Details matter! Multimodal personalization increases the efficacy of transcranial direct current stimulation for modulation of sensorimotor integration

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Abstract

Neural networks subserving smooth pursuit eye movements provide an ideal model for investigating the modulation of sensorimotor integration during ongoing movements by transcranial direct current stimulation (tDCS). Within these networks, visual motion area V5 is a core hub to integrate visual motion information with oculomotor control. Here, we applied personalized tDCS explicitly targeting individual V5 in healthy human participants using algorithmic optimization informed by functional MRI and combined EEG/MEG. We hypothesized subtle impairment or facilitation of sensorimotor integration during pursuit and assessed the gain by personalized, compared to conventional normative tDCS. Indeed, pursuit initiation was specifically delayed during personalized cathodal tDCS targeting right V5 pointing towards the involvement of distinct functional subareas of V5. The results were well-controlled by anodal and sham tDCS, different pursuit tasks, and by two additional control experiments, one that applied personalized tDCS targeting FEF and another that applied normative tDCS over V5, for all of which no pursuit modulation was observed. Importantly, in contrast to normative tDCS, personalized tDCS effectively modulated pursuit by adapting electric fields to individual anatomical and functional V5 properties. Our results indicate the huge potential of personalized tDCS and transcranial electric stimulation in general to alter behavior as the main aspect of interest in human neuromodulation.

Keywords: non-invasive brain stimulation (NIBS); individualized transcranial electric stimulation (tES); oculomotor; human MT+; sensorimotor transformation; targeted transcranial brain stimulation (TBS)

Abbreviations: SP: Smooth pursuit eye movements; tES: transcranial electric stimulation; tACS: transcranial alternating current stimulation; tDCS: transcranial direct current stimulation; FEM: finite element method; DWI: diffusion weighted imaging; MRI: magnetic resonance imaging; EEG: electroencephalography; MEG: magnetoencephalography; MEEG: combined EEG and MEG; FEF: frontal eye field; BOLD: blood oxygen level dependent; SMS: simultaneous multislice; TRI: continuous pursuit task; LCMV: linearly-constrained minimum variance; DCMI: distributed constrained maximum intensity; TRIBL: continuous pursuit task with blanking; SR: foveopetal step-ramp task; LMM: linear mixed model; MT: middle temporal visual area; MST: medial superior temporal area;

1. Introduction

Smooth pursuit eye movements (SP) significantly shape our daily interactions with the environment [1] and provide an ideal model for studying sensorimotor integration mechanisms [2,3]. Based on the temporal dynamics of pursuit and the involved brain regions, SP initiation is typically dissociated from sustained SP maintenance. As part of the neural network underlying eye movement control [4,5], the extrastriate visual motion area V5/MT+ [6] has been identified as a key hub for the integration of visual motion processing during both SP initiation and maintenance [2,7–12].

Animal physiology studies demonstrated that the initiation of SP is predicted by activity in the V5-equivalent area MT+ [12–15]. Furthermore, lesion studies of MT+ in macaque monkeys demonstrated impaired SP initiation and maintenance [16–19]. This evidence is complemented by microstimulation of MT+ that increased SP velocities towards the stimulated hemisphere (i.e., ipsiversive SP), and decreased contraversive eye velocities [10]. Accordingly, human lesion studies including area V5 have demonstrated both impaired SP initiation and maintenance [20–22]. In line with this, suprathreshold neuromodulation by transcranial magnetic stimulation (TMS) targeting right V5 in humans induced an overall decrease of ipsiversive (i.e., rightward) SP velocity [23]. Furthermore, functional imaging studies associated activity in the human area V5 with SP stimulus velocity on the one hand as well as the corresponding eye velocity on the other hand, with pronounced V5 activity in the right hemisphere, compared to the left hemisphere [24–26].

Subthreshold neuromodulation of V5 in the healthy brain provides an interesting model for a better understanding of the role of V5 for SP [27]. Furthermore, such techniques can be used to mimic subtle functional impairments of sensorimotor integration, observed in the elderly or clinical populations [28–34]. More specifically, subtle subthreshold neuromodulation by transcranial electric stimulation (tES), including direct current (tDCS) and alternating current stimulation (tACS) can induce transient online-effects and after-effects that outlast the actual stimulation. Several studies induced altered visual motion processing using tDCS or tACS [35–40], but the effect of tDCS on sensorimotor transformation remains elusive. To our knowledge, only one recent study applied normative tDCS over V5 [27] to explicitly modulate sensorimotor integration during SP but did not describe tDCS-induced changes of SP performance.

105 Conventional tDCS, and tES in general, suffers from a high proportion of non-responders
106 [41–43] and overall small effect sizes in meta-analyses [44,45]. This may partly be explained
107 by the fact that conventional tDCS uses the identical normative scalp electrode montage
108 across subjects. However, based on extensive research on finite element method (FEM)
109 simulations of individual transcranial electric fields [46], it has been shown that, due to volume
110 conduction, inter-individual anatomical differences shape individual tES electric fields that
111 vary near the putative effective threshold to induce subthreshold neural modulation [46–49].
112 Importantly, neurophysiological markers of tES effects [50–52] and behavior [53–55] have
113 been related to individually simulated electric fields as the putative effector of tES. Based on
114 these challenges of normative tES, it has been suggested to use algorithmic optimization to
115 personalize tES montages, based on explicit assumptions about the individual anatomy and
116 target properties [46,56–58] to control individual transcranial electric fields [59,60]. In the
117 above-mentioned study [27], although no SP modulation by tDCS was described, FEM
118 simulations of transcranial electric fields indicated low directional intensities for the applied
119 normative montage that were significantly smaller compared to personalized electric field
120 intensities. However, actual experimental applications of personalized tES remain sparse
121 [53,61–63], probably due to the resource-intensive approach and, consequently, limited
122 examples for the actual gain of personalized compared to normative tES.
123 In the present study we applied personalized multichannel tDCS targeting V5 in the right
124 hemisphere (experiment 1) to specifically modulate V5-associated SP initiation and
125 maintenance of ipsiversive (i.e., rightward) SP (Fig. 1). We tested this hypothesis by explicit
126 definition of the individual target V5 and realistic anatomical head models (structural MRI and
127 diffusion weighted imaging, DWI) to compute personalized tDCS montages and thus
128 individually targeted and algorithmically optimized tDCS electric fields. Functional magnetic
129 resonance imaging (MRI) was employed to estimate individual V5 target location and
130 combined electro- (EEG) and magnetoencephalography (MEG; combined MEEG) to estimate
131 target orientation. We assessed the effect of personalized anodal, cathodal and sham tDCS on
132 different aspects of sensorimotor integration during SP, namely SP initiation (as assessed by
133 the step-ramp task, SR), maintenance of continuous SP (TRI task), and top-down control of SP
134 during continuous pursuit with blanking (TRIBL task; Fig. 1 and S3). We hypothesized
135 antagonistic effects of personalized cathodal versus anodal tDCS targeting V5 on ipsiversive
136 SP initiation and maintenance that builds up during tDCS (online-effects) and outlasts the

actual stimulation (after-effects). Furthermore, two control experiments were included to test a) the spatial specificity of tDCS targeting V5 compared to personalized tDCS targeting the right frontal eye field (FEF; experiment 2), and b) the gain by personalized tDCS targeting V5 compared to normative tDCS over V5 (experiment 3).

2. Materials and methods

2.1 Participants and procedure

Twenty healthy participants were recruited for the application of personalized tDCS targeting V5 (experiment 1) and FEF (experiment 2), respectively. One participant did not complete the experiment due to personal reasons. Thus, complete datasets of nineteen participants were included in the analyses (Tab. 1). To compare results from personalized tDCS to the application of normative tDCS, a subsample from a previous study applying normative tDCS over V5 [27] was statistically matched to the personalized tDCS sample with respect to age, gender, laterality index, MWT-B percentile ranks and BDI-II raw values (paired *t*-tests, all $p \geq .25$; Tab. 1) and data was re-analyzed. All participants reported no history of psychiatric or neurological disorders and no psychotic disorders of first-degree family members. Participants had normal or corrected-to-normal visual acuity (1 ± 0.1) and gave written informed consent in line with the declaration of Helsinki prior to the experiment. The study was approved by the ethics committees of the Universities of Lübeck and Münster (#20-459 and #2015-263-f-S).

