Theta Band Transcranial Alternating Current Stimulation Enhances Arithmetic Learning: A Systematic Comparison of Different Direct and Alternating Current Stimulations

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Abstract—Over the last decades, interest in transcranial electrical stimulation (tES) has grown, as it might allow for causal investigations of the associations between cortical activity and cognition as well as to directly influence cognitive performance. The main objectives of the present work were to assess whether tES can enhance the acquisition and application of arithmetic abilities, and whether it enables a better assessment of underlying neurophysiological processes. To this end, the present, double-blind, sham-controlled study assessed the effects of six active stimulations (three tES protocols: anodal transcranial direct current stimulation (tDCS), alpha band transcranial alternating current stimulation (tACS), and theta band tACS; targeting the left dorsolateral prefrontal cortex or the left posterior parietal cortex) on the acquisition of an arithmetic procedure, arithmetic facts, and event-related synchronization/desynchronization (ERS/ERD) patterns. 137 healthy adults were randomly assigned to one of seven groups, each receiving one of the tES-protocols during learning. Results showed that frontal theta band tACS reduced the repetitions needed to learn novel facts and both, frontal and parietal theta band tACS accelerated the decrease in calculation times in fact learning problems. The beneficial effect of frontal theta band tACS may reflect enhanced executive functions, allowing for better control and inhibition processes and hence, a faster acquisition and integration of novel fact knowledge. However, there were no significant effects of the stimulations on procedural learning or ERS/ERD patterns. Overall, theta band tACS appears promising as a support for arithmetic fact training, but effects on procedural calculations and neurophysiological processes remain ambiguous.

INTRODUCTION

Over the last two decades, transcranial electrical stimulation (tES) has attracted the interest of researchers in a wide range of fields. This is due to the opportunity of having a tool that not only allows the modulation of brain activity, hence a causal assessment of brain processes and their relation to behavior, but one that might also be used to enhance cognitive processes (Nitsche et al., 2008; Santaracchi et al., 2015; Polania et al., 2018). In fact, several studies have reported beneficial effects of tES on a variety of cognitive functions, including working memory, short term memory, and language learning (e.g. Flöel et al., 2008; Vosskuhl et al., 2015; Zaehle et al., 2011). In the domain of mathematics learning, this research has sparked interest in the potential of tES to support knowledge acquisition in individuals with mathematical learning difficulties, in particular dyscalculia (Krause and Cohen Kadosh, 2013; Sarkar and Cohen Kadosh, 2016), especially as it has been shown that the application of some tES protocols has beneficial effects on arithmetic problem-solving and learning (Schroeder et al., 2017). However, because of the limited number of studies and the lack of direct comparisons between different stimulation protocols, it has remained unclear which type of tES is most effective in fostering arithmetic learning.

In the present study, we provide the first systematic comparison of the effects of different transcranial direct
(tDCS) and alternating current (tACS) stimulations (three versions of tES: anodal tDCS, alpha band tACS, and theta band tACS; targeting the left dorsolateral prefrontal cortex; DLPFC or the left posterior parietal cortex; PPC) on arithmetic learning. Additionally, an electroencephalogram (EEG) was recorded to investigate the impact of stimulation during learning on oscillatory brain activation patterns.

Arithmetic learning involves the acquisition and application of two types of knowledge. Procedural knowledge about arithmetic operations, allowing the calculation of solutions to arithmetic problems, and declarative knowledge about arithmetic facts, allowing the direct retrieval of solutions to memorized arithmetic problems. In adults, the former competence is typically used in larger, more complex problems (e.g. 36 + 47), while the latter is mainly used in small or highly overlearned problems like the multiplication table (e.g. 2 * 4 = 8; Campbell and Xue, 2001; De Smedt et al., 2009; Grabner and De Smedt, 2011). While the application of calculation procedures is slower, cognitively more demanding and more error-prone, fact retrieval is fast and comparatively easy.

Procedural and retrieval processes in solving arithmetic problems have been found to be accompanied by different brain activation patterns. Procedural calculation has been found to be associated with stronger alpha and beta band event-related desynchronization (ERD) over bilateral parieto-occipital areas, possibly reflecting executive demands, while fact retrieval was accompanied by theta band event-related synchronization (ERS) over the left hemisphere, possibly reflecting memory processes (De Smedt et al., 2009; Grabner and De Smedt, 2011). A similar dissociation has been observed in functional magnetic resonance imaging (fMRI) studies. Procedural calculation was associated with stronger activations in a wide-spread cortical network, including the (left) DLPFC and the intraparietal sulcus (IPS), which have been interpreted to reflect the involvement of working memory functions and the manipulation of numerical quantity. Fact retrieval, in contrast, was associated with stronger activation (or less deactivation) of the angular gyrus (AG; Arsalidou and Taylor, 2011; Delazer et al., 2005; Grabner et al., 2009; Menon, 2015; Zamarain et al., 2009), indicating the reliance on memory networks, which the AG is thought to be part of (Destefano and LeFevre, 2004; Menon, 2015). Training studies further corroborated this neural dissociation by showing that fact learning is accompanied by a change from procedural activation patterns to retrieval patterns (Pauli et al., 1994; Ischebeck et al., 2007; Grabner and De Smedt, 2012; Soltaniou et al., 2019).

Against this background, many of the prior studies trying to enhance arithmetic performance and learning targeted these regions (Schroeder et al., 2017). So far, however, most studies investigated the question as to whether tES increases performance in arithmetic processing (e.g. improving accuracy and calculation times in the application of already acquired arithmetic knowledge). The results of these studies are mixed. While some studies found beneficial effects, one of the studies even reported detrimental effects of stimulation (e.g. Artemenko et al., 2015; Clemens et al., 2013; Hauser et al., 2013; Hauser et al., 2016; Klein et al., 2013; Mosbacher et al., 2020; Pasqualotto, 2016; Pope et al., 2015; Rütsche et al., 2015). The reasons for these inconclusive results are unclear. However, different stimulation protocols and arithmetic tasks across the various studies might have contributed to heterogeneity of results (see Schroeder et al., 2017 for a review).

The results of studies investigating the effects of tES on arithmetic learning (e.g. the acquisition and application of new arithmetic knowledge), have been more promising. Prior studies found beneficial effects of tES to the PPC and the DLPFC on subtraction training and a video game-based training for fractions, respectively (Grabner et al., 2015; Looi et al., 2016). Multiple tES sessions led to improved learning and training of novel arithmetic procedures and facts, with some effects being present for up to six months (Snowball et al., 2013; Popescu et al., 2016). Importantly, beneficial effects were not only found in healthy adults, but also in children with mathematical learning disabilities (Looi et al., 2017). Although these learning studies also differed in various ways, the results seem to converge to the notion that tES is effective to support arithmetic learning. This view was supported by a recent meta-analysis aggregating 35 tES studies on language and math that indicated much stronger effects of tES when applied during learning ($d = 0.712$) as compared to an application during testing ($d = 0.207$; Simonsmeier et al., 2018).

