., Walsh, V., Yovel, G., & Duchaine, B. (2007). TMS evidence for the involvement of the right occipital face area in early face processing. *Current Biology*, CB, 17, 1568–1573. <https://doi.org/10.1016/j.cub.2007.07.063>
- Polanía, R., Nitsche, M. A., & Ruff, C. C. (2018). Studying and modifying brain function with non-invasive brain stimulation. *Nature Neuroscience*, 21, 174–187. <https://doi.org/10.1038/s41593-017-0054-4>
- Purpura, D. P., & McMurtry, J. G. (1965). Intracellular activities and evoked potential changes during polarization of motor cortex. *Journal of Neurophysiology*, 28, 166–185. <https://doi.org/10.1152/jn.1965.28.1.166>
- Regan, D. (1966). Some characteristics of average steady-state and transient responses evoked by modulated light. *Electroencephalography and Clinical Neurophysiology*, 20, 238–248. [https://doi.org/10.1016/0013-4694\(66\)90088-5](https://doi.org/10.1016/0013-4694(66)90088-5)
- Regan, D. (1989). *Human brain electrophysiology: Evoked potentials and evoked magnetic fields in science and medicine*. New York.
- Renzi, C., Ferrari, C., Schiavi, S., Pisoni, A., Papagno, C., Vecchi, T., ... Cattaneo, Z. (2015). The role of the occipital face area in holistic processing involved in face detection and discrimination: A tDCS study. *Neuropsychologia*, 29, 409–416. <https://doi.org/10.1037/neu0000127>
- Retter, T. L., & Rossion, B. (2016). Uncovering the neural magnitude and spatio-temporal dynamics of natural image categorization in a fast visual stream. *Neuropsychologia*, 91, 9–28. <https://doi.org/10.1016/j.neuropsychologia.2016.07.028>
- Retter, T. L., Rossion, B., & Schiltz, C. (2021). Harmonic amplitude summation for frequency-tagging analysis. *Journal of Cognitive Neuroscience*, 1–22. [https://doi.org/10.1162/jocn\\_a\\_01763](https://doi.org/10.1162/jocn_a_01763)
- Rossion, B. (2018). Prosopagnosia? What could it tell us about the neural organization of face and object recognition? *Cognitive Neuropsychology*, 35, 98–101. <https://doi.org/10.1080/02643294.2017.1414778>
- Rossion, B. (2022). Twenty years of investigation with the case of prosopagnosia PS to understand human face identity recognition. Part I: Function. *Neuropsychologia*, 173, Article 108278. <https://doi.org/10.1016/j.neuropsychologia.2022.108278>
- Rossion, B., & Jacques, C. (2011b). The N170: Understanding the time course of face perception in the human brain. In E. S. Kappenman, & S. J. Luck (Eds.), *Oxford Handbook of Event-*

- Related Potential Components (pp. 116–142). Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780195374148.013.0064>.
- Rossion, B., & Michel, C. (2011a). An experience-based holistic account of the other-race face effect. In A. J. Calder, G. Rhodes, M. H. Johnson, & J. V. Haxby (Eds.), *Oxford Handbook of Face Perception* (pp. 215–244). Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780199559053.013.0012>.
- Rossion, B., Retter, T. L., & Liu-Shuang, J. (2020a). Understanding human individuation of unfamiliar faces with oddball fast periodic visual stimulation and electroencephalography. *The European Journal of Neuroscience*, 52, 4283–4344. <https://doi.org/10.1111/ejn.14865>
- Rossion, B., Retter, T. L., & Liu-Shuang, J. (2020b). Understanding human individuation of unfamiliar faces with oddball fast periodic visual stimulation and electroencephalography. *The European Journal of Neuroscience*, 52, 4283–4344. <https://doi.org/10.1111/ejn.14865>
- Rossion, B., Retter, T. L., & Liu-Shuang, J. (2020c). Understanding human individuation of unfamiliar faces with oddball fast periodic visual stimulation and electroencephalography. *The European Journal of Neuroscience*, 52, 4283–4344. <https://doi.org/10.1111/ejn.14865>
- Rossion, B., Torfs, K., Jacques, C., & Liu-Shuang, J. (2015). Fast periodic presentation of natural images reveals a robust face-selective electrophysiological response in the human brain. *Journal of Vision*, 15. <https://doi.org/10.1167/15.1.18>, 15.1.18.
