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Research Report

The role of frontal cortex in novel-word learning and consolidation: Evidence from focal transcranial direct current stimulation

Steffen Riemann [a,*], Jil van Lück [a], Antoni Rodríguez-Fornells [b,c], Agnes Flöel [a,d] and Marcus Meinzer [a]

[a] Department of Neurology, University Medicine Greifswald, Germany
[b] Catalan Institution for Research and Advanced Studies, ICREA, Barcelona, Spain
[c] Department of Cognition, Development and Educational Psychology, University of Barcelona – IDIBELL, Barcelona, Spain
[d] German Center for Neurodegenerative Diseases (DZNE), Rostock, Greifswald, Germany

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ABSTRACT

Previous studies have demonstrated that conventional transcranial direct current stimulation (tDCS) can enhance novel-word learning. However, because of the widespread current that is induced by these setups and lack of appropriate control conditions, little is known about the underlying neural mechanisms. In the present double-blinded and sham-tDCS controlled study, we investigated for the first time if regionally precise focal tDCS targeting two key nodes of the novel-word learning network at different time points would result in regionally and temporally distinct effects. 156 participants completed a contextual novel-word-learning paradigm and learning success was probed immediately after the acquisition period and 30-min later. Participants were randomly assigned to six stimulation conditions: Active tDCS (1.5 mA) was administered to left inferior frontal (IFG) or middle temporal gyrus (MTG), either during acquisition or delayed recall. Control groups received sham-tDCS either during acquisition or delayed recall (50% IFG/MTG). Data were analyzed with a generalized linear mixed model with a binomial link function in a Bayesian framework. Our results showed that frontal tDCS selectively increased accuracy gains from immediate to delayed recall, irrespective of timing of the stimulation. There was no evidence for beneficial effects of middle temporal gyrus tDCS. Our findings confirm that IFG tDCS can enhance novel-word learning in a regionally, but not timing specific way. Tentatively, this may be explained by enhancement of semantic selection processes resulting in more effective consolidation and/or retrieval. Future studies using longer time intervals between assessments are required to clarify the potential contribution of neurophysiological after-effects of IFG tDCS administered during acquisition to enhanced consolidation.

* *Corresponding author*. Department of Neurology, University Medicine Greifswald, Germany.
E-mail address: steffen.riemann@med.uni-greifswald.de (S. Riemann).

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1. Introduction

Learning associations between words and their referents is an essential component of language learning in the developing brain (Shtyrov, 2012). Even in adulthood, new words and expressions appear in the native tongue, and increased globalization frequently requires learning of foreign languages later in life (Laine & Salmelin, 2010). Language proficiency is also crucial for interpersonal relationships, an important predictor of academic and socioeconomic success in native and non-native speakers (Greenberg et al., 2001; Kaestle et al., 2001; Young et al., 2002). Because of the outstanding importance of novel-word learning in this context, there is increasing interest to facilitate this process, e.g., by non-invasive brain stimulation techniques like transcranial direct current stimulation (tDCS).

During tDCS, a weak constant current is administered via scalp-attached electrodes to modulate excitability of underlying target brain regions. TDCS is easy to administer, has an excellent safety profile and an effective placebo stimulation mode (sham tDCS), that allows blinding of participants and researchers (Antal et al., 2017). Previous studies in healthy individuals that employed associative or contextual learning paradigms have shown that both acquisition and maintenance of newly learned words can be improved by tDCS (e.g., Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014; Perceval et al., 2017, 2020; Perikova et al., 2022).

However, most previous studies that investigated tDCS effects on language learning used so-called "conventional" montages to increase excitability of left inferior frontal gyrus (IFG; Filippova et al., 2023; Perceval et al., 2020; Perikova et al., 2022) or left temporoparietal junction (TPJ; Filippova et al., 2023; Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014), which are regions associated with controlled semantic retrieval, and storage of semantic information or phonological working memory, respectively (Binder & Desai, 2011; Rodríguez-Fornells et al., 2009). Notably, conventional setups use two electrodes (e.g., 5 × 5 or 5 × 7 cm^2), and the ingoing current is projected from an anode to a distant cathode (typically attached over the contralateral hemisphere or the shoulder), resulting in non-focal stimulation due to the large size of the electrodes and current flow between the electrodes (Kuo et al., 2013). Moreover, previous studies that targeted the left TPJ (Flöel et al., 2008; Meinzer et al., 2014) used the same montage that was used in other studies to target superior temporal gyrus (STG; Pisoni et al., 2012) or middle temporal gyrus (MTG; Meinzer et al., 2016); please see Fig. 1 for current flow simulations based on TPJ montages reported in previous language learning experiments. These montages mainly differed regarding the placement of the cathode, which was attached either over the contralateral supraorbital cortex (Fig. 1A; Flöel et al., 2008; Meinzer et al., 2014) or the left shoulder (Fig. 1B; Filippova et al., 2023; Kurmakaeva et al., 2021; Perikova et al., 2022). Results suggest that both montages induced current flow peaks in posterior MTG, while current flow was less pronounced in left TPJ (Fig. 1A and B). Additionally, the montage with the return electrode attached over the contralateral supraorbital cortex induced a strong electric field in motor, premotor and prefrontal regions (Fig. 1A). This complicates attribution of stimulation effects to the intended target brain region (Bergmann & Hartwigsen, 2021).

To address the problem of widespread current flow induced by conventional setups, focal tDCS setups have been developed that constrain the electric field to more circumscribed brain regions by using circular arrangements of small cathodes around a center anode in the same hemisphere (Gbadeyan et al., 2016; Villamar et al., 2013). To date, only two studies have investigated effects of focal tDCS on word learning ability. Perceval et al. (2017) applied focal tDCS to left TPJ during an associative novel-word learning paradigm, which resulted in facilitation of lexical access to newly learned word forms compared to sham stimulation. Nikolin et al. (2015) used focal montages to target planum temporale or dorsolateral prefrontal cortex during Rey Auditory Verbal Learning Test, i.e., learning a list of previously known words. Short-term learning rate was increased after prefrontal stimulation compared to sham, but no difference during delayed recall was found. However, aside from placebo stimulation, additional control conditions are highly desirable in tDCS studies to establish causality of brain–behavior relationships (Bergmann & Hartwigsen, 2021). These include assessment of regional specificity of stimulation effects (e.g., by active stimulation of a control region, optimally with focal tDCS setups) or potential effects of the timing of tDCS administration (i.e., temporal specificity).