However, where and how to stimulate during arithmetic learning to achieve the best effects are still open questions and again, direct comparisons between different stimulation protocols are scarce. Furthermore, one promising version of tES, tACS, has not been investigated so far. Most prior studies assessing tES effects on mental arithmetic used tDCS protocols. The primary effect of tDCS is a modulation of cortical excitability in the regions beneath the electrodes, with anodal tDCS having excitatory effects at the macroscale level with standard protocols, and inducing long-term potentiation like neuroplastic effects (Paulus, 2011; Coffman et al., 2014). In contrast, tACS allows the entrainment and enhancement of brain oscillations in specific frequency bands and affects spike-timing-dependent plasticity (Zaehe et al., 2010; Antal and Paulus, 2013; Battleday et al., 2014; Vossen et al., 2015), although it needs to be mentioned that tDCS might also alter oscillatory patterns (Ullam et al., 2015; Hanley et al., 2016; Mancini et al., 2016), albeit in a less targeted fashion.

As oscillatory activity in the theta and alpha bands has been linked to arithmetic processing and learning as well as working memory in general (e.g. Bastiaansen and Hagoort, 2003; De Smedt et al., 2009; Grabner and De Smedt, 2011, 2012; Klimesch, 1999; Klimesch et al., 2005; Polania et al., 2012; Tschentscher and Hauk, 2016), it seems plausible that modulation of activity in these frequency bands might affect the acquisition of a novel arithmetic procedure and novel arithmetic facts.
Hence, against this background, the present study was planned to assess the effects of left frontal and left parietal anodal tDCS, theta band tACS, and alpha band tACS in adults (a) on the acquisition and application of a novel, artificial arithmetic operation and corresponding facts in a setup mimicking typical arithmetic learning processes, and (b) on the changes in ERS/ERD patterns accompanying arithmetic training. Thereby, these tES protocols were chosen as these tACS versions have the potential to influence ERS/ERD patterns in frequency bands and regions related to arithmetic processing and possibly support learning related changes (De Smedt et al., 2009; Grabner and De Smedt, 2012; Soltanlou et al., 2019) and as anodal tDCS targeting similar regions has already been found to be promising (e.g. Grabner et al., 2015; Hauser et al., 2013; Mosbacher et al., 2020). Cathodal tDCS on the other hand was excluded as prior work found little evidence for beneficial effects, but some for potentially detrimental ones (e.g. Grabner et al., 2015).

As all active stimulation protocols used have the potential to enhance arithmetic learning, either by modulating activity in regions relevant for domain-general functions (e.g. executive functions like WM or memory processes associated with the DLPFC and the AG), or by modulating activity in regions relevant for more domain-specific functions (e.g. numeric quantity processing associated with the IPS), we explored which of these stimulation protocols show beneficial effects on the acquisition of the novel procedural and declarative (fact) knowledge. At the electrophysiological level, we expected stimulation effects on procedural learning to be reflected more strongly by ERD within the alpha and beta bands, while effects on fact learning should be reflected in theta band ERS patterns.

**EXPERIMENTAL PROCEDURES**

**Sample**

In total, 140 persons participated in the study. They were randomly divided into 7 groups of 20 persons each, receiving one of 7 different stimulation/montage combinations (anodal tDCS, alpha band tACS, and theta band tACS targeting either the left DLPFC, or the left PPC, and sham). Three participants had to be excluded from further analysis. Two did not solve any trials correctly in the first block and another participant’s EEG could not be analyzed because of excessive artifacts. Inclusion criteria were an age between 18 and 45 years, right-handedness, German-speaking, no current or prior history of neurological or psychiatric diseases and no regular use of substances that could affect brain function (however, nicotine and caffeine consumption were not explicitly assessed or defined as exclusion criteria). Demographic data of the final sample of 137 participants are given in Table 1. Groups did neither differ significantly in age, F(6, 130) = 0.726; p = .629, nor in sex ratio, χ²(N = 137) = 1.368; p = .968. The study was approved by the ethics committee of the University of Graz, all participants gave written informed consent and were compensated with either 20 € or a study-participation certificate for course credits of 2.5 hours.

**Arithmetic learning task**

To investigate the acquisition and training of procedural knowledge and fact knowledge, a novel arithmetic task based on the “pound arithmetic” by Rickard (1997) was used. Similar tasks have been applied in previous training studies (Delazer et al., 2005; Snowball et al., 2013; Popescu et al., 2016). Problems were presented as A # B, and participants had to conduct a series of basic arithmetic operations to find the solution. The procedure to solve A # B was 2 * B − A + 3. For example, 4 # 36 results in 71 because 36 * 2 = 72 → 72 − 4 = 68 → 68 + 3 = 71. Thereby, “A” could take numbers from 2 to 9 except 3 (as 2 * 3 − 3 would have reduced the problem to 2 * B) and “B” from 13 to 49, except for full decades and numbers in which units and tens digits are the same (e.g. 35) or the units digit was 5. Furthermore, we excluded all problems with full decades as solutions. This resulted in a total of 141 unique problems.

Every person was asked to solve 196 trials over the course of five blocks, whereby 80 of these were “procedural learning trials” and 116 “fact learning trials”. The 80 procedural learning trials consisted of 20 anchor problems that were the same for all participants (eight in blocks 1 and 5 and four in block 3; used for a separate study assessing the learning characteristics of the used problems) and 60 randomly chosen problems that were different for each participant. The problems in the “procedural learning trials” were never repeated and, consequently, had to be solved by procedural calculation always, which should lead to a training of the procedural operation. With exception of the anchor items, the appearance of these problems was random, and there were 16 procedural learning problems per block. For the fact learning trials, four fact learning problems were randomly selected per person and repeated 29 times each (once in block 1 and seven times each in blocks 2 to 5). Hence, block 1 consisted of 20 trials (4 fact and 16 procedural trials) and blocks 2 to 5 of 44 trials (28 fact and 16 procedural trials). To acquire fact knowledge, participants were asked to try to memorize the solutions to the repeating fact learning problems over the course of the five blocks and to try to solve them by use of fact retrieval. The difference in the number of repetitions of the fact learning problems between the first and the subsequent blocks was implemented so that fact learning started after familiarization with the task and together with the stimulation.

A single trial (depicted in Fig. 1) started with a fixation cross (1 s), followed by the problem. Participants had a maximum of 8 s to solve the problem and indicate so by pressing a button. After the button was pressed (or time ran out) three possible solutions appeared and participants had a maximum of 3 s to choose the correct one by pressing the respective button. Subsequently, they received feedback (1.5 s) on whether their answer was correct or incorrect, and the problem with the correct solution was displayed. Finally,
participants were asked to report their applied problem-solving strategy. They had 3 s to choose from (a) retrieved from memory, (b) calculated, and (c) neither (only to be used when, for example, they pressed the wrong button by mistake). After an inter-trial interval (ITI) with the length of the remaining time from problem-solving (max. 8 s), solution selection (max. 3 s), and strategy selection (max. 3 s), the next trial followed. The ITI was implemented to keep the total duration of the blocks and the number of trials during stimulation constant for all participants. The distractor answers were randomly generated for all trials and consisted of the correct result ±1, ±2, or ±10. Also, the order (left, middle, right) of the three possible solutions (one correct, two distractors) to select from was randomly changed for every trial. The procedure was explained in detail in the instructions, and participants could process five practice trials and ask final questions before the training started. Participants were asked to solve all problems as fast and accurately as possible and to try to learn the solutions to the repeating fact learning problems. The feedback was intended to give additional learning aid, and there were short breaks between the single blocks.

