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Transcranial Alternating Current Stimulation Modulates Risky Decision Making in a Frequency Controlled Experiment

tACS risky decision making frequency

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Abstract

In this study, we investigated the effect of transcranial alternating current stimulation on voluntary risky decision making and executive control in humans. Stimulation was delivered online at 5 Hz (theta), 10 Hz (alpha), 20 Hz (beta), and 40 Hz (gamma) on the left and right frontal area while participants performed a modified risky decision making task. This task allowed participants to voluntarily select between risky and certain decisions associated with potential gains or losses, while simultaneously measuring the cognitive control component (voluntary switching) of decision making. The purpose of this experimental design was to test whether voluntary risky decision making and executive control can be modulated with transcranial alternating current stimulation in a frequency-specific manner. Our results revealed a robust effect of 20 Hz stimulation over the left prefrontal area that significantly increased voluntary risky decision making, which may suggest a possible link between risky decision making and reward processing, underlined by beta oscillatory activity.

Significance Statement

This is the first study that demonstrated a frequency-specific effect on risky decision making demonstrated by online 20 Hz tACS applied to left DLPFC. Our results suggest that left frontal 20 Hz tACS specifically modulates risky decision making, perhaps by entraining endogenous beta-activity underlying a frontal-striatal network associated with gain anticipation.

Introduction

Much research has been conducted on the neurobiological mechanisms of risky decision making demonstrating a large neural network comprised of the ventral striatum, amygdala, insula, cingulate, and prefrontal cortices (Kohls et al., 2013; Mohr et al., 2010; Fujiwara et al., 2009; Rao et al., 2008; Kuhnen & Knutson, 2005; Knutson et al., 2001a; Knutson et al., 2001b; O'Doherty et al., 2001). In particular, the prefrontal cortex (PFC) plays an important role in *voluntary* risky decision making. For instance, Rao and colleagues (2008) demonstrated a link between the PFC and voluntary decisions to accept greater risk. They suggested that the PFC mediates the active volitional control or agency of the risk taker by means of an executive control component.

The PFC also plays a prominent role in executive control (see Kim et al., 2012; Rottschy et al., 2012; Swick et al., 2011; Derrfuss et al., 2005; Owen et al., 2005, for fMRI meta-analyses on executive functions), which in turn comprises of three separate, independent components; working memory updating, inhibition, and set shifting/task switching (Diamond, 2013; Miyake et al., 2000). Risky decision making and executive control have been thoroughly investigated. Inspired by Kahneman's dual process theory, that irrational decision making increases when cognitive resources become depleted (Kahneman, 2011; Kahneman & Frederick, 2007; Kahneman, 2003), some have tested the influence of executive control on risky decision making by administering the n-back task, a popular working memory task, in parallel with various risky decision making tasks (e.g. Gathmann et al., 2014a; Gathmann et al., 2014b; Pabst et al., 2013; Farrell et al., 2012; Starcke et al., 2011; Whitney, Rinehart & Hinson, 2008). Likewise, many have examined inhibitory processes and risky decision making by employing the Go No-Go (Welsh et al., 2017; Ba et al., 2016; Yeomans & Brace, 2015; Verdejo-García et al., 2007). However, to date few have examined the link between set-switching and risky decision making (Fröber & Dreisbach, 2016; Verdejo-García et al., 2007); therefore we proposed to investigate this link by using brain stimulation of the PFC.

Theta-related activity (4 – 8 Hz) has been inferred to reflect aspects of risky decision making and executive control. While numerous accounts have associated theta band oscillations with executive control functions (e.g. working memory, set-switching, conflict monitoring, error detection; Cavanagh & Frank, 2014; Ontone et al., 2005; Jensen & Tesche, 2002), a recent EEG study reported fronto-central theta oscillations inferred to reflect an action monitoring system that compares potential outcomes of high and low risk options (Zhang et al., 2014). Furthermore, theta-band transcranial alternating current stimulation (tACS) applied on the left PFC was demonstrated to increase risky decision making (Sela et al., 2012). This stimulation technique allegedly entrains ongoing electrophysiological oscillatory activity (Veniero et al., 2015; Vosskuhl et al., 2015; Helfrich et al., 2014a; Thut et al., 2011), suggesting that theta tACS entrains frontal-central theta oscillations. However, a disadvantage to this study is that frequency specificity could not be assessed since the authors did not control for other stimulation frequencies. In other words, the increase in risky decision making may have been driven by the stimulation alone and not necessarily by theta stimulation (for further details see, Feurra et al., 2012).

For this study, we tested whether voluntary risky decision making under varied levels of executive control can be modulated by applying online tACS at various frequencies (sham, 5, 10, 20, 40 Hz) to the left and right frontal hemispheres. To isolate these components of decision making, we adopted and modified a task-switching paradigm that allows participants to choose between risky and safe (certain) decisions depending on the decision to switch or repeat between task-sets (Fröber & Dreisbach, 2016; Arrington et al., 2014; Orr & Banich, 2014; Poljac & Yeung, 2014; Weaver & Arrington, 2013; Arrington & Logan, 2005; Arrington & Logan, 2004). Although relatively new for cognitive neuroscience (e.g., Orr & Banich, 2014; Poljac & Yeung, 2014), the voluntary task switching paradigm is well-established within the cognitive psychological literature (Fröber & Dreisbach, 2016; Weaver & Arrington, 2013; Arrington et al., 2005; Arrington et al., 2004). However, unlike typical executive tasks in which participants are rated on response time and accuracy (e.g. N back, Go Go-No task, Eriksen Flanker task, Wisconsin Card

Sorting Task), the voluntary task switching paradigm investigates voluntary executive control by considering choice as a dependent variable. By combining the voluntary task-switching paradigm with two-choice financial decision making task between lotteries involving risk, it is possible to measure how much executive control participants are willing to exert under the condition of risk. The advantage of this task design was the possibility to measure voluntary executive control and voluntary risky decision making within a single response, thus allowing us to test whether tACS can modulate voluntary risky decision making under varied levels of voluntary executive control. Given that voluntary, but not involuntary, risky decision making yields frontal-ventral striatum activity (Rao et al., 2008), we hypothesize that theta band tACS should modulate voluntary risky decision making under high levels of executive control.

