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Modulating risk-taking behavior with theta-band tACS

Aline M. Dantas [a,b,c,*], Alexander T. Sack [a,b,c], Elisabeth Bruggen [d,e,f], Peiran Jiao [g], Teresa Schuhmann [a,b]

[a] Section Brain Stimulation and Cognition, Department of Cognitive Neuroscience, Faculty of Psychology and Neuroscience, Maastricht University. Oxfordlaan 55, 6229 EV, Maastricht, the Netherlands
[b] Maastricht Brain Imaging Center, Maastricht University. Oxfordlaan 55, 6229 EV, Maastricht, the Netherlands
[c] Department of Psychiatry and Neuropsychology, School for Mental Health, and Neuroscience (MHeNs), Brain+Nerve Center, Maastricht University Medical Center+ (MUMC+). P. Debyelaan 25, 6229 HX, Maastricht, the Netherlands
[d] Department of Marketing and Supply Chain Management, School of Business and Economics, Maastricht University. P.O. Box 616, 6200 MD, Maastricht, the Netherlands
[e] BISS – Brightlands Institute for Smart Society, Maastricht University, Heerlen, the Netherlands
[f] Netspar – Network for Studies on Pension, Aging and Retirement
[g] Department of Finance, School of Business and Economics, Maastricht University. P.O. Box 616, 6200 MD, Maastricht, the Netherlands

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ABSTRACT

Although risk is prevalent in decision-making, the specific neural processes underlying risk-taking behavior remain unclear. Previous studies have suggested that frontal theta-band activity plays a crucial role in modulating risk-taking behavior. The functional relevance of theta in risk-taking behavior is yet to be clearly established and studies using noninvasive brain stimulation have yielded inconsistent findings. We aimed to investigate this relevance using transcranial alternating current stimulation (tACS) over right or left dorsolateral prefrontal cortex (DLPFC). We also studied the influence of stimulation intensity on risk-taking behavior and electrophysiological effects.

We applied theta-band (6.5 Hz) tACS over the left (F3) and right (F4) DLPFC with lower (1.5 mA) and higher (3 mA) tACS intensities. We employed a single-blinded, sham-controlled, within-subject design and combined tACS with electroencephalography (EEG) measurements and the Maastricht Gambling Task (MGT) to elicit and evaluate risk-taking behavior.

Our results show an increase in risk-taking behavior after left DLPFC stimulation at both intensities and a reduction of risk-taking behavior after 3 mA (and not 1.5 mA) right DLPFC stimulation compared to sham. Further analyses showed a negative correlation between resting-state frontal theta-power and risk-taking behavior. Overall, frontal theta-power was increased after left, but not right, theta-band tACS independent of stimulation intensity.

Our findings confirm the functional relevance of frontal theta-band activity in decision-making under risk and the differential role of left and right DLPFC. We also were able to show that stimulation intensity did have an effect on behavioral responses, namely risk-taking behavior. Significant right hemisphere stimulation effects were observed only after high-intensity stimulation. Nevertheless, electrophysiological effects were only significant after left DLPFC stimulation, regardless of tACS intensity. Furthermore, the results indicate the role of the baseline frontal theta-power in the direction of behavioral effects after theta-band tACS.

1. Introduction

Risk is a constant feature of life. In economics, risk refers to a situation in which one is unsure about which outcome will happen; however, the probability distribution of these outcomes can be determined (Drichoutis and Lusk, 2016). In contrast, ambiguity refers to situation in which outcome probabilities are unknown (Fairley and Sanfey, 2020).

Examples of risky decisions are numerous; they include trivial choices, such as taking an umbrella based on the probability of rain displayed on a weather app, and highly impactful decisions, such as

* Corresponding author.
E-mail address: a.dantas@maastrichtuniversity.nl (A.M. Dantas).

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choosing an optimal portfolio of financial assets based on calculated risk and return characteristics, or choosing a floor insurance coverage for one's house based on the probability of flood and expected loss in the area. Since risk plays such a crucial role in our lives, it is important to understand the neural processes underlying decision-making concerning risks. Evidence from electroencephalography (EEG) studies indicates that frontal theta-band activity is an important component of those neural processes.