### EEG

EEG was recorded using a BioSemi (BioSemi, Amsterdam, Netherlands) ActiveTwo amplifier with 64 channels. Channels were arranged according to the extended 10–20 system (based on Jasper, 1958), and active electrodes were mounted using BioSemi head caps and Signagel (Parker Laboratories, Fairfield, USA) to ensure good electrode–skin contact. As the stimulation electrodes were mounted at F3 (targeting the left DLPFC) and P3 (targeting the left PPC) and, in the tDCS protocols, above the right eye covering the positions Fp2, AF8, and F8, these EEG electrodes were not mounted. In addition to the EEG recording during the arithmetic training (EEG was recorded during all 5 blocks, also concomitant to tES), resting-state recordings took place before and after the training task, each consisting of two minutes with eyes closed and two minutes with eyes opened.

### Transcranial electrical stimulation

Stimulation was applied in a double-blind way with a NeuroConn DC-Stimulator Plus (NeuroConn, Ilmenau, Germany); participants received either one of six active
stimulations or sham stimulation. The six active stimulations were anodal tDCS targeting the left DLPFC (tDCS-f) or the left PPC (tDCS-p), alpha band tACS targeting the left DLPFC (alpha-tACS-f) or the left PPC (alpha-tACS-p), and theta band tACS targeting the left DLPFC (theta-tACS-f) or the left PPC (theta-tACS-p).

We used a 3 × 3 cm² rubber electrode as target electrode (placed over F3, targeting the left DLPFC or P3, targeting the left PPC for frontal and parietal stimulation respectively) and a 5 × 7 cm² return electrode (in tDCS; cathode placed above the contralateral supraorbital area; in tACS: return electrode placed on the left shoulder; similar montages have been used in prior work; see Elmasry et al., 2015; Galli et al., 2019; Schroeder et al., 2017; Tavakoli and Yun, 2017 for an overview). Participants receiving sham stimulation were spread evenly over all stimulation conditions and electrode montage followed the same procedure as for the other participants receiving the respective active stimulation. To ensure good contact, electrodes were mounted directly to the scalp with a 1–2 mm thick layer of Ten20 paste (Weaver and Company, Aurora, USA) and held in place by an EEG cap.

Blinding was implemented using the study mode of the NeuroConn DC-Stimulater Plus. In this mode, the intended stimulation has to be set before the stimulation is started and the experimenter enters a pre-defined code that determines whether true stimulation or sham stimulation is started. These codes are provided in the manual of the stimulation device and were randomly assigned to the participants by a python script. At the time of stimulation, the experimenter was not aware whether the code is related to an active or a sham stimulation. After the last participant had been investigated, the code lists were unblinded so that the analyses could be conducted.

In the active tES groups, stimulation was applied for 25 min with a fade in/out phase of 30 s in tDCS or 100 periods in tACS. In tDCS, the current intensity applied was fixed to 1 mA. In tACS, intensity and stimulation frequency were adjusted individually. Specifically, the intensity was adjusted by starting with 1 mA peak to peak and increasing the current in 0.25 mA steps until participants felt skin sensations, saw phosphenes, or the maximum of 1.5 mA peak to peak was reached. If any sensations were present, the intensity was set to the last intensity step before sensations occurred. If sensations were present at 1 mA already, it was decreased in 0.1 mA steps until no sensations were reported. The individual stimulation frequencies in the alpha and theta ranges were assessed based on the individual alpha frequency assessment and EEG-band calculations described in the work of Klimesch (1995).

Here, the closed eyes resting-state EEG data recorded before the training task was used. The individual alpha frequency was determined by setting an average reference and applying a high-pass (1 Hz) and a notch filter (49–51 Hz) to the uncorrected data (bad channels were excluded), and using Welch’s method to calculate the power spectral density (PSD) between 7 and 14 Hz. Based on this data, the individual alpha frequency was assessed by automatically searching for the maximum in the average PSD data (over all channels except generally excluded ones). This value was then rounded to the next half Hz. For alpha band stimulation, this value was used as stimulation frequency, for theta band stimulation this value minus 5 Hz was used as stimulation frequency.

In tACS, the mean peak to peak intensity was $M = 1.07 \text{ mA} (SD = 0.25)$; intensity did not differ significantly between tACS groups ($F_{3, 70} = 1.918; p = .134$). The mean frequencies were $M = 9.93 \text{ Hz} (SD = 0.86)$ for alpha band stimulation (no significant difference in stimulation frequency between frontal and parietal stimulation; $f_{90} = -0.547; p = .587$) and $M = 5.06 \text{ Hz} (SD = 0.79)$ for theta band stimulation (again no significant difference between frontal and parietal stimulation; $f_{90} = 0.298; p = .767$).

**Procedure**

Assessments were conducted in a single-person setting at the EEG-Lab of the section of Educational Neuroscience at the University of Graz. After the study was explained and written informed consent was given, participants were asked to answer a demographic questionnaire and to complete assessments on their handedness (FLANDERS; Nicholls et al., 2013) and current mood (MDBF; Steyer et al., 1997). After this first part, participants were brought into a separate, quiet, and normally lit room where the tES and EEG electrodes were attached and the main part of the assessment took place. The main part consisted of the five arithmetic learning blocks with concomitant brain stimulation during blocks 2 and 3 and EEG recording during all blocks (see Fig. 2). Subsequently, tES and EEG electrodes were removed and participants could wash their hair. Finally, participants were presented the mood questionnaire a second time and asked to answer another questionnaire regarding their dynamic mindset, to state if any side effects of stimulation were present (e.g. itching, headache) and to rate the intensity of the side effects on a five-point Likert scale (from very slight to very strong), and whether they thought that they had received active stimulation or sham stimulation. The questions regarding side effects were open, and participants could enter every sensation they deemed a possible side effect of the stimulation and rate it. The question regarding the active or sham stimulation was a forced choice question.

**Data preprocessing and statistical analysis**

**Assessment of learning.** In general, trials were counted as correct if they were solved correctly and in time. Calculation times were only analyzed for correct trials. For fact learning, two markers of learning were assessed. The first of these markers was the mean number of repetitions needed to learn. This was defined as the average number of repetitions needed until a person could solve the four fact learning problems always correct and by use of fact retrieval (as self-reported after every trial). The second marker was based on the change in calculation times. Thereby,
based on the analyses in Snowball et al. (2013), a power-law function ($CT_N = B * N^a$; whereby N is the trial number, $CT_N$ is the estimated calculation time at trial N, B is a constant (intercept) and the $a$-parameter is the power-law exponent) was fitted to the calculation times (using SPSS 25; IBM Corporation, Armonk, USA). Based on Snowball et al. (2013), we used the $a$-parameter as a marker for learning rate. A lower (negative) value of $a$ indicates a faster reduction in calculation times and hence, faster learning. The $a$ parameters were assessed individually for every person on a single problem level and then averaged over the four fact learning problems, resulting in a single mean $a$ value per person. In procedural learning, accuracy and mean calculation times for correctly solved procedural learning trials were assessed per block.