Materials and Methods

Participants

Thirty-four healthy right-handed participants (21 females; mean age 21; age range 18-26 years; SD = 2.54) with normal or corrected to normal vision and with no neurological disorders participated in the study. All participants provided a written consent approved by a local ethics committee in accordance with the Declaration of Helsinki. All participants were screened for psychological/psychiatric disorders and none of them reported use of drugs or alcohol in the days preceding the experiment. Participants were divided into two groups: those who received stimulation on the left frontal area (n = 17; 10 females; mean age 20.52; age range 18-25 years; SD = 2.52) and those who received stimulation on the right frontal area (n = 17; 11 females; mean age 21.17; age range 18-26 years; SD = 2.78).

Stimuli and Procedure

Participants performed a novel neuroeconomic risky decision making task that combines binary lotteries with equal expected value (Selten et al., 1999; Engelmann & Tamir, 2009; Harrison et al., 2013), and the voluntary task-switching paradigm (Arrington & Logan, 2004; Arrington & Logan, 2005) that allows participants to select between risky or certain decisions by switching or repeating task-sets between trials. Each trial began with a centered fixation cross which remained between 500 and 1000 ms followed by the stimuli screen, composed of a randomly selected single digit (1, 2, 3, 4, 6, 7, 8, or 9) centered on the screen until the participant responded. For each trial participants had to select one of the two games: Odd/Even game (participants indicated whether the digit was odd or even) or Higher/Lower game (participants indicated whether the digit was higher or lower than 5) by pressing one of the corresponding buttons (odd, even, high, low). Using a randomized Latin-square blocked design, the instruction varied across blocks as described below.

In the basic version of the task (Figure 1a, "switch = risk" blocks) participants were instructed that if they chose to repeat the same game in successive trials they would make a Certain decision, e.g. they select "odd" button for the digit 3 on trial N-1, and then "even" button for the digit 8 on trial N, repeating the odd/even game. If the participant decided to alternate between game types, participants made a Risky decision, e.g. they select "odd" button for the digit 3 on trial N-1, and then "high" button for the digit 8 on trial N, switching to the higher/lower game. Across half of the blocks these instructions were counterbalanced such that switching between games led to the certain decision and repeating the same game would yield the risky decision. In the Results section these block instructions are referred to as "switch = risk" blocks and "repeat = risk" blocks. In other words, to select a risky decision participants had to switch between games ("switch = risk" blocks), while in the other blocks ("repeat = risk" blocks) participants had to repeat the same game.

[Insert Figure 1 here]

Since gain-framed and loss-framed decisions differentially affect risk preferences (Tversky & Kahneman, 1985), the experiment was also divided into gain and loss blocks. In gain blocks, certain decisions were defined and instructed as “100% probability that you would receive 25 Russian rubles (RUB)”, while risky decisions were defined and instructed as “50% probability that you would receive 50 RUB” (or alternatively 0 RUB). In loss blocks, the certain decision indicated “100% probability that you would lose 25 RUB” while risky decisions indicated “50% probability that you would lose 50 RUB” (alternatively 0 RUB). For each response that determined the game they selected, a feedback screen displayed for 1000 ms indicated the amount of money gained or lost for that particular trial. If response time exceeded 4000 ms or participants responded erroneously, feedback for that particular trial displayed negative feedback (e.g. 0 RUB for gain block, -50 RUB for loss blocks).

Similarly to the voluntary switching task, response buttons were counterbalanced across participants (Arrington & Logan, 2004). Block condition were counterbalanced in random order. Presentation of stimuli and recording of responses were controlled by E-Prime 2.0 software. All text was displayed in black font on a gray scale background and all participants were instructed to use two hands to respond. Due to the difficulty of the task and to avoid learning effects, participants received two rounds of training, which consisted of eight blocks of 10 trials, resulting in 80 trials in total. If accuracy was below 95% additional training sessions were given. This learning phase was reflected in the actual experiment in which accuracy for all participants throughout the task was above 92%. After training, participants received 20 blocks of 20 trials each. At the end of the experiment participants were shown the total cumulative feedback on the computer screen. Participants received 500 RUB for participation (500 RUB ≈ 7 USD) and an additional bonus, between -300 and + 300 RUB, based on the feedback outcomes of six randomly selected trials to maintain an equal motivation for risky decision making across blocks (see Krajbich et al., 2012).

tACS Procedure

By using the international electroencephalography 10-20 system, tACS was applied on the left or right frontal areas by placing a 7 × 5 cm saline-soaked electrode on F3 or F4 locations (Figure 1b). For both location sites, a reference electrode was placed on the ipsilateral deltoid to the target electrode (see Bai et al., 2014; Im et al., 2012). The order of stimuli was randomized across 20 blocks. Standard protocols were employed as in previous frequency-controlled tACS experiments on motor and cognitive tasks (sham, 5, 10, 20, and 40 Hz; Santarnecchi et al., 2013, 2016; Feurra et al., 2011, 2016), accounting for mean centre frequencies (see Klimesch, 2012). Furthermore, tACS set at a fixed frequency has been shown to entrain individualized alpha oscillations converging to 10 Hz stimulation (Helfrich et al., 2014a). Therefore, we contend that these frequency stimulations suffice to entrain endogenous neural oscillations within standard theta, alpha, beta and gamma ranges, irrespective of individual frequency ranges.

Stimulation was delivered online during task performance, with exception to sham stimulation which lasted for 30 seconds. In order to implement a sham stimulation, instead of using a fixed frequency that may bias a single stimulation protocol over another, we applied sinusoidal low-frequency transcranial random noise stimulation (tRNS) between 0.1-100 Hz for 30 seconds. This sham stimulation protocol was necessary in the current experiment due to the unconventional use of multiple stimulation protocols reflecting the harmonics of mean centre frequencies (see Klimesch, 2012). Furthermore, it is important to emphasize that low-frequency tRNS was applied only for a short duration, compared to all other protocols that were applied throughout the entire block; sham stimulation was delivered for 30 seconds with 10 second fade-in/fade-out, while all other stimulation protocols lasted between 5-10 minutes. Moreover, low-frequency tRNS has been shown not to affect cortical excitability (Paulus, 2011). Stimulation current was set at 1 mA (500 mA peak-to-peak). The maximum current density at the stimulation electrode was ~ 14 μA/cm2. The waveform of the stimulation was sinusoidal, and there was no direct current offset. The low intensity of stimulation was used to avoid a perception of flickering lights (Paulus, 2010). Stimulation was delivered using a battery-operated stimulator system (BrainStim, EMS Medical, Bologna, Italy). Impedance was kept below 10 kΩ. All protocols began one minute prior to each block. Due to abundant evidence that tACS affects physiological activity during stimulation (Strüber et al., 2015; Helfrich et al., 2014a; Helfrich et al., 2014b; Antal et al., 2008), breaks of 5 minutes were given after each set of four blocks. In total, stimulation lasted approximately 40 minutes.