This was probed in the present study by using a contextual novel-word-learning paradigm that mimics naturalistic language acquisition (Rodríguez-Fornells et al., 2009). Here, new words are encountered in a context, which provides information about the potential meaning of novel words. This first impression of a word is mapped to possible meanings, which is thought to be supported by the left middle temporal gyrus (MTG; Binder et al., 1997; Rodd et al., 2005). This process is repeated during each encounter with the word and the lexical-semantic mapping is refined by inductive reasoning (Rodríguez-Fornells et al., 2009). During each encounter with the word, the presumed meaning has to be recalled and differentiated from a group of similar words with less likely meanings, which is supported by the inferior frontal gyrus (IFG; Rodd et al., 2005; Thompson-Schill & Botvinick, 2006). In a between-subjects design, focal tDCS was administered either during acquisition or delayed recall and regional specificity was investigated by administering the stimulation at either time point either to MTG or IFG. These two regions were selected because they show robust activation during functional imaging studies of contextual word learning and have been suggested to be involved in the binding of novel-word forms to meaning (MTG) and semantic and phonological selection processes (IFG; Rodríguez-Fornells et al., 2009). This approach allowed testing our hypotheses that MTG-tDCS would selectively enhance the initial meaning acquisition of novel-words (Binder & Desai, 2011; Lindenberg & Scheef, 2007; Patterson et al., 2007), while IFG-tDCS would facilitate meaning retrieval during delayed recall (Mestres-Missé et al., 2008; Moss et al., 2005; Thompson-Schill et al., 1997). In addition, we aimed to clarify the contribution of left MTG to novel-word-learning, which was also affected by tDCS in previous language learning studies using conventional montages based on current flow simulations illustrated in Fig. 1 (Filippova et al.,

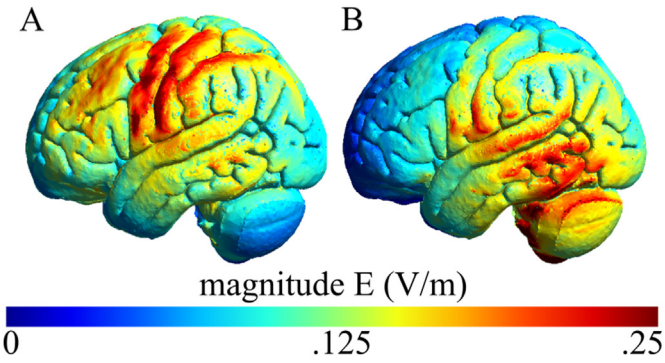

Fig. 1 – Computational models of current flow for the most common electrode montages targeting the left TPJ used during language learning experiments. Strength of the induced electric field (magnitude E) is measured in V/m. Studies targeted the TPJ with return electrodes either supraorbitally over the right hemisphere (A; Flöel et al., 2008; Meinzer et al., 2014) or the left shoulder (B; Kurmakaeva et al., 2021; Perikova et al., 2022). Current strength in the simulations was set to 1 mA to make the current spread in the visualization comparable. Note that, some of the previous language learning studies used 1.5 mA. All studies stimulated the left hemisphere, and current flow is only illustrated for the left hemisphere. SimNIBS (Thielscher et al., 2015) was used for current flow simulations using the workflow described by Saturnino et al. (2019). Simulations were conducted using a standard MNI152 brain, because structural MRI data from previous studies were not available to us. Thus, these analyses only represent an approximation of current flow patterns in individual participants that are not adjusted for inter-individual anatomical differences. Extracted electrode montages, electrode positions and simulation scripts are available at https://osf.io/dwv87/.

2023; Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014; Perikova et al., 2022), by using a focal setup that constrains the current flow to this region (see below).

2. Materials & methods

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

We investigated effects of focal tDCS on meaning acquisition and delayed recall of novel-word forms from context. The study was conducted in double-blinded, between-subjects design with six arms, representing the stimulation conditions (active MTG- or IFG-tDCS, sham tDCS), and time points (tDCS during acquisition or delayed recall). Participants were initially screened with a semi-structured interview for inclusion criteria (right-handedness, German native speakers, no neurological or psychiatric diseases) and tDCS contraindications (metal or electronic implants in brain or skull, metal or electronic device in the body, history of medical procedures involving head or spinal cord, head trauma with unconsciousness, history of epilepsy, convulsions, seizure, or migraine, current pregnancy). These criteria were established prior to data analysis, all manipulations, and all measures in the study. All completed baseline assessments in the first session (including a neuropsychological assessment and a short version of the contextual learning paradigm). Details of the baseline neuropsychological assessments and results are provided in Table A.1. The experimental task (either with active or sham tDCS) was administered during a separate session (Fig. 2). The study was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki. Participants provided written informed consent prior to study inclusion.

2.1. Participants

163 healthy, young participants were initially screened. Seven had to be excluded; for protocol violations (e.g., technical issues with stimulator or experimental procedures; n = 5); heat sensation during stimulation (resulting in immediate termination of tDCS, no injury occurred; n = 1); diagnosis of migraine after the baseline assessment (n = 1). The remaining 156 participants (sex: male/female, N = 57/99; mean ± SD age = 22.40 ± 2.26 years) were randomly assigned to one of six experimental conditions using pre-specified codes. The resulting groups were comparable regarding age, sex, education, and baseline cognitive status (for results of the baseline neuropsychological assessment Table A.1). Study population was skewed towards women and higher educational levels (convenience sample). The sample size was based on previous focal tDCS studies (Martin et al., 2017, 2019; Perceval et al., 2017). No Bayesian adaption of a power analysis was conducted.

2.2. Contextual word learning paradigm

The contextual novel-word-learning task comprised forty sentence pairs that were presented in four blocks of 10 trials each using NBS Presentation® (Version 19.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). During each trial, two sentences ending with the same pseudo-word were presented consecutively. The context provided by the two sentences allowed deriving the meaning of the pseudo-word. Immediately after presentation of each sentence pair, a forced-choice task with four response options was presented and participants were asked to identify the correct meaning of the pseudo-words using a computer mouse. Response options comprised (a) the correct meaning of the pseudo-word, (b) two distractor meanings from the same block, (c) a semantic neighbor, i.e., a word with similar meaning, of the correct