**EEG-data preprocessing and ERS/ERD calculation.** For preprocessing, the open-source Python software MNE (Gramfort et al., 2013; 2014) and additional custom Python code were used. The EEG data collected before and after stimulation were preprocessed in a semi-automatic way. In a first step, the data were visually inspected to remove bad channels and prominent artifacts. This was followed by setting an average reference and filtering the data with a high-pass (1 Hz), a low-pass (60 Hz), and a notch filter (49–51 Hz). Subsequently, an independent component analysis was conducted to remove ocular artifacts, followed by a final visual inspection to exclude remaining artifacts. For the assessment of ERS/ERD values in the different frequency bands (theta 3–6 Hz, low alpha 8–10 Hz, high alpha 10–13 Hz, and beta 13–30 Hz) the data were band-pass filtered for the specific ranges. The frequency bands of interest were chosen in accordance with prior research on mental arithmetic (Grabner and De Smedt, 2011, 2012).

ERS/ERD values were calculated over all correct trials in block 1 (Start) and separately for correct procedural and fact learning trials in blocks 4 and 5. Thereby, blocks 4 and 5 were combined to analyze ERS/ERD post-stimulation, at the end of the learning session. This results in one ERS/ERD value per frequency band for procedural learning trials after stimulation (End-Procedural) and one per frequency band for fact learning trials (End-Fact Retrieval). As basis for ERS/ERD values, the band power for each frequency band of interest was assessed in the reference segments (R; fixation cross; 1000 ms) and during cognitive activation (A; from problem presentation until button press) for these trials. Trials where more than 50% of data had to be removed because of artifacts were excluded. On average, $M = 12.31$ trials ($SD = 4.83$) could be used in block 1 and $M = 22.97$ ($SD = 5.36$) for procedural calculation and $M = 51.29$ ($SD = 3.81$) for fact retrieval in blocks 4 and 5 combined. ERS/ERD values were calculated by ERS/ERD = ((A – R)/R) * 100. Positive values indicate a power increase from the reference phase to the active phase and, hence, an ERS, while negative values indicate a power decrease from the reference phase to the active phase and, hence, an ERD.

For statistical analyses, the ERS/ERD values of the single channels were clustered, by averaging the ERS/ERD values over all EEG channels in a cluster (separately for procedural and fact learning trials and the different points in time). The clusters consisted of a left frontal cluster (electrodes: Fp1, AF3, AF7, F1, F7, FC1, FC3, FC5), a right frontal cluster (electrodes: AF4, F2, F4, FC2, FC4, FC6), and a left (electrodes: CP1, CP3, CP5, P1, P7, P9, PO3, PO7) and right (electrodes: CP2, CP4, CP6, P2, P4, P6, P8, P19, PO8, PO4) parietal one. The channels F5, F6, and P5 had to be excluded as these were the channels closest to stimulation electrodes and hence, did not yield processable EEG data in a large portion of participants.

**Statistical analysis**

All analyses were conducted using SPSS 25 (IBM, Armonk, USA). Differences in fact learning between the sham group and the active stimulation groups were analyzed by two one-way-ANOVAs with the learning rate parameter $a$ and the number of repetitions needed to learn as dependent variables. Planned contrasts were used to compare the active stimulation groups to the sham group one by one. In case of a significant Levene’s test of homogeneity of variances the Welch test results and corrected contrast statistics are reported. Additionally, a Pearson correlation was
calculated to assess an association between the repetitions needed to learn and the learning rate parameter \( \alpha \).

The analysis of stimulation-induced changes in procedural calculation and ERS/ERD patterns were preceded by one-way-ANOVAs to assess whether there were any group differences at baseline. The analysis regarding changes in accuracy and calculation times in procedural calculations were done via mixed-design ANOVAs. The independent variables consisted of one within-subjects (time: Blocks 1 to 5) and one between-subjects factor (stimulation groups). Dependent variables were the accuracy and the mean calculation time at the different time points.

Stimulation-induced changes in ERS/ERD parameters were analyzed by mixed-design ANOVAs as well. Here, the independent variables consisted of two within-subject factors (state: Start, End-Procedural, and End-Fact Retrieval; location: left frontal, right frontal, left parietal, and right parietal) and the stimulation groups as between-subjects factor. This method was chosen as it allows a direct comparison of ERS/ERD patterns between trained procedural calculation (End-Procedural) and fact retrieval processes (End-Fact Retrieval) as well as for a comparison between the start point (Start; untrained procedural calculation) and both, trained procedural calculation and fact retrieval. Thereby, the first block serves as a universal baseline, as in the beginning all problems have to be calculated. As procedural and fact learning problems are randomly chosen and each problem only appears once in the first block, this block can be seen as an untrained performance baseline common for both types of problems. ERS/ERD analyses were conducted separately for all frequency bands. Greenhouse-Geisser correction was used if sphericity could not be assumed as indicated by a significant Mauchly’s test of sphericity. Additionally, successful blinding was ascertained by a chi-squared test, comparing the participant guesses (gathered in the questionnaire) with the true stimulation data. Finally, mixed-design ANOVAs were used to assess whether any stimulation led to changes in mood by comparing the MDBF subscale values before and after the training (within-subjects factor time) between the different stimulation groups (between-subjects factor) and Fisher’s exact tests were calculated to compare the frequency of side effects of stimulation for the most commonly reported side effects (burning/stinging/pain, tingling/itching/prickling, and headache) between the stimulation groups (here, the results of all 140 participants were included).

A significance threshold of \( \alpha = 0.05 \) was used in all analyses, and planned contrasts and post hoc pairwise comparisons were Bonferroni-corrected.

**RESULTS**

**Fact learning**

*Repetitions needed to learn.* The analysis on the repetitions needed to learn indicated a difference between the stimulation groups (\( F_{6, 57.478} = 2.742, p = .021 \)). The planned contrasts showed a significant difference between the sham stimulated group (\( M = 22.12; SD = 5.04 \)) and the group receiving frontal theta band tACS (\( M = 17.15; SD = 5.39; t_{36.993} = -2.976; p_{bonf} = 0.030; d = 0.933 \)). Hence, participants in the group receiving frontal theta band tACS needed significantly less repetitions to learn the novel facts than the sham stimulated control group.