In a full within-subject design, participants completed a battery of SP tasks during eight experimental sessions (Fig. 1). During the first session, structural MRI data was recorded to compute individual FEM head models. Additionally, fMRI activity was recorded while subjects [89,90] performed a SP task to localize areas V5 and FEF, in each participant individually. During the second session, combined MEEG was recorded while SP was performed to define the target neuronal orientation at the fMRI-based locations of V5 and FEF [64]. In addition, MEEG data was recorded during electrical stimulation of the median nerve to estimate individual skull conductivities based on somatosensory evoked MEEG activity [65] to inform combined MEEG source analysis and target orientation determination. In the following sections, we describe how we used the resulting individually skull-conductivity calibrated FEM head models (section 2.2) to compute personalized tDCS montages for the individual targets in V5 and FEF (section 2.3 and 2.4). Subsequently, sham-controlled personalized anodal and cathodal tDCS targeting areas V5 and FEF was applied in six subsequent experimental sessions

169 (section 2.5) to modulate SP performance (section 2.6). In addition, personalized tDCS
170 targeting V5 was compared to normative tDCS over V5, with respect to simulated transcranial
171 electric fields and SP performance under modulation by tDCS (section 2.7). In section 2.8 the
172 statistical analysis is described.
173
174 **2.2 Calibrated individual FEM head models**
175 Structural MRI data were recorded using a 3-T Siemens Magnetom Skyra scanner
176 (Siemens, Germany) and a 64-channel head coil. In addition to T1- and T2-weighted images
177 (T1: 3D MP-RAGE sequence, TR = 2300 ms, TE =3.6 ms, TI = 1100 ms, FA= 8°; T2: spin echo
178 pulse sequence, TR = 3200 ms; TE = 408 ms, FA = 120°; both at 1 x 1 x 1 mm resolution and
179 192 x 256 x 256 mm FoV), DWI data were acquired for 64 direction vectors (turbo spin echo
180 sequence, 69 volumes, 1 x 1 x 1 mm resolution, 100 x 100 x 72 mm FoV, SMS with slice
181 acceleration factor 4, TR = 5500 ms, TE = 128 ms, FA = 90°, b = 1000 s/mm^2) and five additional
182 volumes were acquired with diffusion sensitivity b = 0 s/mm^2.

183 Individual geometry-adapted six-compartment hexahedral FEM head models were
184 computed, including calibrated skull conductivities and white matter conductivity anisotropy
185 [27,66] with the DUNEuro toolbox[i] (see Supplement for details). Conductivities were set to
186 normative values for scalp (0.43 S/m), CSF (1.79 S/m), gray matter (0.33 S/m) and white matter
187 (0.14 S/m). For the EEG lead field, skull conductivities were individually calibrated (skull
188 compacta: 0.013 ± 0.01 S/m, skull spongiosa: 0.0468 ± 0.036 S/m; see Supplement) [65,66].
189 Finally, the EEG lead fields for estimation of the tDCS target orientations, and individual
190 geometry matrices for the tDCS optimization were computed using the calibrated skull
191 conductivities.

192
193 **2.3 Functional localization of V5 and FEF tDCS targets**
194 Personalized tDCS montages were computed based on individual estimates of the
195 stimulation targets in areas V5 (experiment 1) and FEF (experiment 2) of the right hemisphere,
196 respectively (Fig. 1E, Fig. 2) [27], as described in more detail below.
197 First, to determine the target locations of V5 and FEF using fMRI, blood oxygen level
198 dependent (BOLD) activity was recorded (simultaneous multislice (SMS) with acceleration

[i] https://www.medizin.uni-muenster.de/duneuro/startseite.html

factor 4, 307 Volumes, TR = 980 ms, TE = 30 ms, FA = 70°, resolution 3 x 3 x 3 mm, 68 x 68 x 56 mm) while participants performed SP (red dot as SP target, diameter 0.5°, black background; 1920 x 1080 screen resolution, 60 Hz refresh rate, NordicNeuroLab, Norway) and eye movements were recorded (Eyelink 1000Plus, 1000 Hz sampling rate; SR Research Ltd., Canada). Participants completed a test battery of SP-tasks similar to the tasks during the tDCS experiments (see Supplement). Each pursuit block was preceded by fixation intervals with a centrally presented red dot (12 s, diameter 0.5°). Functional images were slice-timing corrected, smoothed (6 mm FWHM Gaussian kernel), and co-registered to the normalized T1 image. Individual locations of visual area V5 and FEF in the right hemisphere were determined as local maxima of BOLD activity during SP near putative V5 and FEF regions (Tab. S1) [7,67] in contrast to fixation intervals (*t*-test, $p < .05$ across 5 adjacent voxels, FWE-corrected).

Second, individual target orientations were estimated using beamforming at the right V5 and FEF target locations defined by functional MRI. Therefore, combined MEEG data were recorded (EEG: 60 channels, Easycap, Germany; MEG: 275 axial gradiometers, VSM MedTech Ltd., Canada; 600 Hz sampling rate) while participants completed a continuous pursuit task (TRI; 18.7°/s, ±15° amplitude, 20 blocks of each 8 ramps to the left and right interleaved with short breaks). Before the first block and after the 10th block, participants fixated a red dot in the center of the screen for 15 s. Data were filtered (0.1 Hz highpass-filter, 50 Hz notch filter considering harmonics), cut into 320 epochs (0 to 1.59 s length relative to ramp onsets to left and right), and demeaned. Invalid epochs were rejected semi-automatically (rejected trials: 15.3 ± 11.3 %) and the EEG data was re-referenced to the average reference. tDCS target orientations were estimated using linearly constrained minimum variance (LCMV) beamforming with Unit-Noise-Gain constraint (regularization parameter $\lambda = 5\%$), following the procedure described in [64] (see Supplement for details).

Electrode positions for the tDCS montage optimization were recorded (FASTRAK, Polhemus Inc., VT/USA). These 74 electrode positions follow the 10-20-system, embedded in a standard EEG cap layout (Easycap, Germany), of which 60 electrodes were used as EEG sensors.

2.4 Computation of personalized tDCS montages and electric field simulations

Based on individual anatomical information, integrated in the head models and individual target information from the localizer tasks, personalized tDCS montages were

computed to target the area V5 (experiment 1) or FEF (experiment 2), respectively. To this end, the distributed constrained maximum intensity (DCMI) algorithm [53,60,61,68] was employed to compute the personalized tDCS montage that maximizes the injected current at the target location along the target orientation (i.e., the directionality; see Supplement for details). Resulting montages described personalized cathodal tDCS montages. Herein, we define the applied personalized tDCS montages relative to the estimated target orientations, i.e., personalized cathodal tDCS results in montages with the cathodes placed on the scalp roughly in the direction of the estimated target orientation. For personalized anodal tDCS, the polarity of each electrode was inverted. This definition does not resemble normative tDCS conventions where the cathodes/anodes are placed on the scalp directly over the proposed target location defining cathodal/anodal tDCS. This convention implicitly assumes quasi-radial targets but does not consider tangential targets or inter-individual target localization variability. The target orientations in the present study were estimated as the MEEG summed dipole orientation that might not directly reflect the local cortical structure, but rather functional properties of the target orientation. Therefore, the definition of personalized cathodal/anodal tDCS considers individual target locations and orientations.

2.5 Application of personalized tDCS

During tDCS (t_{TDCS}) personalized anodal, cathodal, or sham tDCS was applied targeting the right V5 and FEF in six pseudo-randomized sessions, separated by at least four days (7.9 ± 7.8 days, M ± SD; Fig. 1C). During each session, 20 minutes of tDCS was applied using a Starstim 8 device (Neuroelectrics, Spain). Small Ag/AgCl electrodes (NG Pistim, 3.14 cm^2 surface) were placed in custom empty EEG caps (EasyCap, Germany) with the same layout and cap size as used for the EEG measurement and electrode registration to ensure an accurate placement of the stimulation electrodes according to the optimized personalized montages (Fig. 1E). During personalized anodal and cathodal tDCS, a total of 2 mA current was applied (10 s ramp-on and ramp-off). Sham tDCS was applied by the same montages as used for anodal stimulation, but tDCS was applied for only 30 s in addition to the current ramps.

To minimize transcutaneous side-effects, anesthetic creme (2.5 % lidocaine, 2.5 % prilocaine, Anesderm®, Pierre Fabre, Germany) was used [69]. After each t_{TDCS} interval, participants completed a questionnaire asking for their subjectively perceived transcutaneous side-effects during t_{TDCS} (itching, warmth, stitching, throbbing, and pain) on a five-point scale