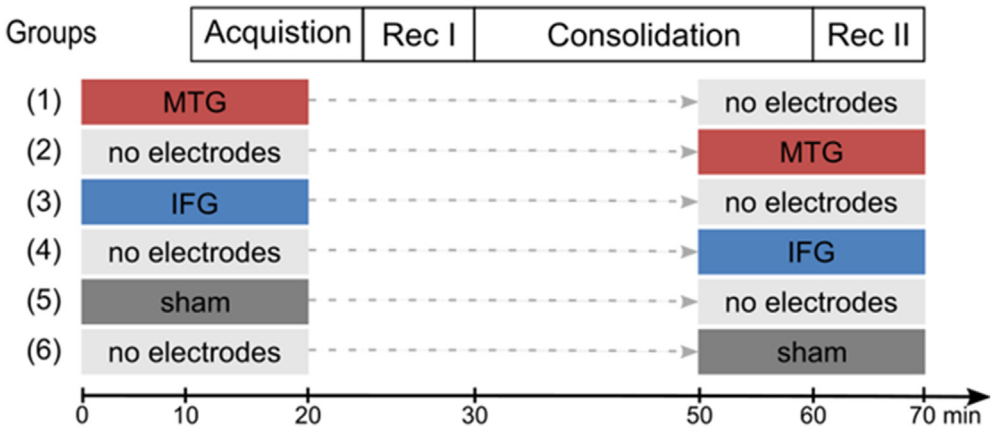

Fig. 2 – Experimental design. In the second session, participants completed acquisition, immediate recall (Rec I) and delayed recall (Rec II) of a novel vocabulary that was acquired from contextual cues. Six groups of participants received tDCS under three different stimulation conditions (anodal MTG or IFG tDCS, sham tDCS; Note: 50% MTG or IFG montages were attached during sham tDCS), either during acquisition or delayed recall of contextually acquired novel-words. Successful meaning extraction was tested during the acquisition. However, the primary outcome was the performance during the first and second recall.

meaning (mean semantic neighborhood via cosine similarity was determined using the German web corpus: r = .78 ± .08, Baroni et al., 2009; for an example, including sentences and forced-choice-task, and trial timing see Fig. 3). All text stimuli (size = 32 points) were presented on a 15-inch screen with a 1366 × 768 pixel resolution. During the forced choice task, the pseudo-word was presented at the center of the screen and the choices were equidistantly arranged around the pseudo-word (150 pixels in x- and y-direction from center). The positions of the distractors and the target meaning were randomized. In addition, learning success was quantified by using the same forced choice task (a) immediately after the acquisition phase and (b) during a delayed recall 30 min after the immediate recall. Here, the semantic-neighbor-distractor remained the same during all forced-choice tasks, while the two remaining distractors were randomly selected each time. The sequence of the items in the forced-choice task was pseudo-randomized, i.e., if the true meaning of a pseudo-word was a distractor in one trial, it would not be the target in the next trial. Accuracy in the immediate and delayed recall was used as primary outcome variable, while the accuracy scores during the acquisition indicated if meaning extraction was possible. Because there was no time limit for responding, response latency was not included in the analyses.

The pseudo-words followed the phonotactic rules of German language and were created by changing one or two letters of existing words. The pseudo-word's meaning was chosen from the CELEX database (mean frequency = 46.38 per million; *SD* = 22.69, i.e., if *gomlet* means *secret* and secret has a frequency of 46.38 per million, this frequency indicates how often the word is used). The sentences describing the pseudo-word meaning were all comprised of seven words and a final pseudo-word. Forty sentences were chosen from Ripollés et al. (2014), which previously were classified as having a low cloze probability, i.e., the probability of ending the sentence with a specific word (*M* = 14.75, *SD* = 7.58). Forty additional sentences were developed by our group to increase the number of items and to enhance task difficulty. Cloze probability for the new sentences was determined by a survey in an independent

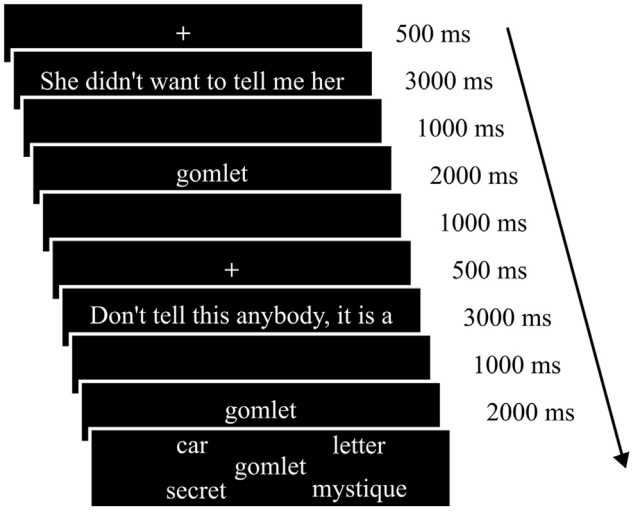

Fig. 3 – Example trial with presentation order (back to front) and timing of the displays in msecs. The forced-choice task was untimed. Sentences and pseudo-words were separately presented. After both sentences were presented the pseudo-word was shown in the center of the screen surrounded by four possible meanings. The possible meanings included: One target word (here: *secret*), which semantically fitted at the end of both sentences. A semantic distractor which was kept the same during all forced-choice tasks (here: mystique). The other two distractors were randomly chosen from the other target words (here: car and letter).

sample of participants for newly generated sentences (N = 26, age: $M = 25.15$ $SD = 2.27$). The participants were provided with a list of sentences with the final word intentionally left blank and were asked to write down the word that first came to their mind. In the combined pool of sentence pairs, the mean cloze probability of the first sentence was .12 ($SD = .08$) and the cloze probability of the second sentence was .44 ($SD = .24$), i.e., the cloze probability in the second sentence was always higher. However, we systematically varied the cloze probability of the second sentence to create trials with varying difficulty. The mean cloze probability after reading both sentences sequentially determined in another independent sample (N = 21, age $M = 22.16$, $SD = 4.17$) was .67 ($SD = .24$). Thus, we successfully decreased the cloze probability compared to previous experiments (previously reported 91.2% ($SD = 8.7$); Mestres-Missé et al., 2010; Ripollés et al., 2014).

2.3. *Transcranial direct current stimulation*

Focal electrical stimulation was administered using a Neuroelectrics® Starstim 8 direct current stimulator. During anodal tDCS, a current of 1.5 mA was administered for 20 min with a 30-s ramp period at the beginning and end of the stimulation, while keeping impedances under 10 kΩ. Note, previous language learning experiments stimulated 15–20 min using 1–2 mA (Filippova et al., 2023; Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014; Nikolin et al., 2015; Perceval et al., 2017; Perikova et al., 2022). All recent studies used 1.5 mA (Filippova et al., 2023; Kurmakaeva et al., 2021; Perikova et al., 2022). Sham stimulation included a 15-s ramp-up, immediately followed by a 15-s ramp-down to induce a similar skin sensation as during active tDCS to ensure blinding of the participants. The blinding mode of the Starstim 8 device ensured staff blinding. After the end of the experiment, potential side effects were formally assessed with a standardized questionnaire (Antal et al., 2017) and participants completed a 1-item questionnaire with three response options asking if they believed active stimulation was administered during the experimental session (response options: yes, no, don't know). Potential effects on positive and negative mood were assessed immediately prior to and after the experimental sessions using the Positive and Negative Affect Schedule (PANAS; Breyer & Bluemke, 2016).