Statistical Analysis

Analysis was performed using R software (R Core Team, 2016) with the software package lme4 (Bates et al., 2014) and lmertest (Kuznetsova et al., 2016). Two separate logistic regression mixed models (Generalized Linear Mixed Model) on the raw data were performed on the following variables: 1) selection of risky decisions and 2) selection of switches between trials. Each model included the following categorical predictors: Valence (gain, loss blocks), Switch Condition ("switch = risk" blocks and "repeat = risk"), Frequency of stimulation (sham, 5, 10, 20, and 40 Hz) with sham as a reference variable, and Hemisphere of stimulation (left, right). Prior to analysis error trials and trials exceeding response time of four seconds were omitted. Wald tests (Kuznetsova et al., 2016) were performed on all levels up to 2 interactions. To account for possible group differences, sham stimulation was used as a reference variable for each effect associated with frequency. In the logistic regression model participants, Valence, Switch condition and Frequency of stimulation were modeled with random effects, while Hemisphere of stimulation (a between-subjects factor) was modeled with fixed effects. The R command lme4 function is as follows: glmer(Risk ~ (Frequency + Valence + Hemi) ^ 2 + (1 + Frequency + Condition + Valence:Condition | Subject), family = "binomial", data = D, control = glmerControl(optimizer="bobyqa", optCtrl=list(maxfun=2e5))). Significance for the regression coefficients was corrected for false positives by using Holm-Bonferroni procedure.

For the following analyses we used SPSS software version 20 (IBM Corp). A mixed ANOVA was performed on the mean response time of the following variables: valence (gain, loss blocks), frequency of stimulation (sham, 5, 10, 20, and 40 Hz), switch condition ("switch = risk" blocks and "repeat = risk" blocks), and hemisphere of stimulation (left and right stimulated group), in which switch condition, valence, and frequency of stimulation were within-participants factors and hemisphere of stimulation was treated as between participants factor. Sphericity was not violated across any of these effects (all $p > 0.05$). To assess whether participants selected more risky decisions than chance level, a one sample t-test was performed.

Results

Figure 2 displays the percentage of risky decisions in all stimulation conditions. The logistic regression mixed model for risky decision making revealed an increase in risky decision making during 20 Hz stimulation particularly when stimulating the left prefrontal cortex ($\beta = 0.989$; $p = 0.00194$; $p' = 0.043$). The effects of other tACS frequencies on risky decision making did not survive Holm-Bonferroni correction for multiple comparisons (see Table 1a for further details). The frequency- and hemisphere-specific effect of 20 Hz stimulation was confirmed by a non-significant main effect of Hemisphere of stimulation ($\beta = 0.072$, $p = 0.885$; $p' > 0.999$). Figure 2 displays means and standard error for each of the comparisons with regards to the Frequency of stimulation x Hemisphere of stimulation interaction effect.

In addition, separate logistic regression models were performed using sham as a reference for each stimulation group (Table 2a and 2b). The model for the left stimulated group (Table 2a) revealed a statistical significant increase in risky decision making from 20 Hz stimulation ($\beta = 0.610$, $p = 0.001$; $p' > 0.021$). Follow-up analysis using 20 Hz as a reference (Table 3) revealed that 20 Hz stimulation applied to the left hemisphere increased risky decision making with respect to Sham ($\beta = -0.989$, $p = 0.001$; $p' > 0.021$) and 40 Hz stimulation ($\beta = -1.265$, $p < 0.001$; $p' > 0.015$). When separately testing Hemisphere stimulation groups with 20 Hz as the reference variable, 20 Hz increased risky decision making compared to sham for the left stimulated group ($\beta = -0.610$, $p = 0.001$; $p' > 0.021$; Table 4a). No effects were found for the right stimulated group (Table 4b).

[Insert Figure 2 here]

After Holm-Bonferroni correction, the logistic regression mixed model yielded no significant effects of tACS on voluntary switching, yet revealed a main effect of Switch Condition ($\beta = 2.005$; $p = < 2\text{x}10^{-16}$; $p' < 0.001$), an interaction effect of Switch Condition x Valence ($\beta = -0.311$; $p = 4.47\text{x}10^{-5}$; $p' = 0.001$), and an interaction effect of Switch Condition x Hemisphere of stimulation ($\beta = 0.908$; $p = < 2\text{x}10^{-16}$; $p' < 0.001$). These effects indicate an increase in voluntary switching in the “switch = risk” blocks compared to “repeat = risk” blocks, especially for loss blocks; perhaps reflecting an influence of executive control on the framing bias. The interaction effect of Switch Condition and Hemisphere may demonstrate an increase in voluntary switching during “switch = risk” blocks compared to “repeat = risk” blocks from the left stimulated group, yet should be interpreted with caution since Hemisphere of stimulation was modeled with fixed effects (see Discussion for details). Analysis of response times revealed that participants responded more slowly in trials in which switching between tasks led to risk ($\mu = 1112.43$ ms) compared to trials in which repeating led to risk ($\mu = 988.98$ ms; $F_{1,32} = 17.455$; $p < 0.001$, partial $\eta^2 = 0.353$). Since participants overall were more likely to select risky decisions ($\mu = 63.6\%$; SE = 0.004; one sample t-test: $t = 33.037$; $p < 0.001$), we infer that this observed difference in response time is likely due to switching costs (for a detailed account on the voluntary switch cost see, Arrington et al., 2014).

In addition, the mixed ANOVA on response time revealed a main effect of Valence ($F_{1,32} = 25.842$; $p < 0.001$, partial $\eta^2 = 0.447$), showing slower mean response times in loss blocks ($\mu = 1085.96$ ms) compared to gain blocks ($\mu = 1015.44$ ms). This significant difference may indicate increased deliberation in loss blocks. No other effects on reaction times were significant. See Figure 3; Table 5 for list of response times for each condition.

Discussion

In the attempt to modulate oscillatory activity underling voluntary risky decision making and executive control we applied tACS (sham, 5, 10, 20, 40 Hz) to the left and right PFC while participants performed a modified risky decision making task that requires choosing between risky and certain decisions by switching or repeating task-sets. The analyses of risky decision making revealed several significant effects, yet the influence of 20 Hz stimulation on risky decision making was the most robust, surviving Holm-Bonferoni correction. Although frequency specificity has been demonstrated with 20 Hz tACS for motor (Pogosyan et al., 2009; Feurra et al., 2011, Joundi et al., 2012) and sensory functions (Kanai et al., 2008; Kanai et al., 2010; Turi et al., 2013), the current experiment is the first to reveal a frequency-specific increase in voluntary risky decision making from 20 Hz tACS.