263 (0 = absent, weak, moderate, pronounced, 4 = intense) [70]. Furthermore, participants rated
264 subjective fatigue for four timepoints during t_{TDCS} on a five-point scale (1 = very alert, awake,
265 moderate, tired, 5 = very tired).
266
267 **2.6 Eye tracking and analysis of eye movement data**
268 During the six tDCS sessions, participants were seated 65 cm in front of an LCD monitor
269 in a closed room with lights off and completed three SP tasks to assess different aspects of SP
270 initiation and maintenance (see Supplement for details) [27]. In short, eye movements were
271 recorded using a video-based eye tracker (Eyelink 1000Plus, SR Research Ltd., Canada). During
272 all tasks, participants were instructed to follow a horizontally moving SP target on the monitor
273 as precisely as possible (red dot with 0.5° diameter, black background; Fig. 1B). During the first
274 task, eight horizontal constant velocity ramps were presented as continuous triangular
275 waveform stimulus (TRI, 18.7°/s, ± 15° amplitude; Fig. 1B-C, Supplement). In the second task,
276 12 similar horizontal velocity ramps were presented with target blanking between 300 to 1000
277 ms relative to ramp onset (18.7°/s, ± 15° amplitude, triangular waveform stimulus with
278 blanking, TRIBL; Fig. 1B-C, Supplement). To specifically assess SP initiation and early SP
279 maintenance eight horizontal foveopetal step-ramp stimuli (SR) were presented [71], pseudo-
280 randomly directed either to the left or the right side of the screen. Step-ramps started with a
281 2.5° step which was immediately followed by a velocity ramp in the opposite direction
282 (18.7°/s, ± 15° amplitude; Fig. 1B-D). To minimize expectation effects, two of eight step-ramps
283 were presented with alternating velocities (9.7 °/s, ± 1.3 ° step-size; 26.7 °/s, ± 3.5 ° step-size).
284 The three tasks were presented in mixed blocks [33] including three task repetitions during
285 each block. This resulted in 24 continuous ramps (TRI), 36 ramps with blanking (TRIBL) and 24
286 step-ramps (SR) per block.
287 Effects of tDCS on SP were assessed by presenting each one block of SP tasks before (t_0),
288 and 15 and 40 minutes after (t_{15}, t_{40}; after-effects) tDCS application in each of the six
289 experimental sessions. Online effects of tDCS were assessed by presenting four repetitions of
290 SP task blocks equally distributed across the 20 minutes tDCS application (t_{TDCS}; i.e., within the
291 first 5, 10, 15, or 20 minutes of tDCS, t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}; Fig. 1C). During t_{TDCS}, SP
292 task blocks were separated by simple oculomotor tasks to activate the oculomotor system
293 during the stimulation, while providing an active rest for the participants at the same time.
294 Overall, this resulted in 504 continuous ramps (TRI), 756 ramps with blanking (TRIBL) and 504

295 step-ramps (SR) that were analyzed for each subject during experiment 1 (V5) and experiment
296 2 (FEF), respectively.
297 SP data analysis focused on SP velocity, computed as the first derivative of eye position.
298 Continuous data were epoched (-100 to 1600 ms for TRI and TRIBL and -100 to 1300 ms for SR
299 relative to the ramp onset) and invalid epochs were rejected (experiment 1 (V5): 1.5 ± 2.1 %
300 epochs were rejected; see Supplement). Median eye velocity across epochs was computed
301 separately for each subject, tDCS condition (anodal, cathodal, sham), timepoint (t_0, t_{TDCS_5},
302 t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}, t_{15}, t_{40}) and stimulus direction (leftward, rightward). SP velocity
303 parameters were computed to assess different aspects of SP performance during SP initiation
304 (SR: SP latency, initial eye acceleration; Fig. 1D) as well as ongoing SP (SR: early maintenance
305 gain; TRI: maintenance gain, gain = eye velocity/target velocity; TRIBL: preblank, residual and
306 postblank velocity gains, deceleration and deceleration latency at the start of the blanking
307 interval, as well as re-acceleration and re-acceleration latency at the end of the blanking
308 interval) [27,72].
309
310 **2.7 Comparing personalized tDCS targeting V5 and normative tDCS over V5**
311 Results from personalized tDCS targeting V5 (experiment 1) were compared to results
312 from the application of normative tDCS over V5 (experiment 3; Tab. 1). The normative
313 application of V5 was designed identically to the personalized procedure with respect to the
314 SP test battery and the overall application of tDCS [27] and data from experiment 3 was re-
315 analyzed according to the analysis procedure in experiment 1. However, instead of
316 personalized tDCS montages, normative tDCS montages were used in experiment 3 that did
317 not vary across subjects, thus also no MEEG and MRI data were acquired before the normative
318 tDCS experiment. In short, to apply normative tDCS, two stimulation electrodes were placed
319 over area V5 of the right hemisphere (PO8, P8) with two central return electrodes (Cp1, Cz)
320 [36,37] according to the 10-20 system. During normative tDCS, 2 mA current was applied for
321 20 minutes, restricted to 1 mA per electrode. Eye movements were recorded during the same
322 timepoints as in the personalized experiment (t_0, t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}, t_{15}, t_{40}). Since
323 SP during t_{TDCS} were not analyzed in detail by Radecke et al. [27], the data from the matched
324 sample were re-analyzed for all tDCS timepoints (t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}) to compare
325 online effects on the SP performance by normative versus personalized tDCS.

Furthermore, electric field simulations were compared between normative and personalized montages to estimate the differences in the potential efficacy between the two tDCS methods, given the individual estimates of the V5 tDCS target. Therefore, normative electric field simulations were computed for the N = 19 subjects from the personalized tDCS sample, using the normative electrode placement, since data for these participants for computation of individual head models and estimation of individual tDCS targets were available. To quantify individual transcranial electric field parameters (see Supplement for details), for each subject, we computed the target intensity ($|E|_{IT}$) the target intensity corrected for the parallelity between the stimulation target orientation vector and the target electric field orientation vector (directionality, $|E|_{DIR}$) [53,60,61], as well as the spatial extent of the electric field relative to the stimulation target ($|E|_{EXTENT}$) [53,60]. The overall cortical electric field ($|\mathbf{E}|$) and electric field parameters with respect to the individual stimulation targets ($|E|_{IT}$, $|E|_{DIR}$, $|E|_{EXTENT}$) were compared between personalized versus normative tDCS. For illustration, individual electric fields were interpolated on a common MNI cortical grid and averaged across subjects (Fig. 2).

2.8 Statistical analysis of tDCS effects

To analyze tDCS effects on SP performance, linear mixed models (LMMs) were fitted to the data (IBM SPSS Statistics, IBM Corp., USA) for each estimated SP parameter and separately for experiment 1 (V5-personalized), experiment 2 (FEF-personalized), and experiment 3 (V5-normative). In a full within-subject design, tDCS condition (anodal, cathodal, sham), timepoint (t_0, t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}, t_{15}, t_{40}) and the visual stimulus direction (leftward, rightward) were included as fixed effect factors. To control inter-individual variability of SP performance, subject ID was included as random effects factor (random intercept; identity covariance structure). tDCS condition, timepoint and ramp direction were considered as repeated factors (first-order autoregressive covariance structure). Main and interaction effects were analyzed in a saturated model. In case of specific tDCS effects (i.e., an interaction between tDCS condition, timepoint, and ramp direction), separate LMM analyses were computed for timepoints of online effects (t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}) and (after-)effects relative to t_0 (t_0, t_{TDCS}, t_{15}, t_{40}, using the averaged performance across all t_{TDCS} timepoints), further including tDCS condition and ramp direction as factors.

The significance level was set to α = .05 and post-hoc contrasts of estimated marginal means were computed for the highest-order interaction or main effect (Bonferroni-corrected for multiple comparisons). *F*-values and *p*-values are reported for significant main or interaction effects. For post-hoc tests, Bonferroni-corrected *p*-values, mean and standard error of the mean are reported. Effect sizes were estimated as the absolute value of Cohen's $d_z = \frac{t}{\sqrt{N}}$ with *N* being the respective sample size and *t* being the *t*-value computed based on the mean difference and standard error of the mean of the difference between estimated marginal means of the respective paired post-hoc contrast [73].

Furthermore, significant LMM tDCS condition * timepoint * stimulus direction interactions indicate specific tDCS effects. To follow-up these results in more detail, tDCS online effects were defined as the difference between the first and the last timepoint during t_{TDCS} (t_{TDCS_20} - t_{TDCS_5}) of the respective SP parameter, irrespective of the temporal evolution of this effect. A second, complementary estimate of tDCS effects was computed as the slope (*b*) of a robust linear regression computed across all timepoints during t_{TDCS} (t_{TDCS_5} to t_{TDCS_20}) assuming a quasi-linear evolution of the tDCS effect during the stimulation (Fig. 3). Both tDCS effect measures were compared between stimulus directions for each tDCS condition, as well as between tDCS conditions for each stimulus direction using bootstrapped paired *t*-tests (*n* = 10000 bootstrap samples were computed to determine the H_0 distribution). In addition, tDCS effects for the respective tDCS condition and stimulus direction were compared across experiments using bootstrapped paired *t*-tests to compare between experiment 1 (V5-personalized) versus experiment 2 (FEF-personalized) and unpaired *t*-tests to compare experiment 1 (V5-personalized) versus experiment 3 (V5-normative). For all bootstrap *t*-tests *z*-values and *p*-values (Bonferroni-corrected) are reported and Cohens d_z (paired contrast) or d_s (unpaired contrast) was computed based on the observed values [73].

Electric field simulations were compared between normative versus personalized tDCS montages. Individually simulated electric fields were interpolated on an MNI cortical surface representation and paired *t*-tests were computed for every position of the surface grid between personalized and normative tDCS (FDR-corrected) [74]. Furthermore, separate bootstrap paired *t*-test were computed (one-sided) with 10000 iterations using MATLAB (The Mathworks Ltd., MA/USA) for $|E|_{IT}$, $|E|_{DIR}$, and $|E|_{EXTENT}$. For each test, *z*-value, *p*-value and descriptive means and standard errors of the means are reported. Effect size d_z was estimated based on the observed values [73].