TDCS was administered either during the acquisition phase (with post-stimulation effects overlapping with the immediate recall) or during the delayed recall. In both instances, the stimulation started 10 min prior to task commencement. Stimulation was administered either to left IFG or MTG using NG Pistim electrodes (i.e., Ag/AgCl sintered electrodes, radius = 1 cm). Electrode placement was determined using the 10-10 EEG system and fixated via an electrode cap with inserts for electrodes. Anatomical markers (nasion, inion, preauricular points) were used to measure the head circumference. Cap sizes were chosen based on head circumference and placed based on the position of the anatomical markers and Cz, which was determined as the intersection of the lines between nasion-inion and the preauricular points. While this technique is not as precise as neuronavigated tDCS (De Witte et al., 2018), it is a common, feasible and well standardized approach (Thair et al., 2017). Please note, while focal tDCS allows to target specific brain regions with higher precision than conventional tDCS, it is still less focal and more robust regarding minor placement errors than TMS. For the IFG montage, the anode was placed at F7 and three return electrodes were placed at Fp1, F3, and FC5. For the MTG montage, the anode was placed at TP7 and four return electrodes were placed at FT7, C5, P9 and PO7. In the IFG montage, only 3 return electrodes were used to accommodate the position of the left eye.

Montages were selected prior to study commencement based on current flow simulations using SimNiBS (Thielscher et al., 2015) and an MNI standard brain. These simulations demonstrated that the respective montages are able to maximize the induced current flow to both target regions while minimizing current flow to the respective other stimulation site (Fig. 4). Moreover, simulations based on individual MRIs have shown that focal montages can induce current intensities in the immediate target regions that are comparable to conventional montages, while minimizing current to the surrounding cortex (Niemann et al., 2024). However, it is worth noting our own simulations have used a standard brain and anatomical variations across the participants can lead to variable current strengths within the targeted regions.

2.4. *Statistical analyses*

Accuracy data was analyzed with generalized linear mixed models using the STAN interface *brms* in R version 4.2.2 (Bürkner, 2017; R Core Team, 2022). A Bayesian framework was used that allowed fitting more complex models than frequentist analyses, e.g., to enable more effective incorporation of both between-subject and item difficulty variability into the models, which increases statistical power compared to methods that use aggregated measures like ANOVAs (Barr, 2013; McElreath, 2020).

For population-level effects (fixed effects), the model included stimulation type (with three levels: sham, IFG or MTG), stimulation timing (with two levels: acquisition period or delayed recall) and task (with two levels: immediate or delayed recall) as treatment-coded factors.

Group-level effects (random effects) included a random intercept for subjects with a random slope for the factor task, and a random intercept for the different pseudo-words. This accounted for varying performance and learning ability across subjects, and varying item difficulty.

A logistic regression was fit to the accuracy data, i.e., the probability that an item was answered correctly was modeled. For the model, 32,000 draws were sampled using a Hamiltonian Monte Carlo Algorithm with 4,000 draws per chain to estimate the posterior distributions.

Blinding and side-effects were analyzed with a categorical and a cumulative model to represent the nominal and ordinal nature of the data (Bürkner & Vuorre, 2019). Both models included the applied stimulation type as population-level predictors. The side-effects model additionally included a covariate for side effect type (burning, itching, metallic taste, heat, fatigue) and a group-level intercept for every subject. PANAS responses were aggregated to positive and negative affect scores. The PANAS model also included a time factor,

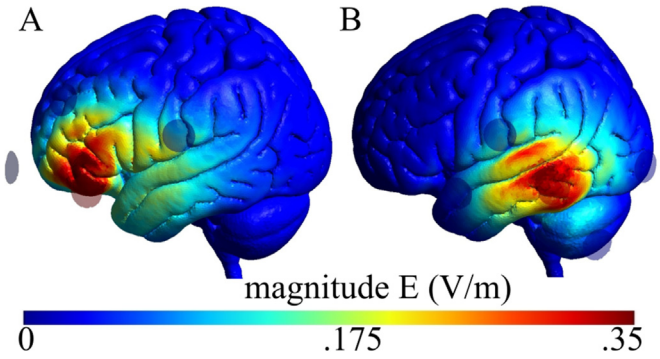

Fig. 4 – SimNIBS simulations for the two planned electrode montages. Target regions were the left IFG (A) and left MTG (B). An MNI152 standard brain was used for modeling that was completed prior to study commencement. Induced electrical fields (magnitude E) in V/m displayed. Workflow based on Saturnino et al. (2019).

since it was administered before and after stimulation, and a factor coding the affect polarity (positive, negative).

2.5. Prior choice

In the Bayesian framework, priors are probability density distributions describing values that a model parameter may take before evidence is considered. The experimental data shifts these probability density functions to display whether there is evidence for or against a given assumption. The resulting probability density functions are posterior probability distributions. Yet, model parameters are not restricte to the area covered by the probability density function of the prior (McElreath, 2020).

The selected priors for population-level effects were normally distributed. The prior choice was based on the results of previous experiments investigating contextual language learning.

Specifically, group-level priors were chosen to represent the hypothesized effect based on prior studies (Flöel et al., 2008; Kurmakaeva et al., 2021; Mestres-Missé et al., 2008, 2010; Perceval et al., 2017; Ripollés et al., 2014). The intercept was set to .61 with a standard deviation of .5 (based on a meta-analysis described in Figure B1; Kurmakaeva et al., 2021; Mestres-Missé et al., 2008, 2010; Ripollés et al., 2014), the beta of the factor task was set to a mean of .3 and a standard deviation .5 to represent a moderate learning effect (Ripollés et al., 2014), the beta of the factors representing our expected simulation effects (i.e., MTG and IFG * Task * Stimulation time) were set to a mean of .2 with a standard deviation of .5. The remaining betas were set to a mean of 0 and a standard deviation of .5. Group-level standard deviations were set to priors of exponential 4 and a correlation prior was represented by Lewandowski-Kurowicka-Joe distribution with a rate of 2.

An in-depth justification of prior choices can be found in Appendix B, and prior distributions are displayed in Figure B2 for population-level effects and Figure B3 for group-level effects. In addition, priors were assessed via the prior *predictive* distribution (instead of prior distribution). For the prior predictive distribution, model parameters are sampled from the prior distributions and the model outcome is simulated using these parameters. The prior predictive distributions should cover all possible plausible outcomes (Figure B4; McElreath, 2020), which was confirmed by visually examining the distribution.

Prior choices for the blinding, side effects and PANAS models were chosen to be wide but informed to regularize the model computation. Coefficients of the predictors were set to a mean of 0 and a standard deviation of 1.