Frontal theta-band activity is correlated to processes such as cognitive control (Cavanagh and Frank, 2014a; Klírová et al., 2021; McFerren et al., 2021; Womelsdorf et al., 2010), response inhibition (Dippel et al., 2017, 2016), reward anticipation (Koul et al., 2019; Wischnewski et al., 2016) and conflict detection (Cohen and Donner, 2013), which are fundamental processes in risk-taking behavior. Moreover, frontal theta-band activity is an important component of the electrophysiological mechanism through which the dorsolateral prefrontal cortex (DLPFC) and medial prefrontal cortex (MPFC) communicate with each other (Başar et al., 2001; Cavanagh and Frank, 2014b)—two areas crucial for human decision-making and, specifically, decision-making under risk (Dantas et al., 2021a; Koul et al., 2019; Schmidt et al., 2019, 2018; Sela et al., 2012; Zhang and Gu, 2018).

One approach used to investigate the role of frontal theta-band activity in individual economic risk-taking behavior is to focus on the correlation between resting-state frontal theta-power and risk-taking behavior (Gianotti et al., 2009; Massar et al., 2014, 2012; Pinner and Cavanagh, 2017; Schmidt et al., 2018). Examples include Massar et al. (2012 and 2014) and Gianotti et al. (2009). The former found that the higher the resting-state frontal theta-power (measured in the frontal midline in FZ, FCz, and CZ), the more risk-prone participants were (Massar et al., 2014, 2012). On the other hand, the latter found that it was not the midline theta-power but the frontal theta-band asymmetry in resting-state (measured as the difference between right and left prefrontal theta-power) that was correlated to increased risk-taking behavior (Gianotti et al., 2009).

Another approach used to explore the role of theta-band activity during risk is studying the occurrence of prefrontal theta-band activity during the decision-making process itself (Christie and Tata, 2009; Pinner and Cavanagh, 2017). The results of such studies indicated a negative correlation between midline frontal theta-band activity measured immediately before making a risky choice (Christie and Tata, 2009; Pinner and Cavanagh, 2017). Christie and Tata (2009), however, argue that the midline increase in frontal theta-power observed during exposure to risky choices likely originates in the right anterior cingulate cortex (ACC) (Christie and Tata, 2009), indicating that the two hemispheres are not equally involved in this process.

To determine the functional relationship between frontal theta-power and risk-taking behavior using noninvasive brain stimulation techniques, such as transcranial alternating current stimulation (tACS) (Huang et al., 2005; Reinhart and Nguyen, 2019), is fundamental, as it allows us to experimentally manipulate oscillatory neural activity. tACS inputs an electric stimulus in a predefined frequency and sinusoidal shape over a specific brain area through electrodes placed on the scalp. This is assumed to induce or entrain brain oscillations in the same oscillatory pattern (Antal et al., 2017; Bland and Sale, 2019; Helfrich et al., 2014).

Only a few studies have used tACS to investigate the functional relevance of theta-band power in risk-taking behavior. Sela et al. (2012) had participants perform the balloon analog risk task (BART) while stimulating either the right or left DLPFC (electrodes F4/CP6 and F3/CP5, respectively) with tACS at 6.5 Hz and 1 mA peak-to-peak intensity (Sela et al., 2012). They hypothesized that tACS applied to the left DLPFC reduces frontal theta-band asymmetry and, consequently, reduces risk-taking behavior, and right DLPFC tACS increases both frontal theta-band asymmetry and risk-taking behavior. Participants exhibited riskier behavior during left but not right or sham theta-band (6.5 Hz) DLPFC tACS, contradicting the authors' initial hypotheses (Sela et al., 2012).

Yaple et al. (2017) explored the effects of tACS in different frequency ranges on risk-taking behavior. Their design included online stimulation at theta (5 Hz), alpha (10 Hz), beta (20 Hz) and gamma-band (40 Hz). In their study, theta band stimulation did not significantly affect risk-taking behavior, with significant behavioral changes observed only during beta frequency tACS (Yaple et al., 2017).