Within recent years, EEG studies investigating oscillatory activity in gambling tasks have demonstrated a correspondence between frontal beta oscillations (20-35 Hz) and anticipation of probable rewards (Bunzeck et al., 2011), as well as receiving unexpected rewarded feedback (Marco-Pallares et al., 2008; HajiHosseini et al., 2012; HajiHosseini et al., 2014; Mas-Herrero et al., 2015). Marco-Pallerés et al. (2015) proposed that frontal beta oscillatory activity during gambling paradigms might signify the functional coupling between cortical and subcortical regions such as the ventral striatum, known to be involved in reward processing. This was recently confirmed in an EEG-fMRI study that reported correspondence between mid-frontal beta oscillatory activity and engagement of the fronto–striatal–hippocampal network (Mas-Herrero et al., 2015). This may indicate that 20 Hz stimulation increased motivation to select risky decisions by indirectly affecting brain regions of the reward system, such as the ventral striatum. Importantly, the ventral striatum is a key subcortical region for risky decision making since the activation of this area predicts risky decision making and increases in activation as rewards become more probable (Knutson & Greer; 2008; Niv et al., 2012). Taken together, we speculate that stimulation of the frontal cortex with 20 Hz tACS may have resulted in a boost in reward-related processes involving the ventral striatum, thus resulting to an increase in voluntary risky decision making. Further support for this claim derives from electrical simulations of the left PFC (F3, EEG 10-20 system) with an extra-cephalic electrode placed on the shoulder demonstrating modulation of the PFC and deep medial structures (see Bai et al., 2014).

It is important to underline that although several effects involving Hemisphere of stimulation were statistically significant, these effects should be generalized to the population cautiously since we used a between group design combining random effects (Valence, Switch condition, and Frequency of stimulation) with fixed effects (Hemisphere of stimulation). Importantly, the specific effect of 20 Hz tACS of the left PFC on risky decision making was further confirmed by separate statistical analyses for the left and right side stimulation; see Table 2a and 2b. Another potential caveat to the study is that potential after-effects of tACS cannot be ruled out as no simultaneous EEG recording took place. Despite the growing evidence that tACS effects neural oscillatory activity online (Strüber et al., 2015; Helfrich et al., 2014a; Helfrich et al., 2014b; Antal et al., 2008), it was not possible to control within the current experiment.

The results of the current study seem contradictory to a previous study using tACS on risky decision making (Sela et al., 2012). However, the effect of theta band tACS in the previous study (Sela et al., 2012) could be due to a modulation of feedback-related adjustments (Luft, 2014; Zhang et al., 2014; Cavanagh et al., 2011; Cavanagh et al., 2010) since the previous tACS paper used the Balloon Analog Risk Task which measures risk-taking propensity across a cumulative number of responses, as opposed to measuring risky decision making within a single response, as in the current study. A possible explanation for the alternate results may be due to the differences in montage. For instance, a previous study that modulated executive functions, specifically working memory, stimulated both frontal and parietal areas using an F3 – P3 montage (Polania et al., 2012). We suggest that stimulation of the frontal lobe may modulate either a frontal-striatal network associated with voluntary risky decision making (Rao et al., 2008) or a frontal-parietal network in association with voluntary executive control (Orr & Banich, 2014) depending on the placement of the reference electrode (Bai et al., 2014). Whereas the F3 – EC (extracephalic) montage used in the current study likely modulates frontal and deep medial structures, an F3 - P3 montage likely modulates frontal and parietal structures (Bai et al., 2014). Therefore, modulation of voluntary executive control may require an F3 - P3 montage. Some have reported that the ratio of theta and beta oscillations at resting state can be used to predict risk preferences in individuals (Schutter & van Honk, 2005; Massar et al., 2014). Therefore, it is also plausible that both theta and beta band stimulation may modulate different cognitive components of the decision making process within different states and/or contexts. Alternatively, one may suggest that 20 Hz stimulation could modulate working memory during risky decision making. Some studies suggest that risky decision making is associated with the capacity to maintain and organize information in working memory as an estimation of executive processes (e.g. Brevers et al 2014a; Brevers et al 2014b). Unfortunately our study design did not allow testing of this hypothesis. However, we think that a modulation of working memory should not affect our results since subjects continued to receive training until their performance became above 95%, as specified in the "Stimuli and Procedure" section, thereby eliminating potential confound learning effects and an overload of working memory.

Finally, our findings are consistent with the previous studies demonstrating that laterality (left and right frontal hemisphere) strongly influences the effect of voluntary risky decision making (Knoch et al., 2006; Fecteau et al., 2007a; Fecteau et al., 2007b; Sela et al., 2012; Cheng & Lee, 2016). Together, these previous studies show that exciting the left and/or inhibiting the right PFC increasing risky decision making and vice versa. This suggests that 20 Hz stimulation increases cortical excitability of the left frontal area, presumably by entraining the frontal-striatal network. Together these results offer novel insight into the role of beta oscillatory activity in neural mechanisms of risky decision making.

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Figure Legends

Figure 1a. Rewarded Voluntary Switch Task – a combined risky decision making and task-switching paradigm. In trial N, subjects may select the Certain decision (25 RUB with a probability of 100%) or the risky decision (50 RUB or 0 RUB with a probability of 50%) depending on decision to switch (or non-switch) between task-sets from trial N-1. Figure represents trial in the Reward "Switch = Risk" block. **Figure 1b.** tACS montage. Active electrodes were placed on F3 and F4 electrode, representing left and right frontal area. Placement of the reference electrode was the ipsilateral deltoid for F3 and F4.

Figure 2. Mean percentage of risky decisions for each tACS condition with respect to sham. 20 Hz stimulation of the left frontal area increased selection of voluntary risky decisions. Error bars correspond to standard error of the mean.

Figure 3. Mean response times for each Hemisphere group across Frequency Stimulation.

Table 1a. Results of the logistic regression for risky decision making. **Table 1b**. Results of the logistic regression for voluntary switching. Each frequency is referenced to sham and for hemisphere, left stimulated group (L) is respect to right frontal stimulated group (R). β = Beta coefficient; SE = Standard error of mean; z-value based on Wald test; p' indicates adjusted p-values by Holm-Bonferroni correction; bold text signifies significant p-values.