2.6. Hypothesis testing

Hypotheses were tested using evidence ratios. For one-sided hypotheses, the evidence ratio is equal to the posterior probability under the hypothesis against its alternative (i.e., the evidence ratio for the effect of task: $\textit{evidence ratio} = \frac{\textit{effect of task} > 0}{\textit{effect of task} < 0}$). Note that evidence ratios for one-sided hypotheses are different from classic Bayes factors, which compare posterior models to prior models. However, it is a matter of debate how to define the prior model (see van Doorn et al., 2023a, and the multiple responses summarized here: van Doorn et al., 2023b). The *brms* package implements the *evidence ratio* as an alternative since the evidence ratio for one-sided hypotheses only depends on samples from the posterior distribution. The population-level effects were tested to be greater than zero according to our hypotheses as confirmatory data analysis. Evidence ratios range from 0 to ∞ and are interpreted as how many more draws from the posterior distribution are in favor of the hypothesis compared to the counter hypothesis, e.g., an evidence ratio of 19 means that 19 times more samples were greater zero than smaller than zero. To the best of our knowledge, formal comparisons of evidence ratios for generalized linear mixed models with frequentist statistics have not yet been reported. However, for reference, simulations have shown that an evidence ratio of 19 and 39 in linear and logistic regressions corresponds to one-sided and two-sided hypothesis tests with an alpha-level of .05 (99 and 199 for an alpha-level of .01; Makowski et al., 2019). The hypotheses tests included a credible interval of 90% in case of one-sided hypotheses. Please note that these intervals cannot

be compared to classical confidence intervals in frequentist statistics (i.e., inclusion of zero does not mean non-significant). For the blinding, side effects and PANAS models, hypotheses were tested that applying a certain type of stimulation did introduce group differences in blinding, side effects, or the modulation of the affect pre-to post-stimulation, i.e., null hypotheses were tested that the predictors are equal to zero. Here evidence ratios indicate an in–or decrease of evidence compared to the prior model.

3. Results

3.1. *Blinding efficacy, adverse effects, and mood*

Overall, our data suggested that participants' blinding was successful, only minimal side effects were observed and potential mood changes over the experiment were small and comparable between the stimulation groups. Specifically, 81.82 % of the participants stated they believed that they received active stimulation during their experimental session. Evidence ratios greater 1 suggested an increase of evidence that blinding success was the same in all groups ($IFG_{\text{do not know/no}}$: evidence ratio = 1.31, β = .3, estimation error = .68, 95% CI = [−1.02; 1.62]; $IFG_{\text{no/yes}}$: evidence ratio = 1.57, β = .11, estimation error = .64, 95%CI = [−1.3, 1.22]; $MTG_{\text{do not know/no}}$: evidence ratio = 1.35, β = .15, estimation error = .69, 95% CI = [−1.19, 1.52]; $MTG_{\text{no/yes}}$: evidence ratio = 1.09, β = .58, estimation error = .65, 95%CI = [−.65, 1.85]). Most participants reported no (62.93%) or mild side effects (27.56%). Evidence ratios suggested similar frequency of side effects across groups (*MTG*: evidence ratio = 2.43, β = .23, estimation error = .16, 95%CI = [−.1; 0.56]; *IFG*: evidence ratio = 4.98, β = .11, estimation error = .16, 95%CI = [−.21, .42]). The PANAS scores were generally higher for positive affect (*positive affect*: evidence ratio = ∞, β = 1.95, estimation error = .03, 95% CI = [1.90, 2.00]). Evidence ratios suggested an increase of evidence that all groups reported minor and comparable changes in affect between pre- and post-stimulation assessments (*IFG*time*: evidence ratio = 11.92, β = −.04, estimation error = .08, 95%CI = [−.20, .12]; *MTG*time*: evidence ratio = 12.75, β = −.02, estimation error = .08, 95%CI = [−.17, .14]). While zero is generally included as possible value in the posterior distributions and evidence ratios suggested an increase of evidence that groups are similar (i.e., coefficients are zero), evidence ratios are generally small and confidence intervals show a wide range of possible true values. See Table C.1-3 and Figure C1-2 for more detail.

3.2. *Language learning*

Descriptive statistics with group means and standard deviations of accuracy during the novel-word acquisition and both (immediate and delayed) recall time points are displayed in Fig. 5 and Table D.1. During the acquisition period, participants in all groups performed close to ceiling (mean across all groups = 98.83, *SD* = 1.89; Table D.1 for individual group means), suggesting that the meaning extraction of the novel-words from sentence context was successful.

R-hat values equal to 1 suggest that all our model parameters converged and the number of effective sampling sizes is sufficient for reliable estimates (Bürkner, 2017). Population-level effects indicate that there is a learning effect between the immediate and the delayed recall (*Task* effect in Fig. 6A:

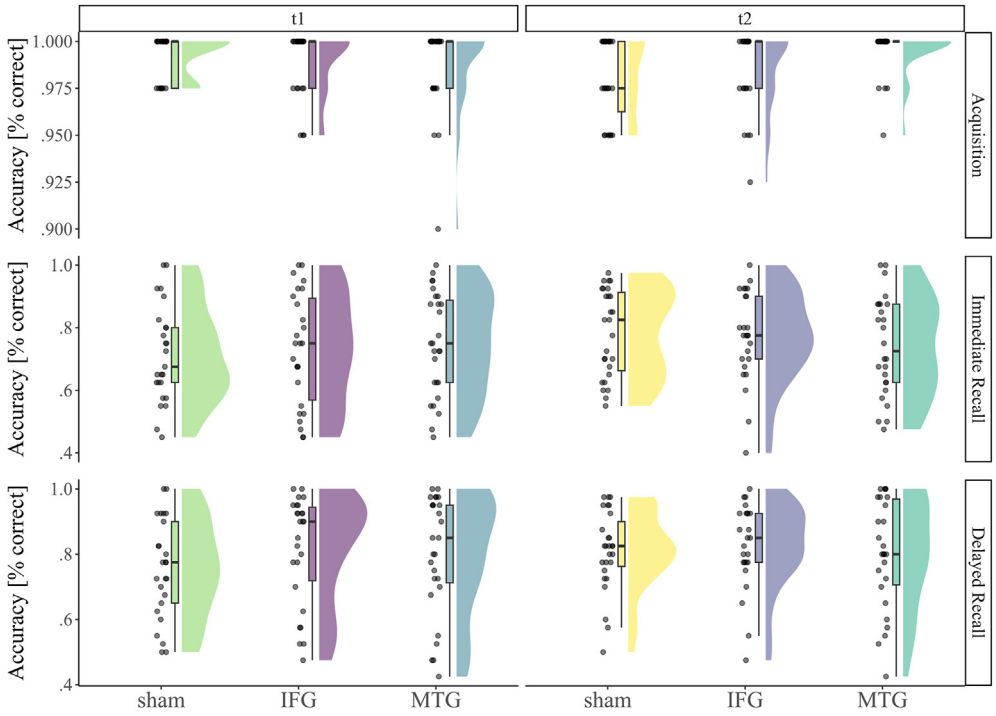

Fig. 5 – Raincloud plot of the accuracy in the different stimulation groups for the acquisition phase and the immediate and delayed recall tasks. The successful meaning acquisition is indicated by the ceiling effect in all groups (upper panel). Note that all data in this figure are raw data.