389 ## 3. Results

390 ### 3.1 Personalized tDCS adapts to inter-individual target variability

391 Individual stimulation targets showed varying location and orientation (Fig. 2A-B).
392 Specific SP-related BOLD activity was observed in individually estimated V5 locations near
393 previously reported V5 coordinates (x/y/z MNI-coordinates, V5: 45/-67/2 ± 3/6/4; Tab. S1)
394 [7,67]. Individual V5 activation maxima deviated by 7 ± 3 mm to the mean location, yielding a
395 considerable inter-individual variability of tDCS target locations (Fig. 2B). Second-level analysis
396 of BOLD activity revealed a significant increase of V5 activity during continuous pursuit,
397 compared to fixation in a cluster in inferior and middle occipital, as well as middle and inferior
398 temporal cortex of the right hemisphere (cluster size k = 97, cluster p = .007, local maximum:
399 42/-73/2, t_{18} = 7.6) [75]. For illustration, individual statistical maps from the Pursuit versus
400 Fixation contrast were interpolated on the MNI brain, and FDR-corrected one-sample t-tests
401 are shown (Fig. 2A). A mask of the V5-equivalent cytoarchitectonic area hOc5 was additionally
402 applied and confirmed a significantly increased BOLD activity in V5 during SP compared to
403 fixation (t_{18} = 6.3, p < .001, center coordinates: 45/-61/2) [6]. In line with the heterogenous
404 cortical structural organization of V5, the estimated stimulation target orientations showed a
405 variety of quasi-radial, and quasi-tangential orientations across participants (Fig. 2B).

406 Personalized tDCS montages targeting individual right V5 confirmed a clear adaptation
407 to the target location and orientation, placing cathodes on the scalp roughly over the target
408 in the direction of estimated target orientation. Across subjects, exemplary for the application
409 of personalized cathodal tDCS, a cluster of anodes was observed including electrode positions
410 P6, P8, and CP6, whereas a cluster of cathodes was observed including electrode positions
411 PO8, PO10, O2, and O10. However distinct target orientations and quasi-radial target
412 orientations are reflected by varying tDCS electrode positions across the scalp (Fig. 2C) [60].
413 Overall SP performance was high in the expected range for young healthy participants (Tab.
414 2, see Supplement) [27].

415

416 ### 3.2 Personalized tDCS targeting V5 specifically modulates pursuit initiation

417 Personalized tDCS was applied to modulate SP performance depending on tDCS
418 condition (sham, anodal, cathodal), timepoint (t_0, t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}, t_{15}, t_{40}) and
419 SP stimulus direction (leftward, rightward). Personalized tDCS targeting V5 specifically
420 modulated SP latencies in the SR task, as revealed by an omnibus analysis (three-way

interaction: p = .044; Fig. 3A-C, Tab. S2). Additional LMM analyses indicated an online effect during tDCS (p = .015; Fig. 3A-C, Tab. 3), but no tDCS after-effects (p = .484; Tab. 4). Specifically personalized cathodal tDCS delayed rightward SP latencies for t_{TDCS_20}, relative to t_{TDCS_5} (p = .002, d_z = 0.93). A follow-up analysis confirmed that overall SP latencies across all timepoints of the sham session (t_0, t_{TDCS_5} to t_{TDCS_20}, t_{15}, t_{40}) were delayed for leftwards compared to rightwards SP (p = .007, d_z = 0.64; compare Fig. 3A), indicating that personalized cathodal tDCS targeting the right V5 hampered latencies of rightward SP to the level of initially delayed leftward SP latencies. In addition, a paradoxical effect by personalized cathodal tDCS was observed during t_{TDCS_15} between leftward and rightward SP latencies (p = .002, d_z = 0.89) and latencies for leftward SP during t_{TDCS_15} were significantly delayed for personalized cathodal tDCS, compared to sham (p = .042, d_z = .72; Fig. 3A).

To follow-up tDCS online effects for rightward SP latencies (Fig. 3A), these were defined both as difference between the first and last timepoint during t_{TDCS} ($t_{TDCS_20} - t_{TDCS_5}$; 18 [12, 29] ms, bootstrapped mean and [95%-confidence interval]; Fig. 3B), as well as the slope of a linear fit across all four t_{TDCS} timepoints (t_{TDCS_5} to t_{TDCS_20}; 4.9 [2.8, 8.3] ms/5 minutes ; Fig. 3C). While the difference tDCS effect can be directly related to the significant post-hoc contrasts of the LMM analysis, the slope tDCS effect yields a more robust estimate considering the paradoxical effect, but thereby introduces potential noise from the SP latencies observed during t_{TDCS_10} and t_{TDCS_15}. Therefore, we consider the difference and slope estimates of the tDCS effect as complementary. Significant differences between personalized anodal and cathodal tDCS for the rightward SP latencies were revealed for both difference (z = -3, p = .008, d_z = 0.72) and slope estimates (z = -2.58, p = .03, d_z = 0.61) of tDCS effects. In addition, difference tDCS effects differed between leftwards and rightwards SP latencies during personalized cathodal tDCS (z = -2.41, p = .024, d_z = 0.59). The corresponding effect for the slope estimate did not survive Bonferroni-correction (p = .11). In addition, the difference tDCS effect was significantly larger for personalized cathodal tDCS targeting V5, when compared to personalized tDCS targeting FEF (z = 2.08, p = .019, d_z = 0.5) while the same effect for the slope estimate missed significance (p = .057).

During tDCS, an online effect on initial acceleration was also observed (p = .02; Tab. 3), however, this effect was not indicated by the preceding omnibus analysis and post-hoc tests did not survive correction for multiple comparisons.

452 Besides the modulation of SP latencies, no specific tDCS effects (i.e., tDCS condition *
453 timepoint or tDCS condition * timepoint * direction interaction effects) were observed for
454 tasks indicating sustained SP maintenance performance with continuously visible targets (TRI),
455 top-down mechanisms involved in ongoing SP with temporary target blanking (TRIBL) or
456 ongoing SP performance during the SR task following SP initiation (all $p > .523$; Tab. 3-4, Tab.
457 S2). Furthermore, neither personalized tDCS targeting the right FEF as a control region (within-
458 group, $p = .862$; Fig. 3D-F, Tab. S4), nor normative tDCS over V5 ($p = .93$; between-group,
459 matched sample of N = 19; Fig. 3G-I, Tab. S5) induced a modulation of SP latencies during tDCS
460 comparable to the observed effects for personalized tDCS targeting V5 (Fig. 3A-C). Finally, the
461 results were not compromised by individual tDCS side-effects (see Supplement).
462
463 **3.3 Personalized tDCS targeting V5 increases tDCS efficacy compared to normative tDCS over**
464 **V5**
465 To evaluate the electric field differences presumably leading to distinct tDCS effects,
466 electric field simulations were compared between the applied personalized tDCS targeting V5
467 and the normative V5 montage for the N = 19 subjects from experiment 1 (personalized V5;
468 Fig. 2C-F). Normative electric fields across the cortex showed significantly increased intensities
469 in non-target dorsal and medial parts of bilateral parietal cortex compared to personalized
470 electric fields. In contrast, personalized electric fields showed increased intensities in the right
471 lateral occipital-parietal-temporal cortex compared to the normative electric fields (Fig. 2F).
472 In addition, directionalities were significantly increased for personalized compared to
473 normative electric fields ($z = -4.87$, $p < .001$, $d_z = 1.11$; normative $|E|_{DIR} = 0.05 \pm 0.32$ V/m,
474 personalized $|E|_{DIR} = 0.42 \pm 0.28$ V/m, M ± SD; Fig. 2F). Electric field spatial extent was
475 significantly decreased for personalized, compared to normative tDCS ($z = 6.81$, $p < .001$, $d_z =$
476 1.74 normative $|E|_{EXTENT} = 70 \pm 2$ mm, personalized $|E|_{EXTENT} = 57 \pm 8$ mm, M ± SD; Fig. 2F). In
477 conclusion, personalized electric field topographies were shifted towards individual tDCS
478 targets in the right V5, thus effectively considering the varying individual tDCS target locations
479 and orientations in the right V5 and reducing co-stimulation of non-target parietal cortex,
480 compared to the normative electric fields.
481 Indeed, the evaluation of tDCS effects on ipsiversive SP latencies revealed significantly
482 increased tDCS effects for personalized cathodal tDCS targeting V5 compared to normative

483 tDCS over V5 (difference tDCS effect: z = 2.1, p = .018, d_s = 0.7; slope tDCS effect: z = 1.81, p
484 = .036 , d_s = 0.61).
485

486 ## 4. Discussion

487 We conducted a comprehensively controlled experiment to assess the effects of
488 personalized tDCS targeting V5 on SP initiation and maintenance as a direct behavioral read-
489 out of tDCS effects on sensorimotor integration. We found a spatially and functionally specific,
490 significant modulation of SP initiation by personalized cathodal tDCS that was absent during
491 anodal or sham tDCS. This effect was independent from possible practice effects [27] and tDCS
492 side-effects (Supplement). Furthermore, electric field simulations and a control experiment
493 applying normative tDCS over V5 signify more precise electric fields and an increased gain by
494 personalized tDCS in contrast to normative tDCS.
495

496 **4.1 Personalized tDCS targeting V5 specifically modulates pursuit initiation**

497 To interpret our key finding of specific SP initiation modulation (i.e., SP latencies) by
498 personalized cathodal tDCS, it is important to consider the multimodal role of the human
499 visual area V5/MT+. V5 can be functionally dissociated into the middle temporal visual area
500 (MT) and the medial superior temporal area (MST) [7,9]. In the macaque monkey, it has been
501 shown that MT receives bottom-up visual information [76,77] and integrates these to signal
502 visual motion on the retina as a velocity signal during SP [11]. MST receives projections from
503 MT [77] and MST itself maintains reciprocal connections to various visual areas, as well as
504 parietal and premotor nodes of the oculomotor network [76,78] that govern top-down signals
505 during ongoing SP, e.g., predicting target motion even in the absence of a visual target [11].
506 Importantly, neural activity in MT+ is involved in SP initiation, but relies on gain control by
507 higher-order network nodes such as the FEF [12,13,15]. In line with these studies, human
508 V5/MT+, comprising putative MT and MST, has been suggested as a key hub for the
509 sensorimotor transformation during SP [7,79], thus integrating bottom-up visual motion
510 information with top-down oculomotor control during SP initiation and SP maintenance.