The repetitions needed to learn in the groups receiving frontal tDCS (\( M = 19.55; SD = 6.98; t_{34.575} = -1.322; p_{bonf} > 0.999; d = 0.422 \)) or alpha band tACS (\( M = 18.38; SD = 8.31; t_{31.572} = -1.711; p_{bonf} = 0.058; d = 0.545 \)), and parietal tDCS (\( M = 20.17; SD = 5.60; t_{34.131} = -1.113; p_{bonf} > 0.999; d = 0.367 \)), alpha band tACS (\( M = 22.88; SD = 4.69; t_{36.428} = 0.485; p_{bonf} > 0.999; d = 0.156 \)), or theta band tACS (\( M = 19.41; SD = 4.59; t_{36.228} = -1.751; p_{bonf} = 0.528; d = 0.562 \)) did not differ significantly from the sham stimulated group (see Fig. 3).

**Learning rate.** Regarding the learning rate parameter \( \alpha \), the analysis indicates significant differences between the groups (\( F_{6, 130} = 2.468; p = .027 \)). The planned contrasts showed differences between the sham stimulated group (\( M = -0.387; SD = 0.183 \)) and the group receiving frontal theta band tACS (\( M = -0.578; SD = 0.209; t_{130} = -2.892; p_{bonf} = 0.024; d = 0.971 \)) as well as the group receiving parietal theta band tACS (\( M = -0.586; SD = 0.222; t_{130} = -3.013; p_{bonf} = 0.018; d = 0.979 \)). Hence, both groups receiving theta band tACS showed a faster acceleration of calculation times than the sham stimulated control group.

The \( \alpha \) values in the groups receiving frontal tDCS (\( M = -0.511; SD = 0.152; t_{130} = -1.872; p_{bonf} = 0.384; d = 0.733 \)) or alpha band tACS
The amount of repetitions needed to learn. There was a significant correlation between the learning rate parameter $\alpha$ and the amount of repetitions needed to learn ($r_{130} = -0.762; \rho_{bonf} > 0.999$; $d = 0.258$), and parietal tDCS ($M = -0.549; SD = 0.236; t_{130} = -2.394; \rho_{bonf} = 0.108; d = 0.767$) or alpha band tACS ($M = -0.502; SD = 0.225; t_{130} = -1.738; \rho_{bonf} = 0.510; d = 0.559$) did not differ significantly from the sham stimulated group (see Fig. 4).

Correlation between the learning rate parameter $\alpha$ and repetitions needed to learn. There was a significant correlation between the learning rate parameter $\alpha$ and the amount of repetitions needed to learn ($r_{130} = -0.476; p < .001$), demonstrating that a lower $\alpha$ value (indicating a faster decline in calculation times) was associated with less repetitions needed to learn the novel arithmetic facts.

Procedural learning

Baseline comparisons indicated a group difference in accuracy ($F_{6, 130} = 2.268; p = .041$), but not in calculation times ($F_{6, 57.388} = 1.992; p = .378$). However, post hoc tests revealed no significant accuracy differences between single groups (all $\rho_{bonf} > 0.074$).

Accuracy changes. For accuracy in procedural learning, the ANOVA showed a significant main effect of time ($F_{3,251} = 422.618 = 18.247; p < .001; \eta^2 = 0.123$) but no significant effect of stimulation ($F_{6, 130} = 1.700; p = .126; \eta^2 = 0.073$) or time $\times$ stimulation interaction ($F_{18,505} = 1.011; p = .447; \eta^2 = 0.045$). Pairwise comparisons showed a lower accuracy in block 1 ($M = 62.55%; SD = 24.26$) than in blocks 2 to 5 (all $\rho_{bonf} < 0.001$). Accuracy in blocks 2 ($M = 69.75%; SD = 21.04$), 3 ($M = 72.72%; SD = 19.01$), 4 ($M = 73.27%; SD = 18.69$), and 5 ($M = 72.77%; SD = 18.56$) did not differ significantly from each other (all $\rho_{bonf} > 0.144$).

Calculation time changes. Similar to accuracy the ANOVA conducted on calculation times in procedural problems showed a significant effect of time ($F_{2,938} = 381.989; p < .001; \eta^2 = 0.250$), but no significant effect of stimulation ($F_{6, 130} = 0.957; p = .457; \eta^2 = 0.042$) or time $\times$ stimulation interaction ($F_{17,630} = 381.989; p = .487; \eta^2 = 0.043$). Pairwise comparisons showed no significant difference in calculation times between block 1 ($M = 5.40$ sec.; $SD = 1.01$) and block 2 ($M = 5.32$ sec.; $SD = 0.98$; $\rho_{bonf} > 0.999$), a significant reduction in calculation time from block 2 to block 3 ($M = 4.94$ sec.; $SD = 1.01$; $\rho_{bonf} < 0.001$), no significant difference between block 3 and block 4 ($M = 4.85$ sec.; $SD = 1.03$; $\rho_{bonf} = 0.797$), but a further reduction from block 3 to block 5 ($M = 4.73$ sec.; $SD = 0.98$; $\rho_{bonf} = 0.005$).

EEG results

Means and standard deviations for the single time points and locations are given in Table 2 and an overview is given in Fig. 5. Estimated marginal means and post hoc pairwise comparison results of significant effects not related to stimulation are given in the supplementary materials (tables S1–13). Baseline comparisons between the stimulation groups showed no significant differences in any of the frequency bands or locations (all $p > .155$; see table S14).

Theta band. The ANOVA conducted for the theta band data showed a significant effect of state ($F_{1,755} = 35.526; p < .001; \eta^2 = 0.215$), location ($F_{2,436} = 316.652 = 26.207; p < .001; \eta^2 = 0.168$) and a significant state $\times$ location interaction ($F_{2,579} = 35.526; 595.240 = 8.446; p < .001; \eta^2 = 0.061$). However, there were no significant effects of stimulation ($F_{6, 130} = 0.670; p = .736; \eta^2 = 0.030$), nor significant state $\times$ stimulation ($F_{10,531} = 228.167 = 0.262; p = .990; \eta^2 = 0.012$), location $\times$ stimulation ($F_{14,615} = 316.652 = 0.743; p = .736; \eta^2 = 0.033$), or state $\times$ location $\times$ stimulation ($F_{27,473} = 595.240 = 0.984; p = .489; \eta^2 = 0.043$) interactions.

Lower alpha band. In the lower alpha band, the main effects of state ($F_{1,881} = 244.583 = 6.676; p = .002; \eta^2 = 0.049$) and location ($F_{2,298} = 298.337 = 12.704; p < .001; \eta^2 = 0.089$) were significant. The effects of stimulation ($F_{6, 130} = 0.635; p = .702; \eta^2 = 0.028$) as well as the state $\times$ location ($F_{4,597} = 467.668 = 0.471; p = .737; \eta^2 = 0.004$), state $\times$ stimulation ($F_{11,288} = 244.583 = 0.784; p = .659; \eta^2 = 0.035$), location $\times$ stimulation ($F_{13,769} = 298.337 = 1.190; p = .283; \eta^2 = 0.052$), and state $\times$ location $\times$ stimulation interactions ($F_{21,586} = 467.668 = 1.193; p = .250; \eta^2 = 0.052$) were not significant.