evidence ratio = 2132.33, β = .33, estimation error = .11, 90% CI = [.16, .51]). Further model parameters are displayed in Fig. 6A. The *MTG* effect in our model directly corresponds to our first hypothesis, stating that we expected MTG stimulation would increase meaning acquisition and thus accuracy during the first recall compared to sham stimulation (Note: the MTG effect in Fig. 6A corresponds to the effect in the upper panel of Fig. 6B). However, there was little evidence for increased accuracy during the immediate recall due to MTG stimulation administered during the acquisition phase (Fig. 6B upper effect: evidence ratio = 2.99, β = .15, estimation error = .23, 90% CI = [−.23, .53]). There was also little evidence for our second hypothesis that IFG-tDCS during the delayed recall would selectively enhance delayed recall performance (Fig. 6B lower panel: evidence ratio = 10.16, β = .44, estimation error = .33, 90%CI = [−.1, .98]). Hence, we were not able to demonstrate a double dissociation between effects of tDCS administered at two different time points (acquisition; delayed recall) at two different sites (MTG; IFG).

Yet, when examining the population-level model parameter, we observed the consolidation effect, i.e., increase from immediate to delayed recall, was larger in the group receiving IFG stimulation during the acquisition phase compared to sham stimulation during the acquisition phase (Fig. 6A *Task * IFG* or Fig. 6C *Slope IFG t1 − sham t1*: evidence ratio = 43.63, β = .30, estimation error = .15, 90%CI = [.06, .55]). Therefore, we proceeded by directly comparing the consolidation effect of the IFG group receiving tDCS during the acquisition phase with every other experimental group. These comparisons showed that the consolidation effect in this group was larger than in the group receiving sham tDCS during the delayed recall (Fig. 6C *slope IFG t1 − sham t2*: evidence ratio = 109.73, β = .41, estimation error = .17, 90%CI = [.13, .70]). However, evidence that the consolidation effect in the group that received IFG tDCS during acquisition was larger than in either MTG stimulation group remained insufficient (Fig. 6C *slope IFG t1 − MTG t1*: evidence ratio = 6.14, β = .18, estimation error = .17, 90%CI = [−.09, .46]; *slope IFG t1 − MTG t2*: evidence ratio = 7.49, β = .41, estimation error = .34, 90%CI = [−.16, .97]). Finally, an evidence ratio of ~1 suggested that there was equal evidence for the hypothesis that the consolidation in the group that received IFG tDCS during acquisition is smaller *or*

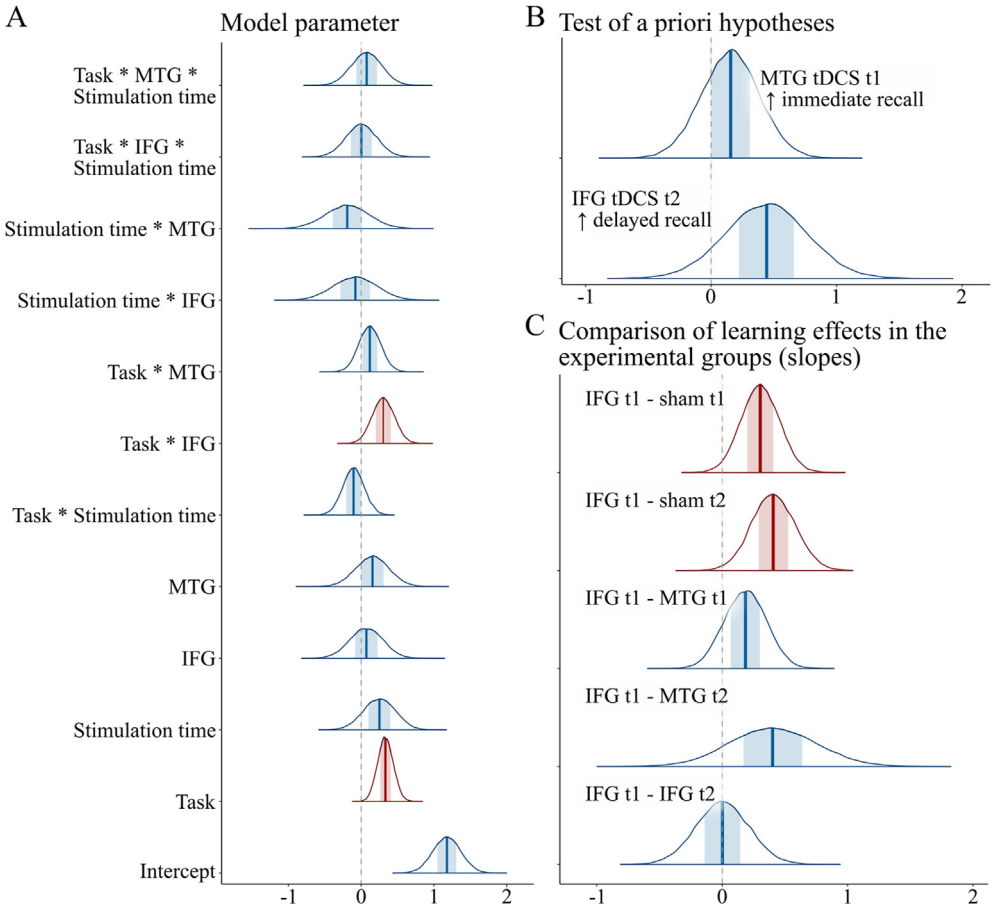

Fig. 6 − Posterior distributions of the population-level effects as defined within our model (A), direct test of our hypothesis (B), and comparison of the learning effects, i.e., the slope between immediate and delayed, recall with 50%CI (light). Distributions with an evidence ratio greater 19, which corresponds to an alpha-threshold of .05 in linear and logistic regressions, are highlighted red (Makowski et al., 2019). Note, the *MTG* effect in A is the same as the upper effect tested in B, and that the *Task * IFG* effect in A is the same as *Slope IFG t1 − sham t2* in C. Also note that credible intervals are not equivalent to frequentists' statistics confidence intervals (i.e., inclusion of zero does not mean non-significant), evidence ratios test the ratio of how many draws are greater than zero compared to the number of draws smaller zero.

larger than in the group that had received IFG tDCS during the delayed recall (Fig. 6C *slope IFG t1 − IFG t2*: evidence ratio = 1.01, $\beta = .00$, estimation error = .21, 90%CI = [−.35, .35]). Conditional effects that illustrate the interaction between task and stimulation type are displayed in Fig. 7. The population-level and group-level effects are also summarized in Table D.2 and Table D.3.