511 In the present study, SP initiation (SP latency in the SR task) was hampered by
512 personalized cathodal tDCS targeting V5. The observed impairment of ipsiversive, but not
513 contraversive, SP is in line with previous TMS modulation of the right V5 in humans [23].
514 Animal studies described an impairment of ipsiversive SP for foveopetal step-ramps after

515 lesions of the foveal representation of MT [17,19] anduman lesion studies including V5
516 described similar ipsiversive SP deficits [20–22]. However, the same authors also differentiate
517 contralesional SP deficits (retinotopic) from directional deficits that affect SP ipsiversive to the
518 lesion site [17,20–22]. During the step of the applied SR task, the visual target is moved 2.5 °
519 to one side, before it starts to move in the opposite direction with a constant velocity ramp.
520 This paradigm allows subjects to start pursuit without an initial saccade as soon as the visual
521 target crosses the point of the subject's central fixation at the start of each trial. However, this
522 also implies that in the time between the step onset and the midline-crossing of the visual
523 target, subjects fixate the center of the screen and thus are presented a retinotopic visual
524 stimulus moving from the step eccentricity towards the participant's central fixation, before
525 the visual target is then fixated during the actual pursuit. Thus, in the present experiment
526 personalized cathodal tDCS presumably induced retinotopic deficits that affected
527 sensorimotor transformation after the leftward target step onset moved the visual target to
528 the hemifield contralateral to the targeted right V5, but before the onset of rightward SP. This
529 would explain the observed isolated deterioration of SP latencies that might follow retinotopic
530 deficits in the hemifield contralateral to the targeted right V5. At the same time initial
531 acceleration (SR task), SP maintenance (TRI task) and top-down aspects of SP in the blanking
532 task (TRIBL task), which would rather indicate directional effects [18], remained unaffected
533 [21]. Retinotopic SP deficits could indicate the involvement of peripheral representations in
534 MT, in contrast to foveal MT representations, and/or adjacent MST parts. Lesions of the latter
535 also result in directional SP deficits [16,17,19]. In contrast to tDCS targeting V5, no SP
536 modulation was observed by tDCS targeting right FEF, further marking the spatial specificity
537 of personalized tDCS targeting right V5. We conclude that in our experiment personalized
538 cathodal tDCS specifically modulated early sensorimotor transformation within V5 putative
539 subregion MT, or feedforward communication from MT to MST. We further speculate, either
540 that sensorimotor transformation of foveated visual motion information was not affected by
541 personalized cathodal tDCS, or that tDCS-induced initial directional disturbances were
542 compensated by higher-order cognitive mechanisms coming into play under maintenance of
543 ongoing SP [28,29,72,80,81].
544
545 **4.2 Personalized cathodal tDCS targeting V5 transiently reduces cortical excitability**

546 Conventionally, cathodal tDCS has been defined as placing the cathode (anode) over the
547 assumed target region to reduce (increase) cortical excitability [82]. Among other mechanistic
548 explanations for tDCS [83], it has been proposed that tDCS electric fields induce cortical
549 membrane polarizations that lead to a subthreshold modulation of neuronal firing-rates and
550 altered cortical excitability [82,84], in addition to changes of blood flow [85] and local
551 GABA/glutamate metabolism at the stimulation site [86–88]. Cathodal tDCS specifically was
552 described to reduce cortical excitability [82,84] and local glutamate concentration [87].
553 Therefore, personalized cathodal tDCS in the present study presumably reduced cortical
554 excitability in V5, thereby hampering the integration of visual motion information to elicit SP
555 initiation as indicated by delayed SP latencies.

556 We observed a transient modulation of SP latencies by single-bout personalized
557 cathodal tDCS (online-effect). No after-effects were observed 15 minutes after tDCS or
558 thereafter. Instead, the online tDCS effect on SP initiation evolved slowly over the 20 minutes
559 tDCS resulting in a significant latency difference between the first (t_{TDCS_5}) and the last (t_{TDCS_20})
560 read-out timepoints. Immediate tDCS modulations were previously shown to induce NMDA-
561 receptor mediated long-term plasticity (LTP) or long-term depression (LTD) that drive longer-
562 lasting tDCS effects [89–91]. Thus, we conclude that personalized cathodal tDCS in the present
563 study induced immediate changes in MT excitability which exerted a statistically robust tDCS
564 effect on behavioral SP performance only when tDCS-induced LTD-like effects were
565 established after several minutes of continuous tDCS.

566 In previous studies, both anodal and cathodal tDCS over V5 induced an improvement in
567 the discrimination accuracy of coherent motion perception in visual scenes [40]. Following
568 previous speculations [37], Battaglini and colleagues [40] suggested that, on the one hand,
569 anodal tDCS increases coherent motion discrimination by increasing the excitability of
570 neurons in the putative subregion MT of V5 that are tuned to correlated motion signals. On
571 the other hand, cathodal tDCS reduces the overall excitability of MT, thereby relatively
572 reducing the response to uncorrelated noise in competing motion scenes with low coherence.
573 At the same time, cathodal tDCS also reduces the discrimination of coherent motion signals in
574 visual scenes with high signal-to-noise ratio. In line with this evidence, we observed a specific
575 impairment of the direct and naturalistic SP sensorimotor response to a single moving visual
576 target without competing motion noise (i.e., with high signal-to-noise ratio) during
577 personalized cathodal tDCS. We further speculate that we did not observe performance

578 facilitation by personalized anodal tDCS in the present young, healthy participants due to a
579 ceiling effect [92] of their anyway high SP performance, in addition to practice-associated
580 improvements obtained during the study (Supplement) [27]. In contrast, impaired SP latencies
581 observed in the elderly and clinical populations [28–30], might be improved by anodal tDCS
582 representing interesting target populations to further examine the clinical benefits of
583 (personalized) tDCS for future studies.

584 Taken together, by applying personalized, i.e., targeted tDCS and differentiating distinct
585 functional properties of SP, we can pinpoint the modulation of SP latencies by personalized
586 cathodal tDCS to an early phase of sensorimotor transformation, presumably involving
587 reduced excitability and LTD-like modulation of V5 subregion MT that delays SP performance.
588

589 **4.3 Normative tDCS over V5 does not modulate pursuit initiation**

590 In contrast to the specific modulation of ipsiversive SP latencies during personalized
591 tDCS targeting V5, no online effect was observed by normative tDCS over V5, extending
592 previous findings [30] that normative tDCS over V5 did not result in any tDCS after-effects on
593 SP [27]. However, simulations of tDCS electric fields in a small sample (N = 6) already suggested
594 rather small target directionalities by normative tDCS that could be increased by personalized
595 tDCS montages with respect to individual targets. Here, we confirm, in a much larger sample,
596 that normative tDCS over V5 yields limited target directionalities, compared to personalized
597 tDCS targeting V5. This improvement of simulated personalized compared to normative
598 electric fields is in line with previous findings of increased personalized directionalities when
599 targeting the parietal cortex [60], the somatosensory cortex [61] and increased electric fields
600 across the brain and within the target region for personalized electric fields targeting the
601 auditory cortex [63]. Furthermore, we extend previous findings by whole-brain analysis of
602 personalized compared to normative simulated electric fields indicating reduced spatial
603 extent of the targeted electric fields and a shift of the electric field topography away from
604 bilateral non-target parietal regions and towards individual target V5 estimates in temporal
605 regions within the right hemisphere (Fig. 2E-F).