Upper alpha band. Similar to the theta band, in the upper alpha band, analyses revealed a significant effect of state ($F_{1,724} = 224.089 = 20.353; p < .001; \eta^2 = 0.135$) and location ($F_{2,667} = 346.691 = 11.503; p < .001; \eta^2 = 0.081$) and a significant interaction

![Fig. 4. Learning rate parameter $\alpha$ in the different groups. The box-and-whiskers plots show the median and the 25th and 75th percentiles with the whiskers reflecting the 5th and 95th percentiles. The dots depict the mean learning rate parameter $\alpha$ of every participant. The * indicates significant differences between groups.](Image)
However, there were not significant effects of stimulation ($F_{6, 130} = 0.816; \ p = .560; \ \eta^2_p = 0.036$), nor significant state \times stimulation ($F_{16, 346} = 1.132; \ \eta^2_p = 0.029$), location \times stimulation ($F_{28, 609} = 0.962; \ p = .523; \ \eta^2_p = 0.043$) interactions.

**Beta band.** Similar to the theta and the upper alpha bands, the results showed a significant effect of state
(F1,725, 224.215 = 7.154; p = .002; ηp2 = 0.052), location (F2,771, 360.161 = 18.146; p < .001; ηp2 = 0.122) and a significant state × location interaction (F4,838, 628.920 = 16.172; p < .001; ηp2 = 0.111). Again, there were no significant effects of stimulation (F6, 130 = 0.224; p = .968; ηp2 = 0.010), nor significant state × stimulation (F10,348, 224.215 = 0.408; p = .946; ηp2 = 0.018), location × stimulation (F16,624, 360.181 = 1.495; p = .095; ηp2 = 0.065), or state × location × stimulation (F29,927, 628.920 = 0.783; p = .787; ηp2 = 0.035) interactions.

Additional analyses

Success of blinding. A chi-squared test showed that participants were not able to discern between active and sham stimulation (κ2 = 2.960; p = .814). Thereby, 7 of 19 persons receiving sham stimulation assumed they had received an active stimulation. In the active groups, there were 11 of 20 (in the tDCS-f group), 8 of 18 (tDCS-p), 7 of 20 (alpha-tACS-f), 10 of 20 (alpha-tACS-p), 9 of 20 (theta-tACS-f), and 7 of 20 (theta-tACS-p) participants assuming they had received active stimulation.

Changes in mood. The results of the analysis showed that the participants felt significantly less awake after the experiment (M = 25.38; SD = 7.21) than before (M = 29.36; SD = 5.93; F1, 130 = 57.538; p < .001; ηp2 = 0.307). However, there were no significant effects of stimulation (F6, 130 = 1.618; p = .147; ηp2 = 0.069) nor a time × stimulation interaction (F6, 130 = 0.500; p = .807; ηp2 = 0.023). Furthermore participants felt calmer after the experiment (M = 33.69; SD = 3.77) than before (M = 32.37; SD = 4.68; F1, 130 = 13.013; p < .001; ηp2 = 0.091), but again no significant effects of stimulation (F6, 130 = 1.023; p = .413; ηp2 = 0.045) or time × stimulation interaction (F6, 130 = 1.562; p = .163; ηp2 = 0.067) were found. For the pleasant-unpleasant subscale no significant effects emerged (all p > .05).

Side effects. A full list of side effects including frequencies and mean intensities is given in Table 3. The most common side effects were a burning/sting/itching/prickling sensation (20% of participants), followed by tingling/itching/prickling sensations (17.14%), and headache (5%). The Fisher’s exact test only showed a significant difference between the groups regarding the frequency of burning/stitching/prayful sensations (p = .001), with the tDCS-f and tDCS-p groups showing the highest numbers of occurrence. Results for tingling/itching/prickling (p = .453) and headache (p = .299) were not significant. Overall, the intensities of side effects were reported as slight to moderate.

DISCUSSION

The main objective of this study was to assess the efficacy of six different tES protocols, with three different tES versions targeting two different stimulation sites each, on the training and acquisition of a novel arithmetic procedure and novel arithmetic facts. Behavioral results showed promising effects of theta band tACS. Both frontal as well as parietal theta band tACS improved arithmetic fact learning, while tDCS and alpha band tACS showed no effects. Interestingly, significant stimulation effects were limited to the acquisition of novel facts. None of the applied stimulation protocols had a significant impact on the acquisition and training of the novel procedure. Finally, and surprisingly, we did not observe any significant stimulation-related changes in ERS/ERD patterns that have been associated with arithmetic processing in previous studies (e.g. De Smedt et al., 2009; Grabner et al., 2021; Grabner and De Smedt, 2011).

Stimulation effects on fact learning

At large, all groups were able to learn the novel arithmetic problems and build up fact proficiency, indicating that the number and type of novel problems were well suited for the present investigation. In comparing the active stimulation protocols with the sham stimulation, we found that only theta band tACS had a beneficial impact on arithmetic fact learning.

The learning rate parameter α was improved by theta band tACS over the left DLPFC as well as by theta band tACS targeting the left PPC, with comparable and large effect sizes (d = 0.971 and d = 0.979 respectively). Importantly, theta band tACS targeting the left DLPFC also significantly reduced the number of repetitions needed to learn the novel facts – again with quite a large effect. On average, the group receiving theta band tACS targeting the left DLPFC needed about 5 repetitions less to learn the novel facts than the sham stimulated control group (theta-tACS-f group: M = 17.15 vs. Sham group: M = 22.12, d = 0.953). Hence, left frontal theta band tACS reduced the repetitions needed by over 22%.

The effectiveness of theta stimulation fits well with the results of previous studies linking activity in the theta band to arithmetic fact retrieval processes and arithmetic training (De Smedt et al., 2009; Grabner and De Smedt, 2011, 2012; Soltanlou et al., 2019). Likewise, in the present study, fact learning was accompanied by an increase in theta band ERS in all but right frontal regions (see tables S1–3). Increased theta band activity and synchronization within and between different regions of the brain (including frontal and parietal sites) has long been linked to memory processes, for example encoding processes, item-context binding, and episodic memory (e.g. Herweg et al., 2020; Klimesch et al., 1996; Summerfield and Mangels, 2005). Hence, the improvement in fact learning by application of theta band tACS is in line with the research body on oscillatory activity in various learning tasks and suggests that the task-relevant memory processes were facilitated through this stimulation protocol.

Interestingly, theta band tACS targeting the left DLPFC showed promising effects in both markers of fact learning, while theta band tACS targeting regions in the PPC only significantly improved the learning rate parameter α. Many studies investigating the brain
regions and networks relevant for arithmetic processes speculate the AG to be important for fact retrieval (probably relevant for establishing the connection between arithmetic problems and their solution; Grabner et al., 2013), or supporting activation control in long-term memory networks (Bloechle et al., 2016). Frontal regions, in contrast, have mainly been associated with procedural calculation (Ischebeck et al., 2007; Grabner et al., 2013), or supporting activation control in long-term memory networks (Bloechle et al., 2016). However, the strong effects of frontal stimulation might be based on the relevance of frontal regions and networks relevant for arithmetic processes.