4. Discussion

The present study investigated potential region and timing-specific effects of focal tDCS using an ecologically relevant contextual novel-word learning paradigm (Mestres-Missé et al., 2008, 2010; Ripollés et al., 2014). In line with previous studies that utilized forced-choice response modes in contextual word learning paradigms (e.g., Ripollés et al., 2014), performance accuracy increased from the immediate to delayed recall in all groups and those gains were more pronounced in both IFG stimulation groups. Contrary to our hypothesis, this enhancement of consolidation was not time-specific, but observed for both IFG tDCS groups. There was no certain evidence that MTG stimulation facilitated novel-word learning. Hence, the IFG appears to be a more promising site to enhance maintenance of novel-word forms.

Previous studies investigating language learning and tDCS have used a number of different word learning paradigms, stimulation setups and target sites, with a wide range of outcomes: These included increased accuracy after anodal or cathodal TPJ tDCS (Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014), lack of accuracy effects after anodal or cathodal TPJ tDCS (Perceval et al., 2017; Perikova et al., 2022), increased accuracy after anodal IFG tDCS (Perceval et al., 2020; Perikova et al., 2022), decreased response latency or lack thereof after anodal TPJ tDCS (Filippova et al., 2023; Flöel et al., 2008; Perceval et al., 2017), and decreased response latency after anodal IFG tDCS (Filippova et al., 2023). However, all of these studies except Perceval et al. (2017) administered conventional tDCS which may induce physiologically relevant levels of current flow in several task-relevant brain regions besides the intended target (Fig. 1; Kuo et al., 2013). The current study, therefore, administered focal tDCS to either IFG or MTG, which are both active during contextual word learning (Mestres-Missé et al., 2008, 2010) and subserve relevant cognitive processes during language learning (Binder & Desai, 2011; Lindenberg & Scheef, 2007; Mestres-Missé et al., 2008; Moss et al., 2005; Patterson et al., 2007; Thompson-Schill et al., 1997). By using a focal tDCS setup that introduces a more focal electric field, we aimed to clarify specific contribution of these regions to novel-word learning, which could not be established in previous studies using conventional tDCS (Filippova et al., 2023; Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014; Perikova et al., 2022). In addition, while previous studies investigated polarity and/or site specificity of stimulation (Filippova et al., 2023; Kurmakaeva et al., 2021; Perikova et al., 2022), this study is the first that tried to investigate the temporal specificity of stimulation effects across different target regions. This approach revealed that stimulation of IFG or MTG during the acquisition phase did not influence the immediate or delayed recall directly. However, the consolidation after learning, i.e., the accuracy-increase from the immediate to the delayed recall, was enhanced in the groups receiving IFG stimulation, suggesting a small regionally specific IFG effect. For comparison, the previous conventional tDCS studies on language learning reported small to medium effect sizes (see Table E.1) when measuring the effect on accuracy (Cohen, 1988). A similar delayed effect of tDCS during contextual word learning was also found by Kurmakaeva et al. (2021), showing more pronounced effects in a delayed recall condition after one day compared to the immediate recall after learning. Direct comparison of the two IFG stimulation conditions revealed no evidence for time-specific stimulation effects at this site. This is in line with previous verbal memory studies, which often found no difference between stimulation administered during recall compared to encoding (e.g., Javadi & Walsh, 2012; Medvedeva et al., 2019). Yet, stimuli in these studies were wordlists and

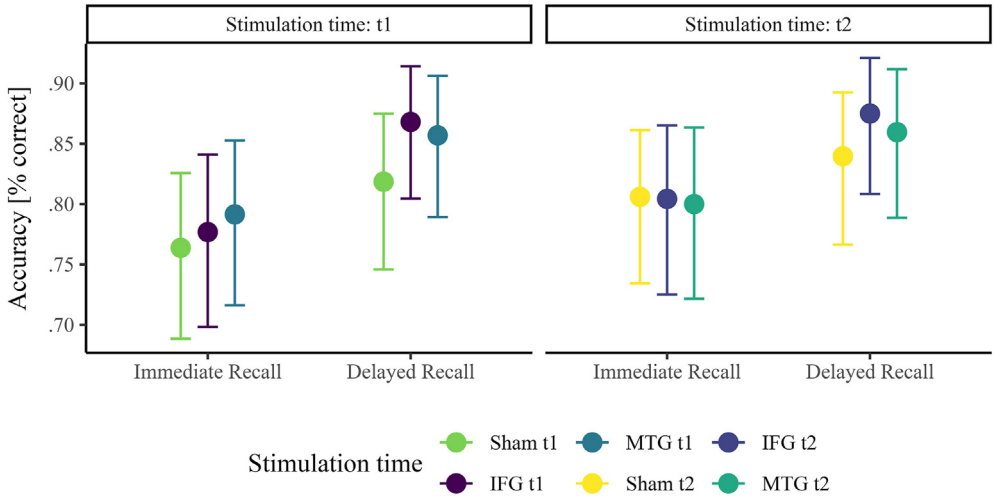

Fig. 7 – Conditional effects of the *Task * Stimulation type* interaction depending on the *stimulation time* with 95% credible intervals based on expected values of the posterior predictive distribution. There is a general effect of the *Task* factor (expected values are higher in the delayed recall than the immediate recall across all groups) and a *Task * IFG* interaction (the increase from immediate recall to delayed recall is higher in the IFG groups).

not newly learned words. In the future, a longer interval between the two recall time points might help to disentangle the temporal specificity of the tDCS effect, i.e., to differentiate whether beneficial effects of IFG stimulation administered during acquisition on the delayed recall can be attributed to (a) enhanced consolidation of the learned material by tDCS during the acquisition period or (b) neural aftereffects of tDCS that can exceed the immediate stimulation period, or both. However, consolidation as a central mechanism for the current findings could also explain the lack of a tDCS-induced effect during immediate recall. Staresina et al. (2013) found that for consolidation an interval is needed without activation of the newly learned material. Since the immediate recall was directly after the acquisition phase, this might have prevented consolidation and the stimulation effect was only observed during the delayed recall, after a 30-min interval in which consolidation did occur. Neurophysiological (after-)effects of tDCS on local cortical excitability in the motor system can be assessed directly via modulation of motor evoked potentials (MEPs). However, this approach cannot be used to quantify neural effects of tDCS on cognition and it also remains unclear if results obtained from motor studies are equally valid for other cortical regions. Nonetheless, in one of the few studies that directly compared effects of focal and conventional motor cortex tDCS, Kuo et al. (2013) demonstrated longer lasting MEP modulation for focal tDCS, with the largest MEP modulation 30 min after the end of the stimulation. While this overlaps with the time course of our experiment (with the delayed recall at around 35–40 min after the acquisition), the following has to be considered: 1.) Kuo et al. (2013) used 2 mA instead of 1.5 mA. 2.) The outcome was MEP amplitude not performance in a cognitive task. 3.) An explanation of our behavioral effects based on neural after effects alone does not explain effects in both stimulation groups.