Table 2. Logistic regression model of risky decision making for each group (**2a** = left stimulated group; **2b** = right stimulated group) with **sham** as a reference variable. Results display beta coefficients (β) with standard error, z-score, original p-value, and corrected p-value (p') for the following predictors: Frequency (5 Hz, 10 Hz, 20 Hz, 40 Hz and sham), Switch condition (trials in which switch = risk minus trials in which repeat = risk), and Valence (gain minus loss trials). All predictors were modelled with random effects.

Table 3. Logistic regression model of risky decision making with **20 Hz** as a reference variable. Results display beta coefficients (β) with standard error, z-score, original p-value, and corrected p-value (p') for the following predictors: Frequency (5 Hz, 10 Hz, 20 Hz, 40 Hz and sham), Switch condition (trials in which switch = risk minus trials in which repeat = risk), Valence (gain minus loss trials) and Hemisphere of stimulation (left group minus right group). Frequency, Switch condition, and Valence were modelled as random effects; Hemisphere of stimulation was modelled with fixed effects due to a between-subjects factor.

Table 4. Logistic regression model of risky decision making for each group (**4a** = left stimulated group; **4b** = right stimulated group) with **20 Hz** as a reference variable. Results display beta coefficients (β) with standard error, z-score, original p-value, and corrected p-value (p') for the following predictors: Frequency (5 Hz, 10 Hz, 20 Hz, 40 Hz and sham), Switch condition (trials in which switch = risk minus trials in which repeat = risk), and Valence (gain minus loss trials). All predictors were modelled with random effects.

Table 5. Mean response times associated with each Hemisphere group across Frequency Stimulation.

Table 1a. Logistic regression model of risky decision making (sham as reference variable)

	β	SE	z-value	p-value	p’
5 Hz (sham)	0.248	0.213	1.163	0.244	> 0.99
10 Hz (sham)	0.172	0.287	0.600	0.548	> 0.99
20 Hz (sham)	0.624	0.251	2.486	0.012	0.265
40 Hz (sham)	-0.204	0.283	-0.720	0.471	> 0.99
Switch Cond	-0.496	0.234	-2.118	0.034	0.581
Hemisphere (L-R) [a]	0.072	0.501	-0.144	0.885	> 0.99
Valence (Gain-Loss)	0.693	0.476	1.455	0.145	> 0.99
5 Hz * (Gain-Loss)	-0.156	0.132	-1.183	0.236	> 0.99
10 Hz * (Gain-Loss)	-0.305	0.133	-2.284	0.022	0.425
20 Hz * (Gain-Loss)	-0.166	0.133	-1.247	0.212	> 0.99
40 Hz * (Gain-Loss)	-0.233	0.131	-1.768	0.076	> 0.99
5 Hz * Switch Cond	-0.125	0.132	-0.945	0.344	> 0.99
10 Hz * Switch Cond	0.076	0.133	0.573	0.566	> 0.99
20 Hz * Switch Cond	0.003	0.133	0.026	0.979	> 0.99
40 Hz * Switch Cond	-0.026	0.131	-0.205	0.837	> 0.99
5 Hz * (L-R) [a]	0.202	0.270	-0.747	0.455	> 0.99
10 Hz * (L-R) [a]	0.418	0.384	-1.091	0.275	> 0.99
20 Hz * (L-R) [a]	**0.989**	**0.319**	**-3.099**	**0.001**	**0.043**
40 Hz * (L-R) [a]	-0.276	0.380	0.726	0.467	> 0.99
Switch Cond * (Gain-Loss)	-0.385	0.154	-2.494	0.012	0.265
Switch Cond * (L-R) [a]	-0.284	0.305	0.931	0.351	> 0.99
(Gain-Loss) * (L-R) [a]	1.442	0.657	-2.195	0.028	0.507

Table 1b. Logistic regression model of voluntary switching (sham as reference variable)

	β	SE	z-value	p-value	p’
5 Hz (sham)	-0.196	0.170	-1.153	0.249	> 0.99
10 Hz (sham)	-0.034	0.148	-0.232	0.816	> 0.99
20 Hz (sham)	-0.054	0.138	-0.394	0.693	> 0.99
40 Hz (sham)	-0.225	0.162	-1.394	0.163	> 0.99
Switch Cond	**2.005**	**0.103**	**19.361**	**$< 2x10^{-16}$**	**< 0.001**
Hemisphere (L-R) [a]	-0.402	0.198	2.031	0.042	0.714
Valence (Gain-Loss)	-0.110	0.103	-1.068	0.285	> 0.99
5 Hz * (Gain-Loss)	0.027	0.121	0.229	0.818	> 0.99
10 Hz * (Gain-Loss)	0.258	0.119	2.163	0.030	0.540
20 Hz * (Gain-Loss)	0.058	0.120	0.486	0.626	> 0.99
40 Hz * (Gain-Loss)	0.215	0.120	1.790	0.073	> 0.99
5 Hz * Switch Cond	0.083	0.123	0.676	0.499	> 0.99
10 Hz * Switch Cond	-0.174	0.120	-1.450	0.147	> 0.99
20 Hz * Switch Cond	0.113	0.122	0.930	0.352	> 0.99
40 Hz * Switch Cond	-0.126	0.122	-1.032	0.302	> 0.99
5 Hz * (L-R) [a]	-0.185	0.202	0.915	0.360	> 0.99
10 Hz * (L-R) [a]	-0.153	0.166	0.919	0.358	> 0.99
20 Hz * (L-R) [a]	-0.027	0.147	0.190	0.849	> 0.99
40 Hz * (L-R) [a]	-0.353	0.187	1.884	0.059	0.944
Switch Cond * (Gain-Loss)	**-0.311**	**0.076**	**-4.082**	**$4.47x10^{-5}$**	**0.001**
Switch Cond * (L-R) [a]	**0.908**	**0.076**	**-11.799**	**$< 2x10^{-16}$**	**< 0.001**
(Gain-Loss) * (L-R) [a]	-0.215	0.076	-2.822	0.004	0.076

Note: β = Beta coefficient represent standardized effect sizes; SE = Standard error of the mean; z-value based on Wald test; p’ = corrected p value; L = left hemisphere; R = right hemisphere; Switch Cond: “switch=risk” blocks - “repeat=risk” blocks; sham as reference variable for Frequency of stimulation; [a] = includes predictor modelled as fixed effects; Bold font indicates significance after Holm-Bonferonni correction

Table 2a. Logistic regression model of risky decision making for Left Hemisphere group
(sham as reference variable)