606 Although it has been proposed repeatedly to implement electric field simulations and
607 optimization in tES protocols [48,56–58,93], actual applications of personalized tES remain
608 rare [53,61–63]. Thus, little is known about the gain of personalized, compared to
609 conventional normative tES. Therefore, in addition to the analysis of simulated electric fields,

610 we investigated whether the observed behavioral online effect of personalized cathodal tDCS
611 on ipsiversive SP latencies were specific to the applied personalization approach, by re-
612 analyzing data from a matched sample where normative tDCS was applied over the right V5.
613 In contrast to personalized tDCS targeting V5, we did not observe a modulation of SP during
614 normative tDCS over V5. A more detailed analysis indicated a significantly increased tDCS
615 effect on SP by personalized cathodal tDCS, compared to normative cathodal tDCS. We thus
616 follow that the increased theoretical efficacy of personalized compared to normative tDCS of
617 V5 as indicated by electric field simulations holds true for the actual modulation of SP latencies
618 as direct behavioral read-out of the tDCS-effect. Only a few previous studies provided data
619 from applied personalized tDCS [61] or tACS [53,62,63] and only two of those provided a direct
620 comparison of personalized versus normative tES [61,63]. To our knowledge, as of now, no
621 study described the gain by personalized compared to normative tDCS with respect to the
622 modulation of behavior. Khan and colleagues [61] found a significant modulation of
623 somatosensory evoked activity by personalized tDCS targeting the primary somatosensory
624 cortex in ten subjects, but no effect by normative tDCS. In the same study, personalized
625 transcranial electric fields optimized with the DCMI algorithm [68] reached simulated target
626 directionalities of 0.38 ± 0.21 V/m, compared to 0.26 ± 0.13 V/m for normative tDCS (2 mA).
627 In line with these results, our present data indicate that personalized tDCS using the DCMI
628 algorithm targeting V5 shifts the electric field topography towards the explicitly defined tDCS
629 target and thereby increases target directionalities above the effective threshold at the group-
630 level. Normative tDCS may not produce reliable results, due to the relatively limited and
631 untargeted electric fields. Especially in the light of a growing interest in tDCS for clinical
632 application [94,95], our present findings support the huge potential of personalized tES
633 approaches directing individual transcranial electric fields to the assumed cortical target,
634 thereby maximizing the individual stimulation efficacy.

635 In another study, the application of 2 Hz tACS targeting the auditory cortex (stimulation
636 intensity: ±0.5 mA) induced a phase-specific modulation of frequency-modulated sounds by
637 personalized tACS, but also for normative tACS [63]. In this light, it must be noted that
638 personalized tES does not necessarily increase effectiveness, compared to normative tES.
639 Indeed, normative tES can greatly reduce the resources required for experimental and clinical
640 applications considering additional data acquisition and analysis for target localization,
641 individual head models, and electrode positions needed for the optimization and careful

application of personalized tES [48]. To conclude, we suggest that personalized and normative approaches should be handled complementary: By specific assumptions about the individual anatomy and the individual functional tES targets, personalized tES is predestined to test hypotheses about the functional mechanisms underlying specific tES applications, for example the role of V5 in the modulation of SP, as shown in the present study. Naturally, personalized tES combines the analysis of tES read-out parameters with simulated electric fields and neurophysiological data that can inform and extend the analysis. These insights can then be used to validate implicit assumptions of normative tES applications or to *a priori* inform the optimization of next-generation, resource-efficient and effective normative tES montages, as a complementary approach to data-intensive *a posteriori* optimization of normative tES montages [55,96].

5. Conclusion

In this study, our main finding shows that personalized cathodal tDCS targeting right V5 specifically delayed latencies of ipsiversive SP due to a transient but LTD-like modulation of early sensorimotor transformation in the MT subregion of V5. FEM simulations of electric fields suggest that the gain of (effective) personalized tDCS, compared to (ineffective) normative tDCS might be attributed to topographical shifts of personalized transcranial electric fields towards the targeted right V5 at group-level, as well as increased target directionalities and reduced spatial extent. We suggest that personalized tDCS, and tES in general, might be an interesting methodological perspective to increase tES efficacy, especially in clinical research and therapeutical settings.

CRediT authorship contribution statement

Jan-Ole Radecke: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - original draft, Visualization. **Alexander Kühn:** Investigation, Data curation, Formal Analysis, Writing – review & editing. **Tim Erdbrügger and Yvonne Buschermöhle:** Investigation, Methodology, Software, Writing - review & editing. **Sogand Rashidi and Hannah Stöckler:** Investigation, Data curation, Writing – review & editing. **Benjamin Sack:** Investigation, Writing - review & editing. **Stefan Borgwardt:** Resources, Supervision, Writing - review & editing. **Till R. Schneider:** Supervision, Methodology, Writing - review & editing. **Joachim Gross:** Supervision, Funding acquisition, Writing - review & editing. **Carsten H. Wolters:** Supervision, Project administration, Funding acquisition, Writing - review & editing. **Andreas Sprenger:** Methodology, Software, Supervision, Writing – review & editing. **Rebekka**

Lencer: Project administration, Funding acquisition, Conceptualization, Writing - review & editing.

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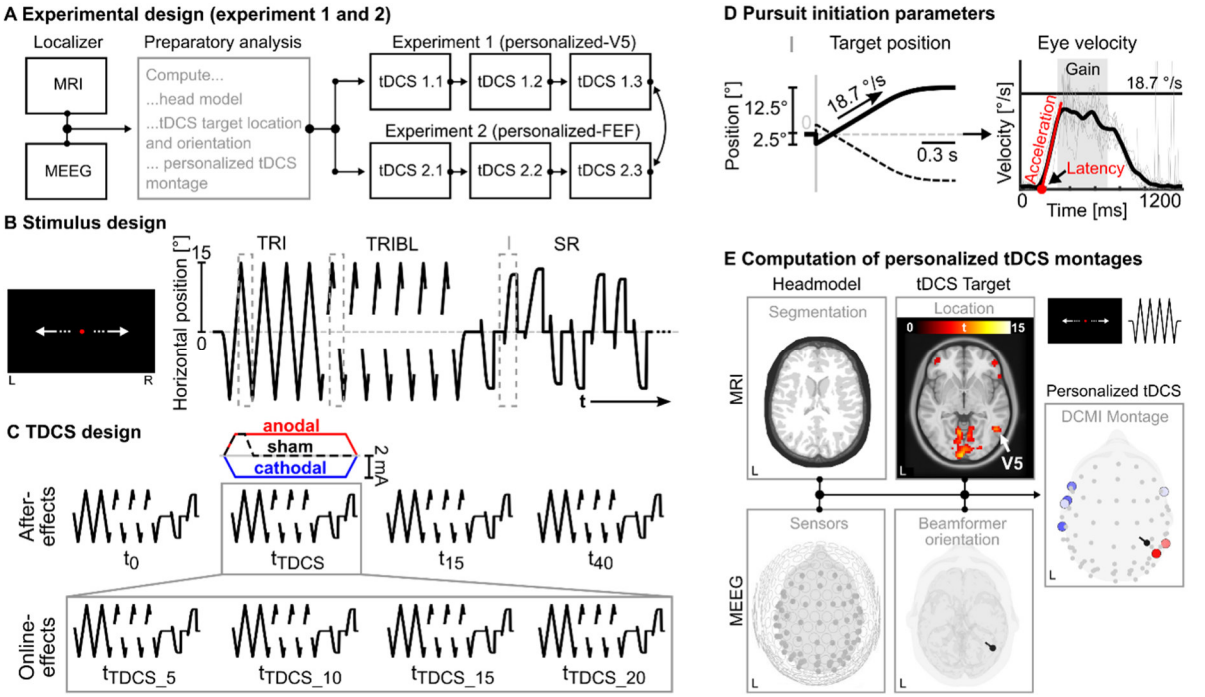

Figure 1. Experimental design. A) Personalized tDCS in experiment 1 and 2 comprised eight experimental sessions on separate days per participant (black boxes). During the first two appointments participants completed MRI and MEEG localizer experiments. Localizer data was used to compute personalized tDCS montages (gray box). Sham, anodal, and cathodal tDCS was applied in three subsequent sessions targeting V5 or FEF. After participants completed the first experiment, three further tDCS sessions were completed for the respective second experiment. The initial assignment to experiment 1 or 2, as well as the order of sham, anodal, and cathodal tDCS within each experiment was counterbalanced across participants. **B)** Horizontally moving visual stimuli were presented. To evaluate the effect of personalized tDCS on different aspects of SP, three tasks were presented, namely continuous SP (TRI), continuous SP with blanking (TRIBL), and foveopetal step-ramp stimuli (I, SR). **C)** In each tDCS session, SP tasks were presented before (t_0), at four timepoints during (t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}), and 15 (t_{15}) or 40 minutes (t_{40}) after tDCS application. **D)** Pursuit initiation parameters were computed based on the eye tracking data recorded during the step-ramp task. Eye velocities (right) were derived from the eye position (left) as a function of time. Pursuit latency and initial acceleration were computed to define SP initiation performance. Early gain was computed to estimate ongoing SP performance (300 to 700 ms after target motion onset). Target velocity is indicated by a black line at 18.7 °/s. **E)** To compute personalized tDCS montages, structural MRI data were acquired to create a six-compartment segmentation of the individual head (top left). Together with the sensor positions from the combined MEEG session (bottom left), as well as individually calibrated skull conductivity and white matter anisotropy (not shown) individual FEM head models were computed. Individual tDCS targets were defined, using functional MRI data acquired during continuous SP to define the target location in the right hemisphere (top middle, MNI z = -4), and combined MEEG data to define the target orientation (bottom middle). Together the head model and tDCS target information were used to compute personalized tDCS montages with the DCMI algorithm. The workflow to target the area V5 is shown for one exemplary subject.