In a recent study by Dantas et al. (2021), participants performed the Maastricht Gambling Task (MGT) while receiving tACS at 1.5 mA intensity at theta-band (6.5 Hz), gamma-band (40 Hz), or sham over the left DLPFC. Stimulation was delivered using a high-definition (HD) tACS setup over F3 [28]. Participants showed less risk-taking behavior after left theta-band tACS, a finding that is in line with the hypothesis that an increase in left theta-band power reduces risk-taking behavior. However, no significant changes in theta or gamma power that outlasted the tACS itself were observed (Dantas et al., 2021a). Since the analysis of data from simultaneous EEG-tACS studies is challenging to analyze, electrophysiological effects of a specific stimulation protocol are best studied after the stimulation ended. However, to be able to do so, effects need to outlast the stimulation. Still, most studies that used both theta and gamma tACS at low intensities did not successfully detect electrophysiological aftereffects (Dantas et al., 2021b; Heise et al., 2019; Reato et al., 2013; Strüber et al., 2015). A recent noteworthy exception is Aktürk et al. (2022), where the aftereffects of theta-band tACS were detected after stimulation at individual theta frequency (Aktürk et al., 2022).

Wischnewski and Compen (2022) also explored the role of theta-band activity in risk-taking behavior. To that end, the group used a modified version of a sequential gambling task while applying tACS at 5 Hz and 1 mA peak-to-peak intensity, targeting the prefrontal cortex bilaterally. The group used Intra- and interhemispheric settings targeting the prefrontal cortex, each using four electrodes (5 × 3 cm). tACS was delivered during task execution, and both behavioral and EEG effects were evaluated. Their results indicated an increased perception of uncertainty but no significant changes in risk-taking behavior. However, their EEG results revealed increased theta-band asymmetry after intrahemispheric tACS and non-significant changes after interhemispheric stimulation (Wischnewski and Compen, 2022a).

These inconsistent results, observed when comparing these studies that indicate behavioral results in opposite directions or null behavioral results, can be due to a methodological choice common in tACS studies: the use of intensities between 1 mA and 1.5 mA (Bland and Sale, 2019). However, recent studies have questioned the effects of low-intensity transcranial electric stimulation (tES) in general, including both transcranial direct current stimulation (tDCS) and tACS (Alekseichuk et al., 2022; Antal et al., 2017; Widge, 2018). Despite a considerable number of studies finding behavioral and electrophysiological effects after electric stimulation, these effects are often inconsistent (Antal et al., 2017; Asamoah et al., 2019; Bland and Sale, 2019). Recent studies have indicated that it is only possible to create a cortical electric field and to obtain consistent effects with the use of higher intensities in electric brain stimulation (Antal et al., 2017; Huang et al., 2017; Widge, 2018). This might explain the inconsistent results observed across studies with similar stimulation settings. Vöröslakos et al. (2018), for example, showed that only intensities higher than 4.5 mA significantly biased cortical alpha frequencies, with reliable electrophysiological effects observed only with intensities above 7 mA (Vöröslakos et al., 2018).

In our study, we used an experimental design that built on previous work to address two main research objectives. The first was to replicate the findings of Dantas et al. (2021) and confirm the functional relationship between frontal theta-band power and risk-taking behavior, given the lack of consistency in the results of previous studies. To this end, we partially replicated the experimental design of Dantas et al. (2021) by examining risk-taking behavior through the MGT in a sham-controlled, within-subject design with theta-band (6.5 Hz) tACS over DLPFC. In doing so, we adopted a design that yielded significant

behavioral effects of theta-band tACS in Dantas et al. (2021), and we used a task known to elicit risk-taking behavior following the economic definition of risk, which means choices that induce greater uncertainty over outcomes.

The second research objective was to clarify the role of theta-power hemispheric asymmetry as an electrophysiological mechanism through which the prefrontal cortex regulates risk-taking behavior. Therefore, unlike Dantas et al. (2021), we stimulated both the right and left DLPFC, aiming to explore the differential effects of right and left theta-band tACS in modulating risk-taking behavior. Finally, to investigate whether higher tACS intensities generate stronger (after) effects, we used two stimulation intensities (1.5 mA and 3 mA) over both stimulation sites (Fig. 1), again adding to the original study of Dantas et al. (2021). This design allowed us to study the potential different effects in terms of behavioral and EEG responses between the different stimulation protocols. In summary, our design includes a 2 (left and right hemisphere stimulation) x 3 (1.5 mA, 3 mA and sham) within subject factorial design with stimulation side and dosage as factors.