	β	SE	z-value	p-value	p'
5 Hz (sham)	0.160	0.241	0.661	0.508	> 0.99
10 Hz (sham)	0.309	0.283	1.091	0.275	> 0.99
20 Hz (sham)	**0.610**	**0.239**	**2.545**	**0.001**	**0.021**
40 Hz (sham)	-0.065	0.299	-0.219	0.826	> 0.99
Switch Cond	-0.361	0.319	-1.131	0.258	> 0.99
Valence (Gain-Loss)	0.672	0.341	1.970	0.048	0.672
5 Hz * (Gain-Loss)	0.119	0.193	0.617	0.537	> 0.99
10 Hz * (Gain-Loss)	-0.373	0.192	-1.937	0.052	0.676
20 Hz * (Gain-Loss)	0.001	0.198	0.006	0.995	> 0.99
40 Hz * (Gain-Loss)	-0.207	0.190	-1.093	0.274	> 0.99
5 Hz * Switch Cond	-0.217	0.193	-1.125	0.260	> 0.99
10 Hz * Switch Cond	-0.373	0.192	-1.937	0.052	0.672
20 Hz * Switch Cond	0.001	0.198	0.006	0.995	> 0.99
40 Hz * Switch Cond	-0.207	0.190	-1.093	0.274	> 0.99
Switch Cond * (Gain-Loss)	-0.476	0.270	-1.758	0.078	0.858

Table 2b. Logistic regression model of risky decision making for Right Hemisphere group
(sham as reference variable)

	β	SE	z-value	p-value	p'
5 Hz (sham)	0.130	0.246	0.529	0.596	> 0.99
10 Hz (sham)	-0.383	0.340	-1.127	0.259	> 0.99
20 Hz (sham)	-0.352	0.326	-1.079	0.280	> 0.99
40 Hz (sham)	-0.114	0.318	-0.359	0.719	> 0.99
Switch Cond	-0.371	0.199	-1.865	0.062	0.868
Valence (Gain-Loss)	-0.844	0.661	-1.277	0.201	> 0.99
5 Hz * (Gain-Loss)	-0.350	0.184	-1.900	0.057	0.855
10 Hz * (Gain-Loss)	-0.268	0.187	-1.437	0.150	> 0.99
20 Hz * (Gain-Loss)	-0.273	0.183	-1.489	0.136	> 0.99
40 Hz * (Gain-Loss)	-0.256	0.186	-1.379	0.167	> 0.99
5 Hz * Switch Cond	-0.040	0.183	-0.223	0.823	> 0.99
10 Hz * Switch Cond	0.231	0.183	1.257	0.208	> 0.99
20 Hz * Switch Cond	0.085	0.180	0.474	0.635	> 0.99
40 Hz * Switch Cond	0.242	0.182	1.327	0.184	> 0.99
Switch Cond * (Gain-Loss)	-0.281	0.209	-1.340	0.180	> 0.99

Note: β = Beta coefficient represent standardized effect sizes; SE = Standard error of the mean; z-value based on Wald test; p' = corrected p value;
L = left hemisphere; R = right hemisphere; Switch Cond: "switch=risk" blocks - "repeat=risk" blocks; Bold font indicates significance after Holm-Bonferonni correction

Table 3. Logistic regression of risky decision making for both groups (20 Hz as reference variable)

	β	SE	z-value	p-value	p’
Sham (20 Hz)	-0.624	0.251	-2.482	0.013	0.216
5 Hz (20 Hz)	-0.375	0.240	-1.565	0.117	> 0.99
10 Hz (20 Hz)	-0.451	0.256	-1.764	0.077	0.975
40 Hz (20 Hz)	-0.828	0.291	-2.844	0.004	0.080
Switch Cond	-0.493	0.236	-2.087	0.036	0.504
Hemisphere (L-R) [a]	1.061	0.423	-2.504	0.012	0.216
Valence (Gain-Loss)	0.526	0.476	1.104	0.269	> 0.99
Sham * (Gain-Loss)	0.166	0.133	1.247	0.212	> 0.99
5 Hz * (Gain-Loss)	0.009	0.134	0.072	0.942	> 0.99
10 Hz * (Gain-Loss)	-0.138	0.134	-1.031	0.302	> 0.99
40 Hz * (Gain-Loss)	-0.066	0.133	-0.499	0.617	> 0.99
Sham * Switch Cond	-0.003	0.133	-0.026	0.979	> 0.99
5 Hz * Switch Cond	-0.128	0.134	-0.959	0.337	> 0.99
10 Hz * Switch Cond	0.073	0.134	0.544	0.586	> 0.99
40 Hz * Switch Cond	-0.030	0.133	-0.228	0.819	> 0.99
Sham * (L-R) [a]	**-0.989**	**0.319**	**3.097**	**0.001**	**0.021**
5 Hz * (L-R) [a]	-0.786	0.304	2.588	0.009	0.171
10 Hz * (L-R) [a]	-0.570	0.321	1.774	0.075	0.975
40 Hz * (L-R) [a]	**-1.265**	**0.374**	**3.380**	**< 0.001**	**0.015**
Switch Cond * (Gain-Loss)	-0.385	0.154	-2.495	0.012	0.216
Switch Cond * (L-R) [a]	-0.284	0.305	0.931	0.351	> 0.99
(Gain-Loss) * (L-R) [a]	1.442	0.656	-2.198	0.027	0.405

Note: β = Beta coefficient represent standardized effect sizes; SE = Standard error of the mean; z-value based on Wald test; p’ = corrected p value; L = left hemisphere; R = right hemisphere; Switch Cond: “switch=risk” blocks - “repeat=risk” blocks; 20 Hz as reference variable for Frequency of stimulation; [a] = includes predictor modelled as fixed effects; Bold font indicates significance after Holm-Bonferonni correction

Table 4a. Logistic regression model of risky decision making for Left Hemisphere group (20 Hz as reference variable)

	β	SE	z-value	p-value	p'
Sham (20 Hz)	**-0.610**	**0.239**	**-2.550**	**0.001**	**0.021**
5 Hz (20 Hz)	-0.450	0.264	-1.703	0.088	0.968
10 Hz (20 Hz)	-0.301	0.355	-0.850	0.395	> 0.99
40 Hz (20 Hz)	-0.676	0.397	-1.701	0.089	0.968
Switch Cond	-0.468	0.325	-1.441	0.149	> 0.99
Valence (Gain-Loss)	0.673	0.346	1.946	0.051	0.714
Sham * (Gain-Loss)	-0.001	0.198	-0.006	0.995	> 0.99
5 Hz * (Gain-Loss)	0.118	0.200	0.590	0.554	> 0.99
10 Hz * (Gain-Loss)	-0.374	0.199	-1.881	0.060	0.780
40 Hz * (Gain-Loss)	-0.209	0.197	-1.060	0.289	> 0.99
Sham * Switch Cond	0.107	0.200	0.536	0.591	> 0.99
5 Hz * Switch Cond	-0.110	0.202	-0.545	0.585	> 0.99
10 Hz * Switch Cond	0.015	0.203	0.077	0.938	> 0.99
40 Hz * Switch Cond	-0.202	0.200	-1.014	0.310	> 0.99
Switch Cond * (Gain-Loss)	-0.476	0.270	-1.759	0.078	0.936