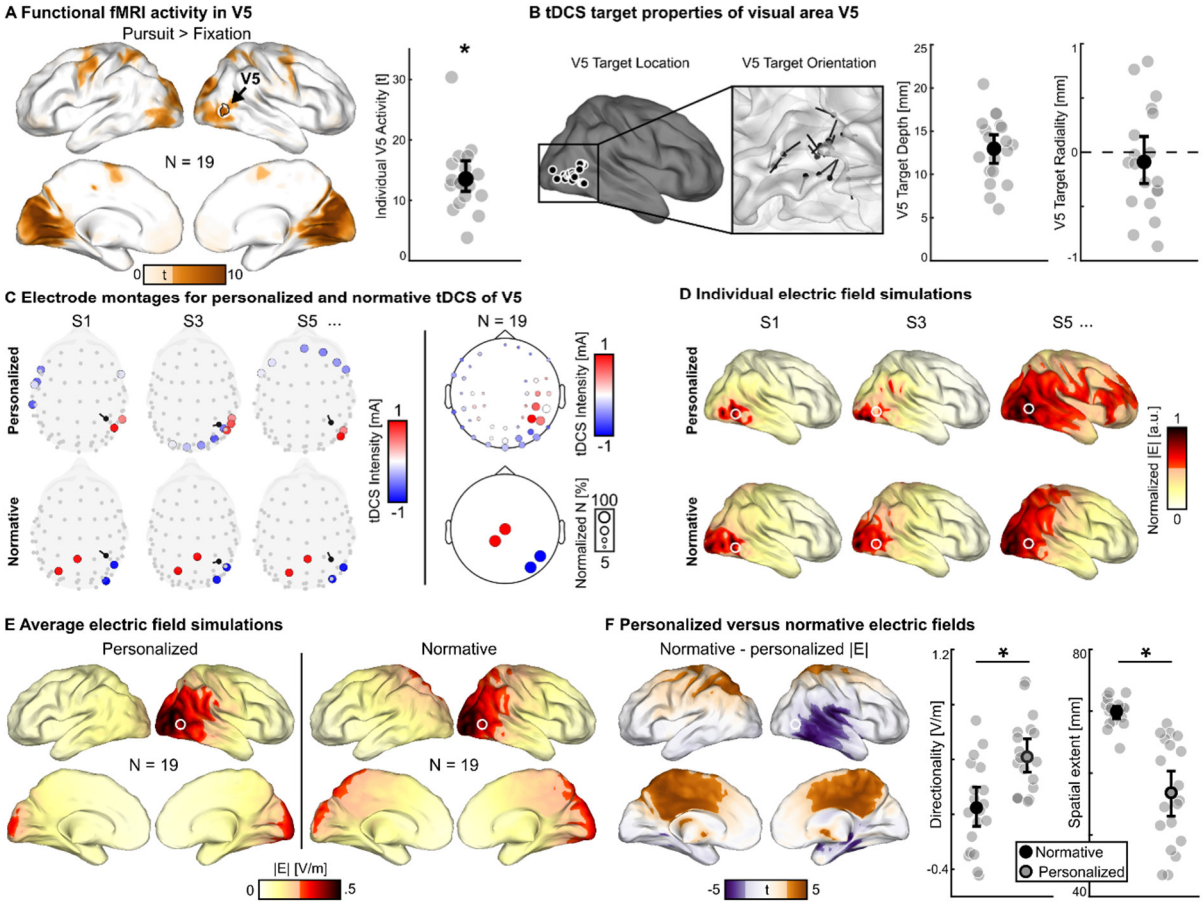

Figure 2. Target V5 and personalized transcranial electric fields. A) Left: Second-level BOLD activity during ongoing SP, compared to fixation, revealed a significant cluster that corresponds to visual area V5. The V5-equivalent cytoarchitectonic area hOc5 (black lines) corresponds to the average coordinate of individual V5 estimates (white circle). FDR-corrected *t*-values are shown, interpolated on the inflated cortical surface of the MNI brain. Right: Individual target V5 activity. Bootstrap mean and confidence interval is depicted together with individual local maxima *t*-values of the first-level statistical contrast of BOLD activity during ongoing SP, compared to fixation. **B)** Target V5 locations (left) are shown on an inflated cortical surface of the MNI brain. Estimated V5 orientations (middle) are shown together with the white matter surface of the MNI brain. Right: V5 target depth relative to the inner skull surface and radiality (1/-1 = radial/anti-radial, 0 = tangential) bootstrap means and confidence intervals are depicted together with individual values. **C)** Personalized tDCS montages targeting individual V5 (top) and normative tDCS montages over V5 (bottom) are shown for three exemplary subjects (left; top view). Topographical representations for the whole sample are shown for personalized (top right) and normative tDCS montages (bottom right). Circle sizes illustrate the normalized number of individual montages that comprised the respective electrode, color illustrates the average tDCS intensity per electrode across the whole sample. **D)** Electric field simulations for the same three subjects and personalized (top) and normative (bottom) tDCS montages, respectively. Normalized electric field intensities |**E**| were interpolated on the inflated right cortical surface of the MNI brain, with values below 50% of the maximal intensity masked (light colors). Individual tDCS target locations in the right V5 are indicated by white circles. **E)** Lateral and medial view of average simulated electric fields for personalized (left) and normative (right) tDCS interpolated on the inflated cortical surface of the MNI brain, with values below 50% of the maximal intensity masked (light colors). The average tDCS target location in the right V5 is indicated by a white circle, respectively. **F)** Left: Comparison between personalized and normative simulated electric fields revealed increased electric field intensities in bilateral parietal and medial brain regions for normative tDCS, whereas personalized electric field intensities were increased in right temporal, and parietal regions anterior to the average V5 location (white circle), corresponding to more anterior individual V5 locations (compare panel B). Lateral and medial view of significant *t*-values are shown (bold colors), with *t*-values corresponding to FDR-corrected *p*-values > 0.05 masked (light colors). Right: Directionalities in the target V5 for electric fields induced by normative tDCS were significantly smaller and spatial extent of the electric field across the cortex was significantly larger, compared to personalized target directionalities and spatial extent. Bootstrap means and confidence intervals are depicted together with individual values. * indicate $p < .05$.