2. Materials and methods

2.1. Participants

Based on the effect size observed in Dantas et al. (2021) ($f = -025$), we calculated a minimum sample size using G-Power of 18 participants (within subjects, repeated measures with 12 measurements and 1 group) (Universität Düsseldorf). Yet, to approximate the sample size used in Dantas et al. (2021), we recruited 39 healthy, right-handed participants: 30 participants (15 female, 1 non-binary, mean age 22.3 years, range 18–32 years, SD = 3.2) concluded the experiment. Four participants reported discomfort during the stimulation in the first session and did not take part in the second session. Five participants were excluded from the study because they were unable to attend the second experimental session within the requested interval of 15 days.

The participants had normal or corrected-to-normal vision and gave written informed consent after being introduced to the experiment and were screened for tACS safety (Antal et al., 2017). The study was approved by the Ethics Review Committee Psychology and Neuroscience (ERCPN) of Maastricht University, the Netherlands (ERCPN 188_07_02_2018).

2.2. Procedure

Participants were invited to the lab for two sessions that followed a similar procedure. The only differences between the sessions were the stimulation site, which was counterbalanced (right for session 1, left for session 2, or vice-versa) and the payment of participants' compensation by the end of session 2. During both sessions, upon arrival, participants received a full explanation of the study, filled in a pre-experimental test, and signed an informed consent form. Then, the EEG and tACS setups were prepared.

In each session, participants received three different conditions, in a counterbalanced fashion, with different stimulation protocols, namely stimulation with an intensity of 1.5 mA, 3 mA, and sham stimulation. During stimulation, participants performed the MGT. Each stimulation block was preceded by and ended with a short five-minute interval, during which we recorded three minutes of resting-state activity using EEG. The subsequent blocks followed the same protocol until the three stimulation conditions were completed. Fig. 2 illustrates the detailed timeline of a session.

2.3. The maastricht gambling task (MGT)

As in Dantas et al. (2021), we used MGT to elicit and evaluate risk-taking behavior [41]. The MGT builds on the Cambridge Gambling task but avoids confounds, such as loss aversion, memory, learning, and wealth effects (Dantas et al., 2021a). Loss aversion is avoided since participants never lose points in the task; the worst case is to win zero points if their guess is a miss. Memory and learning effects are controlled for through random-ordered trials, which are repeated twice in different