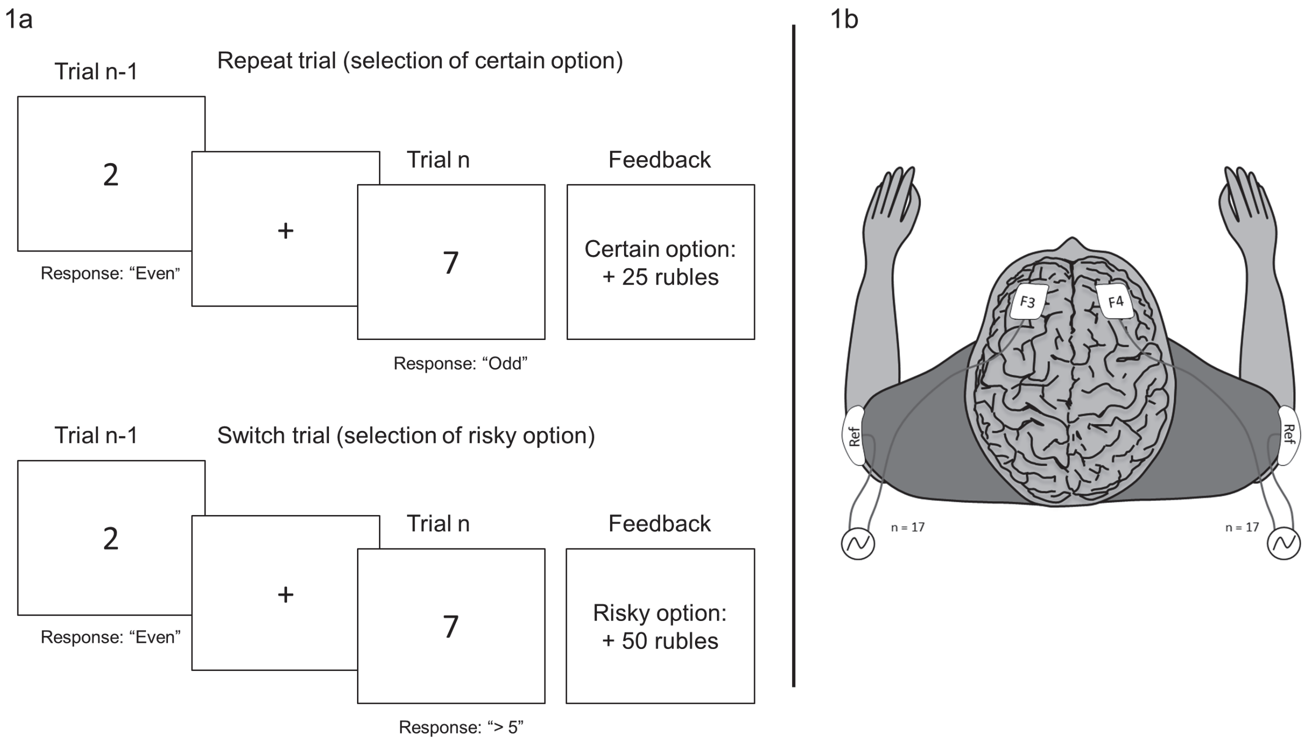
Table 4b. Logistic regression model of risky decision making for Right Hemisphere group (20 Hz as reference variable)

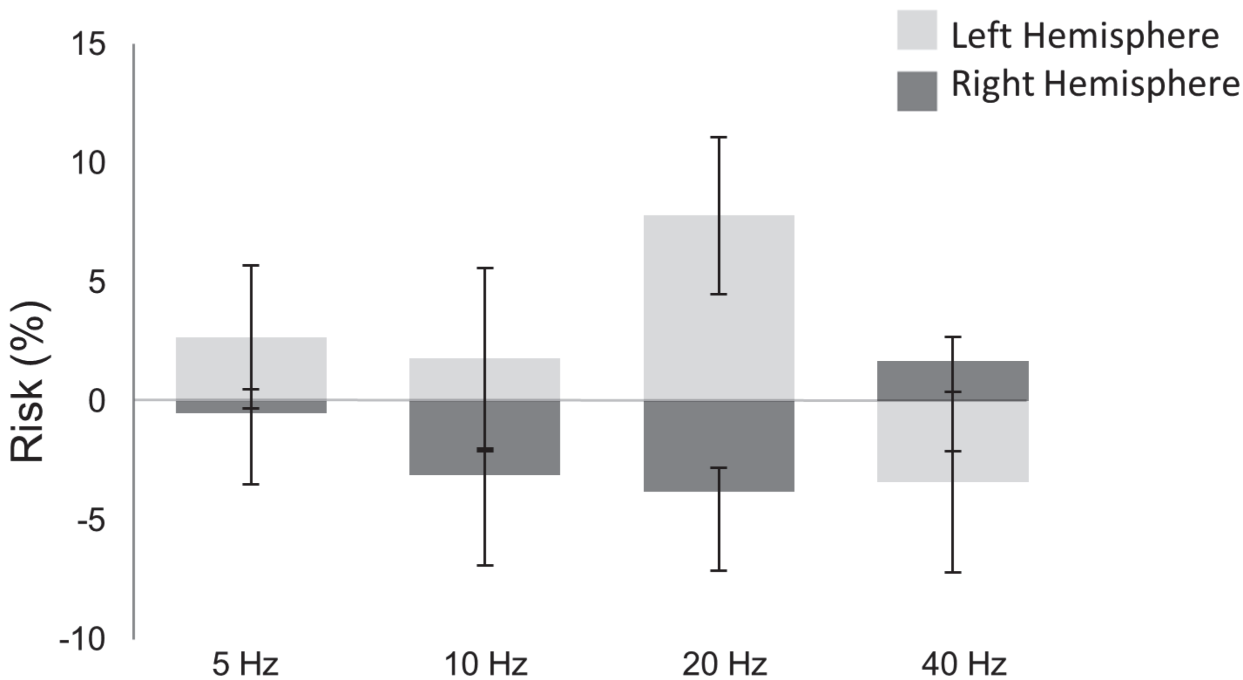
	β	SE	z-value	p-value	p'
Sham (20 Hz)	0.352	0.326	1.079	0.280	> 0.99
5 Hz (20 Hz)	0.483	0.276	1.747	0.080	> 0.99
10 Hz (20 Hz)	-0.031	0.201	-0.155	0.876	> 0.99
40 Hz (20 Hz)	0.237	0.223	1.066	0.286	> 0.99
Switch Cond	-0.286	0.193	-1.475	0.140	> 0.99
Valence (Gain-Loss)	-1.117	0.662	-1.688	0.091	> 0.99
Sham * (Gain-Loss)	0.273	0.183	1.490	0.136	> 0.99
5 Hz * (Gain-Loss)	-0.076	0.183	-0.419	0.675	> 0.99
10 Hz * (Gain-Loss)	0.004	0.184	0.027	0.978	> 0.99
40 Hz * (Gain-Loss)	0.016	0.184	0.091	0.927	> 0.99
Sham * Switch Cond	-0.085	0.179	-0.474	0.635	> 0.99
5 Hz * Switch Cond	-0.126	0.180	-0.698	0.485	> 0.99
10 Hz * Switch Cond	0.145	0.180	0.809	0.418	> 0.99
40 Hz * Switch Cond	0.157	0.179	0.875	0.381	> 0.99
Switch Cond * (Gain-Loss)	-0.281	0.209	-1.340	0.180	> 0.99