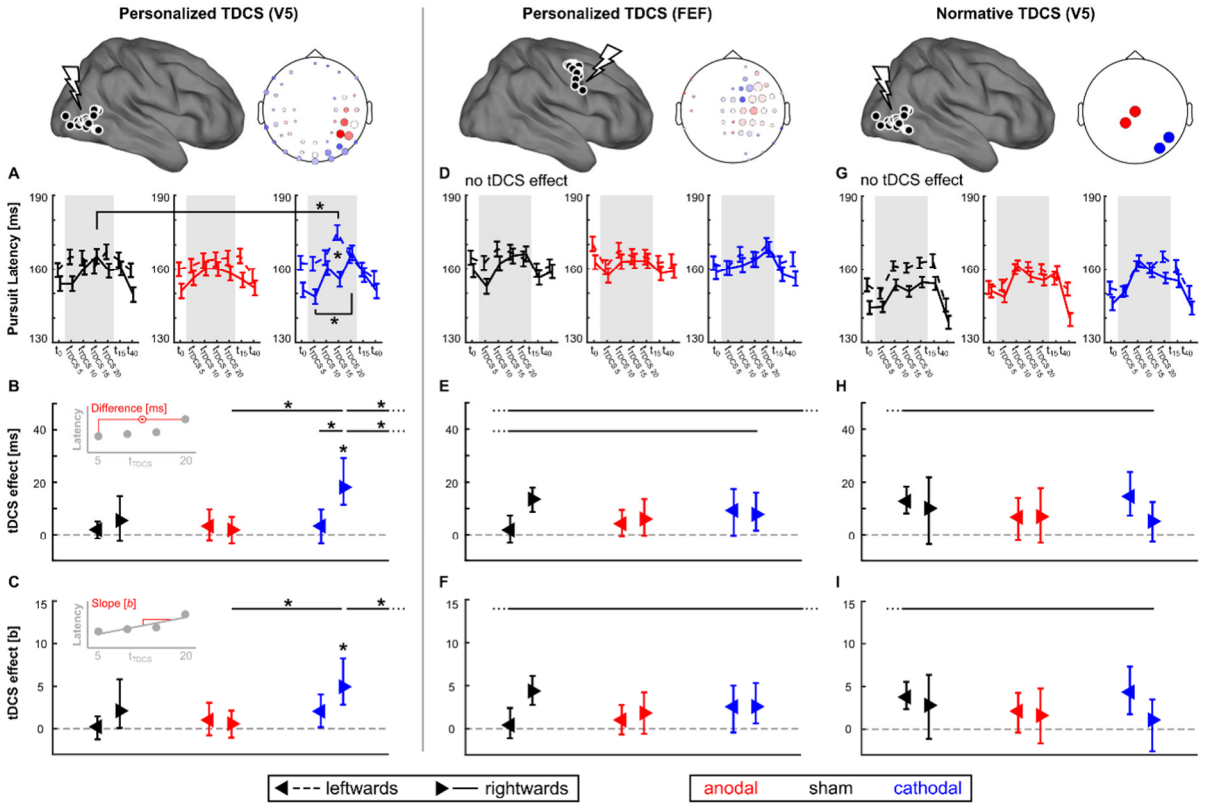

Figure 3. tDCS effects on SP latencies during the step-ramp task. A) to C) In experiment 1 (V5-personalized), significant modulation of SP latencies during the SR task by personalized cathodal tDCS targeting V5 was observed. An effect was observed across **A)** all timepoints (t_0, t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, t_{TDCS_20}, t_{15}, t_{40}). Gray shaded boxes indicate the 20 minutes tDCS interval. LMM analyses revealed an online effect of personalized cathodal tDCS with significantly delayed latencies for ipsiversive (i.e., rightwards) SP during the last timepoint (t_{TDCS_20}), compared to the first (t_{TDCS_5}) timepoint during t_{TDCS}. **B)** tDCS effect estimated as difference between t_{TDCS_20} versus t_{TDCS_5} is plotted for sham, anodal, and cathodal tDCS conditions, as well as leftwards and rightwards SP latencies, respectively (bootstrap mean ± confidence interval). Top left inset illustrates the computation of the difference tDCS effect. Follow-up analysis of difference tDCS effects reveals significant differences for personalized cathodal tDCS for rightward SP latencies, compared to leftward SP latencies of the same tDCS condition, rightward SP latencies during anodal tDCS, as well as an increased difference tDCS effect of personalized cathodal tDCS targeting V5, compared to personalized tDCS targeting FEF and normative cathodal tDCS over V5. **C)** tDCS effect estimated as slope of robust regression across all t_{TDCS} timepoints is plotted for sham, anodal, and cathodal tDCS conditions, as well as leftwards and rightwards SP latencies, respectively (bootstrap mean ± confidence interval). Top left inset illustrates the computation of the slope tDCS effect. Slope estimates of tDCS effects are significantly increased for personalized cathodal tDCS targeting V5, compared to anodal tDCS, as well as normative cathodal tDCS over V5. **D) to F)** No specific tDCS effects were observed for personalized tDCS targeting the right FEF. **G) to I)** No specific tDCS effects were observed for normative tDCS over the right V5. * indicate $p < .05$ (Bonferroni-corrected). tDCS targets and topographical illustration of the cathodal tDCS montage are depicted for the experiment 1 (V5-personalized, top left), experiment 2 (FEF-personalized, top middle), and experiment 3 (V5-normative, top right), respectively.

Table 1. Sample information for the personalized and the normative tDCS participants. For both samples sample size (N), age (M ± SD), gender (frequencies), handedness (frequencies), raw values for the Beck Depression Inventory (BDI-II 126) and percentile ranks for the Multiple Choice Vocabulary Test (MWT-B 127) are provided. F = female, M = male, R = right-handed, L = left-handed, A = ambidextrous.

Parameter	Personalized tDCS targeting V5 and FEF	Normative tDCS over V5
Sample size	19	19
Age	26.2 ± 7.6	25.5 ± 7.1
Gender	F: 11, M: 8	F: 11, M: 8
Handedness	R: 16, L: 2, A: 1	R: 16, L: 3
BDI-II	1.7 ± 2.2	1.4 ± 1.2
MWT-B	47.7 ± 19.6	55.2 ± 20
Days between tDCS sessions	7.9 ± 7.8	8.5 ± 4.7

Table 2. Descriptive smooth pursuit performance. Great grand average pursuit performance for experiment 1 (V5-personalized), experiment 2 (FEF-personalized), and experiment 3 (V5-normative). Mean (± SD) is reported for the respective parameters of continuous pursuit (TRI), continuous pursuit with blanking (TRIBL), and foveopetal step-ramps (SR). a.u. = arbitrary unit.

Task	Parameter	Unit	Experiment 1 (V5-personalized)	Experiment 2 (FEF-personalized)	Experiment 3 (V5-normative)
TRI	Maintenance gain	a.u.	0.957 ± 0.042	0.936 ± 0.044	0.941 ± 0.039
TRIBL	Preblank gain	a.u.	0.839 ± 0.108	0.819 ± 0.108	0.814 ± 0.112
	Deceleration latency	ms	130 ± 17	134 ± 22	134 ± 19
	Deceleration	$°/s^2$	47 ± 9	46 ± 9	54 ± 7
	Resdidual gain	a.u.	0.439 ± 0.223	0.425 ± 0.216	0.314 ± 0.145
	Re-acceleration latency	ms	-132 ± 35	-136 ± 39	-136 ± 39
	Re-acceleration	$°/s^2$	27 ± 10	26 ± 10	26 ± 9
	Postblank gain	a.u.	0.811 ± 0.125	0.786 ± 0.106	0.731 ± 0.145
SR	Pursuit latency	ms	160 ± 13	163 ± 13	154 ± 11
	Acceleration	$°/s^2$	128 ± 34	126 ± 33	109 ± 29
	Early maintenance gain	a.u.	0.827 ± 0.086	0.809 ± 0.087	0.799 ± 0.094

Table 3. Personalized tDCS targeting V5 induces online effects modulating SP initiation. Results of LMM analysis indicate significant transient modulation of SP initiation, specifically pursuit latency and initial acceleration during SR, by personalized tDCS targeting V5 during the tDCS application (online effects, i.e. considering timepoints t_{TDCS_5}, t_{TDCS_10}, t_{TDCS_15}, and t_{TDCS_20}). TRI = continuous pursuit, TRIBL = continuous pursuit with blanking, SR = step-ramp. * indicate *p*-values < .05.

Task	Parameter	tDCS condition		tDCS condition * Timepoint		tDCS condition * Direction		tDCS condition * Timepoint * Direction	
		F	*p*	F	*p*	F	*p*	F	*p*
TRI	Maintenance gain	1.35	.263	0.26	*.955*	1.71	*.183*	0.63	*.705*
TRIBL	Preblank gain	**6.09 ***	***.003***	1.31	*.252*	0.55	*.58*	0.28	*.948*
	Deceleration latency	1.59	.207	0.19	*.98*	1.37	*.257*	0.28	*.945*
	Deceleration	2.61	.077	0.15	*.989*	0.12	*.886*	0.86	*.521*
	Residual gain	0.32	.73	0.26	*.955*	0.54	*.586*	0.11	*.995*
	Re-acceleration latency	**4.79 ***	***.01***	0.7	*.648*	0.77	*.467*	1.1	*.36*
	Re-acceleration	0.02	.978	0.28	*.945*	0.39	*.675*	0.59	*.736*
	Postblank gain	**3.24 ***	***.041***	0.39	*.887*	0.02	*.982*	0.46	*.836*
SR	Pursuit latency	0.63	.534	1.11	*.355*	0.79	*.456*	**2.7 ***	***.015***
	Initial acceleration	0.29	.751	0.77	*.596*	0.25	*.78*	**2.56 ***	***.02***
	Early maintenance gain	**4.74 ***	***.01***	0.41	*.87*	0.15	*.862*	0.74	*.62*

Table 4. No tDCS after-effects. Results of LMM analysis do not indicate a significant modulation of SP parameters after personalized tDCS targeting V5 (after effects, i.e. considering timepoints t_0, t_{15}, and t_{40}). TRI = continuous pursuit, TRIBL = continuous pursuit with blanking, SR = step-ramp. * indicate *p*-values < .05.

Task	Parameter	tDCS condition		tDCS condition * Timepoint		tDCS condition * Direction		tDCS condition * Timepoint * Direction	
		F	*p*	F	*p*	F	p	F	*p*
TRI	Maintenance gain	0.71	*.491*	1.56	*.159*	0.05	*.954*	0.19	*.979*
TRIBL	Preblank gain	0.45	*.638*	1.19	*.312*	1	*.369*	0.46	*.838*
	Deceleration latency	0.87	*.42*	0.58	*.748*	0.06	*.943*	0.9	*.492*
	Deceleration	0.18	*.836*	0.37	*.896*	0.92	*.4*	0.31	*.934*
	Residual gain	0.51	*.599*	0.27	*.95*	0.1	*.902*	0.15	*.99*
	Re-acceleration latency	**6.7 ***	***.002***	1.94	*.074*	0.08	*.924*	0.54	*.782*
	Re-acceleration	0.44	*.644*	0.11	*.995*	0.62	*.542*	1.42	*.207*
	Postblank gain	1.34	*.264*	1.14	*.342*	0.04	*.963*	0.15	*.989*
SR	Pursuit latency	0.72	*.487*	0.53	*.786*	0.07	*.936*	0.92	*.484*
	Initial acceleration	0.28	*.755*	0.48	*.824*	0.01	*.989*	0.43	*.857*
	Early maintenance gain	1.36	*.259*	0.83	*.545*	0.24	*.784*	0.14	*.991*