Overall, beneficial stimulation effects over IFG are in line with previous studies that demonstrated positive effects on novel-word learning using associative and contextual learning paradigms (Filippova et al., 2023; Perceval et al., 2020; Perikova et al., 2022) and the focal stimulation protocol confirms that tDCS effects can be attributed to this specific brain region. This result is also consistent with the role of the anterior ventral part of the IFG (BA45/BA47) in processing and retaining elaborate semantic short-term representations (Shivde & Thompson-Schill, 2004) and the selection, activation, and inhibition of competing semantic alternatives (Thompson-Schill & Botvinick, 2006). As the forced-choice task used in the present design requires to select competing alternatives to choose the correct meaning, it might have enhanced the need to carefully retrieve and select the right meaning that was recently acquired. In this sense, the potential role of the IFG during semantic learning and further consolidation of acquired information might be used to guide semantic retrieval from long-term memory and selection of competing unstable semantic representations via top-down modulations (Badre & Wagner, 2002; Gold et al., 2006; Mestres-Missé et al., 2008; Rodd et al., 2005). Notice also that the forced-choice task could indeed be considered a "third learning context", exposing participants to competitive semantic candidates in the context of an unstable stored novel word, i.e., meaning trace. Thus, the presentation of the test might prompt participants to carefully monitor their retrieved meaning or candidate hypothesis, comparing it to the four potential candidates presented, selecting the appropriate one and updating this information if an error is detected.

While functional imaging studies of contextual word learning demonstrated robust MTG activation (Mestres-Missé et al., 2008, 2010), we did not find evidence for beneficial effects of MTG tDCS on immediate or delayed recall of novel words. No previous tDCS study has directly targeted MTG during novel-word learning and MTG stimulation was chosen because this region has been suggested to be involved in the binding of novel-word forms to meaning (Rodríguez-Fornells et al., 2009). Moreover, while previous studies have targeted the TPJ using CP5 of the EEG 10–20 system using large conventional electrodes (Flöel et al., 2008; Meinzer et al., 2014), the same montage has also been used by other studies to target the MTG (Meinzer et al., 2016). Indeed, current modeling for previous conventional setups demonstrated widespread current flow affecting both left TPJ and MTG, and depending on the position of the cathode, also motor and prefrontal regions (Fig. 1). Moreover, only one study so far used a focal setup to target the left TPJ (Perceval et al., 2017), using a montage for which modeling evidence confirmed focal current delivery (Martin et al., 2017, 2019). Perceval et al. (2017) reported a weak positive effect of left TPJ tDCS on lexical access to novel forms (i.e., faster response latency), but no positive effects on response accuracy. Hence, there is currently no strong evidence to support specific effects of either left MTG or TPJ tDCS on novel-word learning. Importantly, while we did not investigate effects of focal TPJ tDCS in a separate group, the lack of evidence for MTG stimulation effects in our study suggest that co-stimulation of MTG and TPJ explain the stimulation effect found in previous studies (Filippova et al., 2023; Flöel et al., 2008; Kurmakaeva et al., 2021; Meinzer et al., 2014).

Another, more speculative explanation for the lack of MTG tDCS effects may be related to semantic interference effects. Specifically, MTG activation during contextual learning is associated with binding of novel-word forms with meaning provided by sentence contexts. This process is thought to involve recall of several possible meanings and disambiguation due to sentence context (Rodríguez-Fornells et al., 2009). Importantly, semantic interference can be investigated directly in cyclic blocked naming paradigms and previous studies have demonstrated that 1 mA can reduce semantic conflict in picture naming, while higher intensities, like in the present study, increased conflict (Meinzer et al., 2016; Pisoni et al., 2012). Theoretically, this may have increased competition between competing meanings during our contextual learning task and the net-zero effect on performance could be explained by lesser effects on the forced-choice response task in our study compared to those observed during blocked cyclic naming, i.e., stimulation might have increased conflict, but the forced-choice task reduced the number of possible meanings and thus resolved conflict. This interpretation is also supported by Alonso et al. (2024), who found that stimulation of the posterior MTG increased false recognition, but did not affect true recognition in a semantic false memory task. Therefore, assessing novel-word learning effects with forced-choice paradigms might not be ideal and future studies should also consider implementing free recall tasks that may be more suitable to investigate potential differences

between IFG and MTG stimulation. An additional limitation may be related to the relatively short time interval (30 min) between immediate and delayed recall periods and 20 min of tDCS administered during the acquisition phase may induce neurophysiologically relevant after-effects during the delayed recall. Therefore, longer intervals between immediate and delayed recall periods may be required to clarify whether more pronounced learning can be attributed to more effective consolidation and/or stimulation aftereffects.

In sum, by using focal tDCS, the current study demonstrated that tDCS restricted to the IFG enhanced word learning irrespective of the timing of the stimulation, while MTG stimulation did not increase learning performance compared to sham stimulation. Our results provide evidence that left IFG is a promising target for the facilitation of novel-word learning, but future studies are required to clarify if this is explained by enhanced consolidation and/or neural aftereffects of the stimulation. Our data also suggest that previously reported beneficial effects of TPJ tDCS cannot be attributed to co-stimulation of MTG. To assess the temporal specificity of tDCS effects, longer time intervals than the one used in the present study might be required, an issue to be followed up in future studies. Importantly, focal or conventional stimulation setups should be chosen depending on the study goal. While investigation of neural correlates calls for precision of current delivery to facilitate the interpretation of (causal) brain–behavior relationships, augmentation of language learning, e.g., in clinical settings or to learn a foreign language, may benefit from more widespread current flow induced by conventional setups.

Data statement

The conditions of our ethics approval do not permit uploading of data to public repositories. Readers seeking access to the data should contact the lead author. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Scripts for data analysis and the Presentation files for the contextual word learning task are available at: https://osf.io/dwv87/. Note that model fits are also uploaded to OSF, so that hypothesis tests can be replicated or another posterior test can be applied. Neither study procedure nor analysis plans were preregistered prior to the research being conducted.

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Open practices section

The study in this article has earned Open Materials badge for transparent practices. The materials studies are available at: https://osf.io/dwv87/.

CRediT authorship contribution statement

Steffen Riemann: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Jil van Lück:** Writing – review & editing, Data curation. **Antoni Rodríguez-Fornells:** Writing – review & editing, Supervision, Conceptualization. **Agnes Flöel:** Writing – review & editing, Resources. **Marcus Meinzer:** Writing – review & editing, Supervision, Resources, Conceptualization.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2024.05.004.

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