Executive functions, associated with a network containing the DLPFC among other regions, have been found to play an important role in learning in general (Fletcher and Henson, 2001; Ranganath and Knight, 2002; Chein and Schneider, 2012; Diamond, 2013). Cognitive control processes are also important for retrieval of the novel facts in the present study is the acquisition of novel facts by reducing proactive interference (Staudigl et al., 2010; Cavanagh and Frank, 2014). This assumption of course is speculative, and further research to determine the exact mechanisms will be necessary, but there are some possible routes of action. Theta band tACS could, for example, support the acquisition of novel facts by reducing proactive interference and/or increasing the inhibition of non-relevant information retrieval.

Another interesting aspect in the acquisition and retrieval of the novel facts in the present study is the correlation between both markers of fact learning. With almost 23% of shared variance, there is considerable overlap between the repetitions needed to learn and the calculation-time-based learning rate \( \alpha \). However, it is not clear if this is a result of the earlier switch to a faster strategy (calculation to fact retrieval) with fewer repetitions needed to learn, which might be directly converted to a lower learning rate parameter \( \alpha \), or if both markers assess other shared aspects of fact learning.
learning. This adds an interesting aspect when comparing the effects of frontal and parietal theta band tACS. Frontal stimulation improved both markers of fact learning significantly. Hence, it is possible that it directly reduced the repetitions needed to learn and only indirectly the learning rate parameter $a$ or that it had direct beneficial effects on both markers by enhancing either shared or unique factors. Parietal stimulation, on the other hand, only significantly improved the learning rate parameter $a$, without reducing the repetitions needed to learn (although, with a $d = 0.563$ there still was a medium sized effect of parietal theta band tACS on the repetitions needed to learn, even if not significant). Hence, parietal stimulation might have had a more direct effect on aspects unique to the calculation/retrieval time acceleration. However, it still is possible that the participants in this group also switched earlier but made more errors or switched back and forth between fact retrieval and calculation longer.

Interestingly, neither alpha band tACS nor tDCS protocols significantly improved the acquisition of novel facts. In the field of mental arithmetic, alpha band oscillations, more precisely alpha ERD over posterior sites, have mainly been associated with procedural calculations (De Smedt et al., 2009; Grabner and De Smedt, 2011, 2012). Furthermore, arithmetic trainings have been associated with decreased alpha band ERD (Grabner and De Smedt, 2012; Soltanlou et al., 2018). Hence, significant alpha band tACS effects might have been absent in the present study because of the minor relevance of these oscillations in fact learning and retrieval. TDCS, on the other hand, has been the most widely used stimulation method in studies on arithmetic processing and learning (Schroeder et al., 2017) and has been shown to be a promising tool to enhance learning (Simonsmeier et al., 2018). In previous studies on arithmetic learning, it supported subtraction training and improved the learning rate in a fractions-based video game (Grabner et al., 2015; Looi et al., 2016). However, there are some differences between these studies and the present one that could explain the heterogeneity of results: Both used more typical, school-taught arithmetic problems, and Looi and colleagues combined it with a movement-based video game. Furthermore, both used larger electrodes (25 cm$^2$ circular electrodes in Looi et al., 2016, and a 7 × 5 cm active and 10 × 10 cm reference electrode setup in Grabner et al., 2015) and Looi and colleagues stimulated the DLPFC bilaterally (left cathodal/right anodal), while Grabner and colleagues mounted the active electrode between P5 and CP5 and used a higher stimulation intensity (1.5 mA). The multiple differences between those studies and the present one make it hard to discern which aspects were relevant for the outcome differences. However, the differences of the arithmetic tasks and stimulation sites might be the most important ones, especially with respect to the study by Looi and colleagues (Looi et al., 2016). As mentioned already above, the participants in that study had to solve fractions and indicate their solution by moving their bodies to the left or right in front of a video sensor to position a cursor reflecting their result in a number line video game.

Hence, this task included a very strong visuo-spatial component that was absent in the present study. Furthermore, not only did they apply bilateral stimulation to the DLPFC, but the left hemisphere was stimulated with the cathode while in the present study the left DLPFC was stimulated with the anode positioned over the target area. Outcome differences between the studies could thus be expected, whereby anodal stimulation over left frontal regions has been a more commonly used approach in studies in probing tES effects on arithmetic tasks, and with some success with respect to performance improvement (e.g. Mosbacher et al., 2020; Pope et al., 2015; Sarkar et al., 2014). Regarding electrode size and stimulation intensity, the intensity of 1 mA was the same as in the work of Looi and colleagues (Looi et al., 2016). Because of the smaller electrode size the current density at the electrode (0.11 mA/cm$^2$) was even larger in the present study than in the study of Grabner and colleagues (Grabner et al., 2015), although current intensity was lower. However, a direct comparison of different electrode size and intensity combinations might be of interest. There might be non-linear electrode size-dependent differences in electrical field strength between smaller and larger electrodes (Miranda et al., 2009), and smaller electrodes might have more focal effects, which could be either an advantage or a disadvantage (Faria et al., 2011; Bastani and Jaberzadeh, 2013).

Nevertheless, while tDCS did not lead to significant improvements in this study, the effects sizes regarding reduced repetitions needed to learn ($d = 0.422$ and $d = 0.367$ for frontal and parietal stimulation respectively) and $z$-values ($d = 0.733$ and $d = 0.767$ for frontal and parietal stimulation respectively) are in the range of those reported in the meta-analysis by Simonsmeier and colleagues (2018; mean effect size of tES on learning: $d = 0.712$; 95% CI: 0.387–1.040). Interestingly, this also holds true for the effects of frontal alpha band tACS on the repetitions needed to learn ($d = 0.545$) and parietal alpha band tACS on $z$-values ($d = 0.559$). Only the effects of parietal alpha band tACS on the repetitions needed to learn ($d = 0.156$) and of frontal alpha band tACS on $z$-values ($d = 0.258$) can be deemed very small to small. Hence, at least for some of these effects, the lack of significance may be due to the rather small group sizes in the present study. The effect sizes suggest that both stimulation methods may have a moderate beneficial effect on arithmetic learning and should, thus, be further scrutinized in future studies with larger samples.

### Stimulation effects on the acquisition and training of a novel procedure

Overall, participants in all groups successfully learned the pound arithmetic operation and were able to improve on its application, as indicated by an overall increase in accuracy and decrease in calculation times. However, as stated above, results showed no significant differences between sham stimulation and the different active stimulation protocols regarding accuracy or calculation time changes. Hence, in contrast to the acquisition of novel facts, the training of the novel
procedure could not be enhanced in a statistically significant manner by the tES methods used.