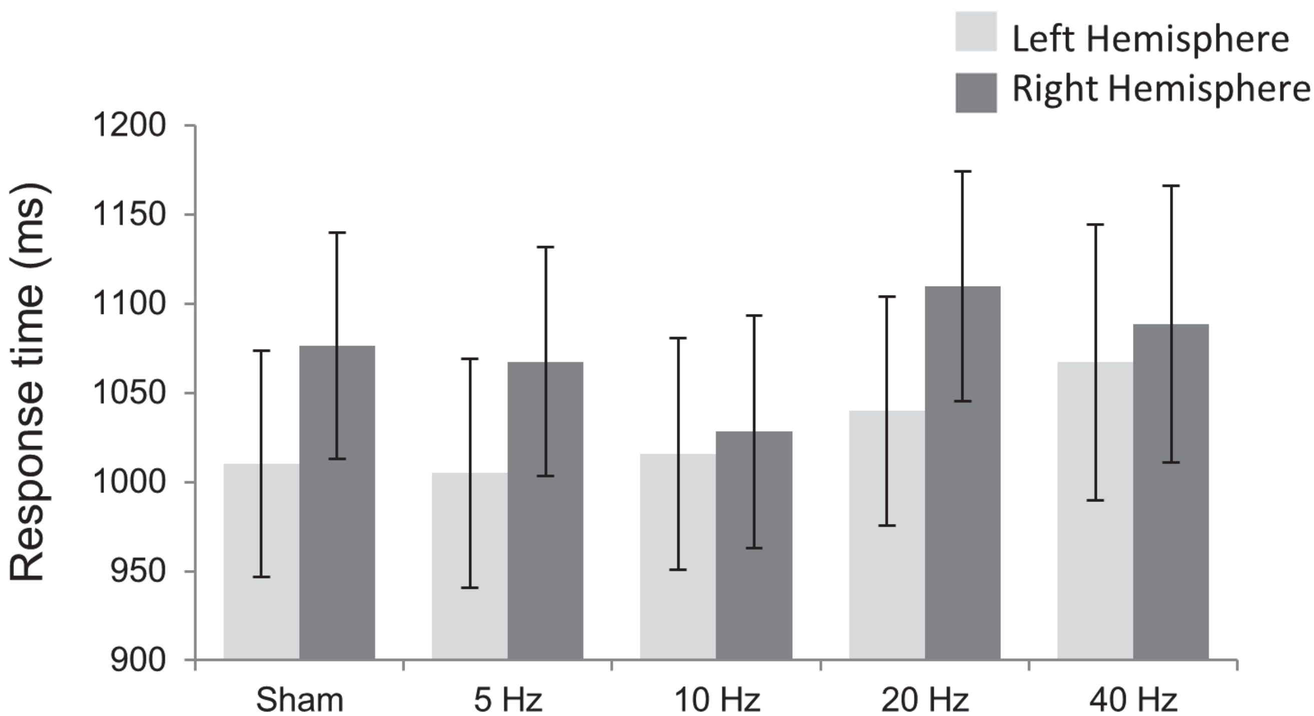
Note: β = Beta coefficient represent standardized effect sizes; SE = Standard error of the mean; z-value based on Wald test; p' = corrected p value;
L = left hemisphere; R = right hemisphere; Switch Cond: "switch=risk" blocks - "repeat=risk" blocks; 20 Hz as reference variable for Frequency of stimulation; Bold font indicates significance after Holm-Bonferonni correction

Table 5. Mean response times associated with Hemisphere and Frequency Stimulation

Hemisphere	Frequency	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Right	Sham	1009.92	63.41	880.75	1139.09
	5 Hz	1004.91	64.29	873.96	1135.86
	10 Hz	1015.71	65.06	883.19	1148.23
	20 Hz	1039.81	64.26	908.91	1170.71
	40 Hz	1067.01	77.55	909.05	1224.98
Left	Sham	1076.12	63.41	946.95	1205.29
	5 Hz	1067.47	64.29	936.52	1198.42
	10 Hz	1028.15	65.06	895.63	1160.66
	20 Hz	1109.68	64.26	978.79	1240.58
	40 Hz	1088.27	77.55	930.30	1246.23


1a
Trial n-1
Repeat trial (selection of certain option)
2
Response: "Even"
+
Trial n
7
Response: "Odd"
Feedback
Certain option:
+ 25 rubles
Trial n-1
Switch trial (selection of risky option)
2
Response: "Even"
+
Trial n
7
Response: "> 5"
Feedback
Risky option:
+ 50 rubles
1b
F3
F4
Ref
Ref
n = 17
n = 17


Left Hemisphere
Right Hemisphere
15
10
5
0
-5
-10
Risk (%)
5 Hz
10 Hz
20 Hz
40 Hz


Left Hemisphere
Right Hemisphere
Response time (ms)
1200
1150
1100
1050
1000
950
900
Sham
5 Hz
10 Hz
20 Hz
40 Hz