- Schestatsky, P., Morales-Quezada, L., & Fregni, F. (2013). Simultaneous EEG monitoring during transcranial direct current stimulation. *Journal of Visualized Experiments: JOVE Electronic Resource*, Article 50426. <https://doi.org/10.3791/50426>
- Seeck, M., Koessler, L., Bast, T., Leijten, F., Michel, C., Baumgartner, C., ... Beniczky, S (2017). The standardized EEG electrode array of the IFCN. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 128, 2070–2077. <https://doi.org/10.1016/j.clinph.2017.06.254>
- Sergent, J., & Signoret, J. L. (1992). Varieties of functional deficits in prosopagnosia. *Cerebral Cortex (New York, NY: 1991)*, 2, 375–388. <https://doi.org/10.1093/cercor/2.5.375>
- 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 and Cognition*, 83, 245–251. <https://doi.org/10.1016/j.bandc.2013.08.007>
- Solomon-Harris, L. M., Rafique, S. A., & Steeves, J. K. E. (2016). Consecutive TMS-fMRI reveals remote effects of neural noise to the “occipital face area”. *Brain Research*, 1650, 134–141. <https://doi.org/10.1016/j.brainres.2016.08.043>
- Stagg, C. J., Antal, A., & Nitsche, M. A. (2018). Physiology of transcranial direct current stimulation. *The Journal of ECT*, 34, 144. <https://doi.org/10.1097/YCT.0000000000000510>
- Tabikh, M., Quetu, T., Maillard, L., Colnat-Coulbois, S., Rossion, B., & Koessler, L. (2025). Transcranial direct current stimulation neuromodulates intracranial cognitive evoked activity in humans. *Proceedings of National Academy of Sciences of the United States of America*, 122, Article e2416541122. <https://doi.org/10.1073/pnas.2416541122>
- Vernieri, F., Assenza, G., Maggio, P., Tibuzzi, F., Zappasodi, F., Altamura, C., ... Rossini, PM (2010). Cortical neuromodulation modifies cerebral vasomotor reactivity. *Stroke; a Journal of Cerebral Circulation*, 41, 2087–2090. <https://doi.org/10.1161/STROKEAHA.110.583088>
- Vettori, S., Dzhelyova, M., Van der Donck, S., Jacques, C., Steyaert, J., Rossion, B., & Boets, B (2019). Reduced neural sensitivity to rapid individual face discrimination in autism spectrum disorder. *NeuroImage Clinical*, 21, Article 101613. <https://doi.org/10.1016/j.nicl.2018.101613>
- Volfart, A., & Rossion, B. (2024). The neuropsychological evaluation of face identity recognition. *Neuropsychologia*, 198, Article 108865. <https://doi.org/10.1016/j.neuropsychologia.2024.108865>
- Volfart, A., Rossion, B., Yan, X., Angelini, L., Maillard, L., Colnat-Coulbois, S., & Jonas, J. (2023). Intracerebral electrical stimulation of the face-selective right lateral fusiform gyrus transiently impairs face identity recognition. *Neuropsychologia*, 190, Article 108705. <https://doi.org/10.1016/j.neuropsychologia.2023.108705>
- Willis, M. L., Costantino, A. I., Michael, N., Palermo, R., & Rivolta, D. (2019). Anodal tDCS and high-frequency tRNS targeting the occipitotemporal cortex do not always enhance face perception. *Frontiers in Neuroscience*, 13, 78. <https://doi.org/10.3389/fnins.2019.00078>
- Woods, AJ., Antal, A., Bikson, M., Boggio, PS., Brunoni, AR., Celnik, P., ... Reato, D., et al. (2016). A technical guide to tDCS, and related non-invasive brain stimulation tools. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 127, 1031–1048. <https://doi.org/10.1016/j.clinph.2015.11.012>
- Wunder, S., Hunold, A., Fiedler, P., Schlegelmilch, F., Schellhorn, K., & Haueisen, J. (2018). Novel bifunctional cap for simultaneous electroencephalography and transcranial electrical stimulation. *Scientific Reports*, 8, 7259. <https://doi.org/10.1038/s41598-018-25562-x>
- Yang, L.-C., Ren, P., & Ma, Y.-Y. (2018). Anodal transcranial direct-current stimulation over the right dorsolateral prefrontal cortex influences emotional face perception. *Neuroscience Bulletin*, 34, 842–848. <https://doi.org/10.1007/s12264-018-0242-6>
- Živanović, M., Paunović, D., Konstantinović, U., Vulić, K., Bjekić, J., & Filipović, S. R. (2021). The effects of offline and online prefrontal vs parietal transcranial direct current stimulation (tDCS) on verbal and spatial working memory. *Neurobiology of Learning and Memory*, 179, Article 107398. <https://doi.org/10.1016/j.nlm.2021.107398>
- Zimmermann, F. G. S., Yan, X., & Rossion, B. (2019). An objective, sensitive and ecologically valid neural measure of rapid human individual face recognition. *Royal Society Open Science*, 6, Article 181904. <https://doi.org/10.1098/rsos.181904>