In earlier studies investigating tES effects on arithmetic learning, who used similar procedural arithmetic problems, different experimental designs and training paradigms were administered (Snowball et al., 2013; Popescu et al., 2016). In both studies, tRNS protocols were applied to support calculation training, and the stimulation led to reduced calculation times in trained problems as well as in new problems, first encountered in a test phase after training. During the training in these prior studies, however, participants repeatedly worked on a small set of problems, whereas in the present study procedural learning problems were never repeated. Hence, in the present study, every procedural problem was a new problem, so that this training might reflect a “purer” procedure training as compared to previous studies. In the previous studies, the repetitions might have led to the acquisition of some fact knowledge or at least familiarity with the procedural problems presented. On the other hand, the procedural learning part in this study might be closer to a performance/test situation than to a learning situation. The administered pound arithmetic problems are, after all, a concatenation of basic arithmetic operations (multiplication, subtraction, and addition). Hence, participants did not need to acquire a completely new procedure. Rather, the application of already known operations in a certain order was required, and without repetitions, this is similar to those paradigms used in performance studies in which participants were asked to solve sets of typical arithmetic problems (e.g. single or double-digit subtractions with borrow; Hauser et al., 2013; Rütsche et al., 2015; Sarkar et al., 2014). Effects of tES have been found to be much smaller in such performance or test situations than in actual learning paradigms (Simonsmeier et al., 2018). Hence, the absence of significant effects of the interventions on procedural learning in the present study could be a result of the procedural learning task itself, that did not allow the acquisition of fact knowledge and that was more akin to a performance test. However, as mentioned, performance improved in the application of the pound arithmetic. Hence, some kind of learning did take place over time, which could have been supported through stimulation. One could however speculate that the range of training-related improvements in the procedural problems were too small to make it possible to detect intervention-related alterations (even in the last block accuracy was at just ~ 73%). Systematic comparisons of the effects of different stimulation intensities and different types of trainings of various durations on training-related performance improvements might be required to conclude about the efficacy of tES on the acquisition of novel arithmetic procedures.

### EEG

The results showed no significant effects of any tES protocol on EEG patterns that have been associated with arithmetic processing, namely theta band ERS, and alpha and beta band ERD (De Smedt et al., 2009; Grabner and De Smedt, 2011, 2012; Tschentscher and Hauk, 2016). This stands in contrast to the observed tES effects on behavioral markers of learning, which can be expected to be reflected in associated ERS/ERD changes. As theta band tACS improved fact learning we would have expected that this stimulation protocol also affects theta band ERS. However, no significant differences in comparison to the sham control group were found. Besides, tACS in general can be assumed to induce frequency-dependent effects on oscillations. In previous studies using tACS, both theta and alpha band stimulations have been found to alter EEG power and oscillatory patterns in their respective frequency bands, with effects lasting for up to 70 min after stimulation (Zaehle et al., 2010; Neuling et al., 2013; Kasten et al., 2016; Pahor and Jaušovec, 2018). Similar performance-independent effects on ERS/ERD patterns also did not emerge in this study.

One reason for the absence of oscillatory correlates of the beneficial theta band tACS effects on fact learning could be the time point of measuring EEG. Participants in all groups had learned the novel arithmetic facts in less than 29 repetitions. Therefore, the ERS/ERD pattern in the last blocks could be similar because participants in the theta band tACS groups only learned faster, but probably not better/different. After the novel facts had been learned, the differences could be negligible and significant stimulation-related effects on ERS/ERD patterns, if any, might only exist in a short period before the switch from procedural calculation to fact retrieval. This happened in the frontal theta band tACS group around the 17th repetition and in the sham group around the 22nd repetition. Hence, the relevant period might have been at the end of the third block (stimulation phase) and shortly after the start of the fourth one (early post-stimulation phase), a time frame the behavioral measures are sensitive to, but the EEG approach used (comparing pre vs. post-stimulation because of the strong tACS induced artifacts in the stimulation phase) is not. A close analysis of this transitional period may be a fruitful approach in forthcoming studies.

It is also interesting that the general changes in ERS/ERD patterns (detailed results are given in the supplementary material) are only partially in line with prior work. In prior work, fact retrieval has been found to be associated with a stronger theta band ERS than procedural calculation, especially over the left hemisphere, while procedural calculation has been associated with stronger alpha and beta band ERD than fact retrieval, especially over posterior regions (De Smedt et al., 2009; Grabner and De Smedt, 2011, 2012; Tschentscher and Hauk, 2016). Furthermore, many studies on arithmetic training found increased theta band ERS and decreased or unchanged alpha band ERD (Grabner and De Smedt, 2012; Soltaniou et al., 2019). While our results regarding theta band ERS are in line with these prior results, our results regarding alpha and beta bands ERD contradict them. Here, fact retrieval trials at the end of the learning session were accompanied by stronger ERD in the upper alpha band over the whole brain and in the beta band over bilateral posterior regions (tables S8-13). This is especially surprising as ERD in these
bands during the processing of difficult procedural calculation problems has been associated with a higher task demand and executive functions (De Smedt et al., 2009; Tschentscher and Hauk, 2016). Hence, in learning a new procedure and novel facts it would be expected that ERD in these bands is largest at the beginning when the procedure is new, and getting smaller towards the end, when the procedure and facts have been trained, with a stronger decrease in fact learning problems than in procedural learning problems.

Taken together, we found that frontal theta band tACS targeting the left DLPFC is the most promising stimulation protocol to foster arithmetic fact learning as it reduced the repetitions needed to learn the novel facts as well as accelerated the decrease in calculation times. This protocol may enhance cognitive control and inhibitory processes, allowing for better integration of novel facts into the associative memory network. If replicable, these results might be of great relevance for the development of tES-supported arithmetic trainings and treatments for developmental dyscalculia, a relatively common and specific learning disorder, with a prevalence of 3–6% (Shalev et al., 2000). Deficits in fact knowledge and problems in the acquisition of novel arithmetic facts are hallmark characteristics of developmental dyscalculia (Butterworth, 2004). In the EEG, fact learning increased theta band ERS, and fact retrieval problems were accompanied by higher theta band ERS values than procedural problems after training. Hence, although no stimulation-related effects were apparent in EEG markers, the results regarding the theta band ERS replicate earlier studies and corroborate the notion that the theta band is associated with fact retrieval processes.

However, there are of course some limitations and other aspects that might be of interest for future studies. As mentioned, the individual groups were rather small, hence, the study might have been underpowered to detect some effects. Furthermore, the arithmetic task was novel, but also artificial. Hence, it allowed an investigation of the acquisition of a novel procedure and novel facts, but it is unclear whether the results can be generalized to real arithmetic operations and knowledge. Furthermore, the stimulation protocols (tDCS and tACS) did not only differ in current, but also in the intensity (constant for tDCS; individually adjusted for tACS) and in electrode configuration. As such, differences between the stimulation protocols cannot be attributed exclusively to the different currents. Future studies might aim to replicate the findings in larger samples and school taught arithmetic tasks. Another important aspect would be to assess executive functions and possible tES effects on these in parallel to an arithmetic training, in order to get a better understanding of the basics of the effects in the present work. Here, it might be assumed that some of the effects which emerged from theta band tACS might be based on improved executive functions, which were however not assessed.

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Michael A. Nitsche is member of the scientific advisory boards of Neuroelectrics and NeuroDevice. The other authors have no conflicts of interest to declare.

DATA AVAILABILITY
Anonymized research data is available at https://osf.io/hvkbw.

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**APPENDIX A. SUPPLEMENTARY DATA**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroscience.2021.10.006.

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