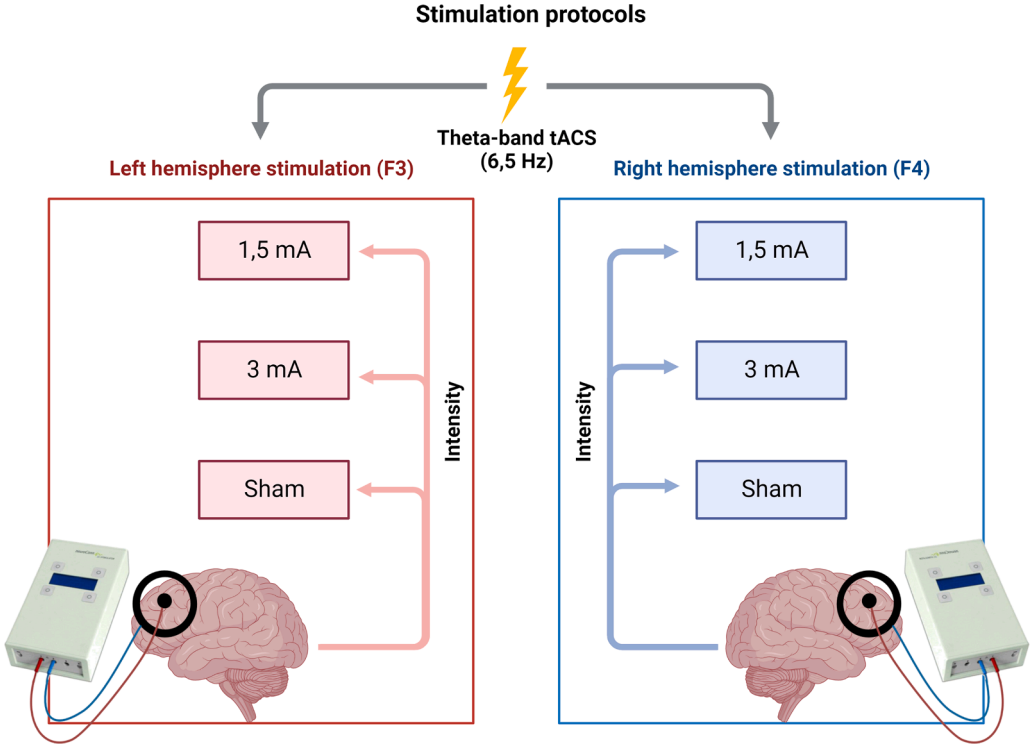

Fig. 1. Stimulation protocols. The left side depicts the protocols (1.5 mA, 3 mA, and sham stimulation) used over the left DLPFC (electrode position F3 of the international 10–20 EEG system); the right side depicts the protocols used over the right DLPFC (electrode position F4 of the international 10–20 EEG system).

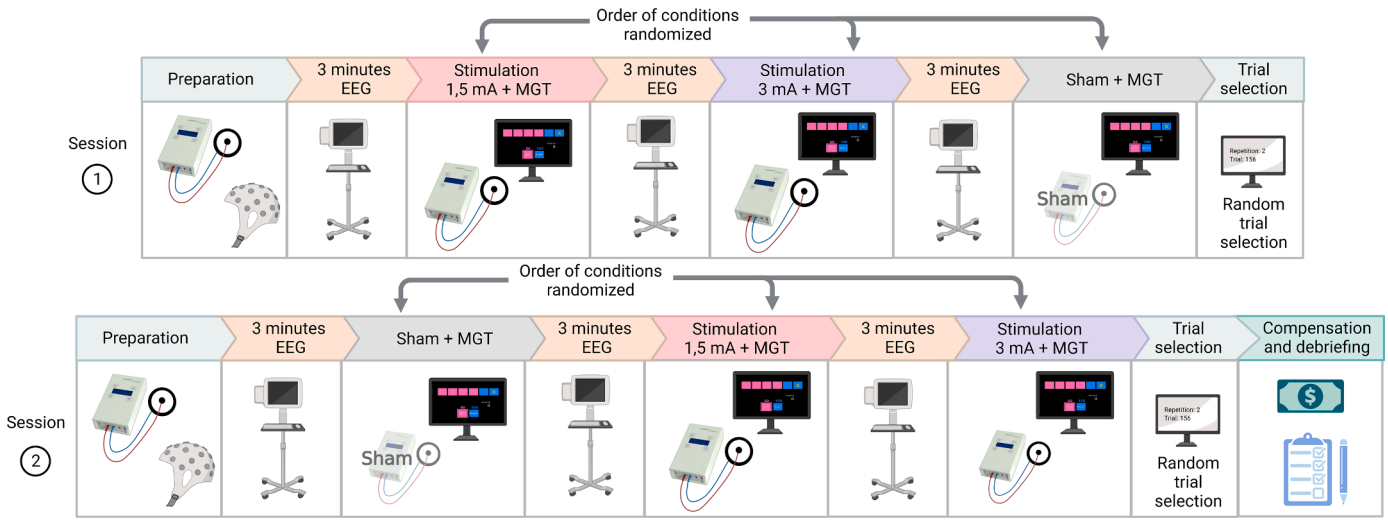

Fig. 2. Experimental design. The figure depicts the experimental design, which includes two sessions. During each session, participants received three different stimulation protocols in randomized order. These protocols could be either theta-band stimulation with (1) 1.5 mA intensity, (2) 3 mA intensity, or sham. The stimulation was either delivered over the right (F4) or left (F3) DLPFC. Stimulation was applied during task execution (online) for approximately 20 min. By the end of session 2, participants were debriefed and compensated accordingly.

order. Finally, wealth effects are avoided since points earned in different trials did not accumulate and participants always start each trial with no points (Dantas et al., 2021a).

In each trial of the task, six boxes were presented, and the distribution ranged from 1/6 pink boxes to 5/6 pink boxes, with the remaining boxes being blue. A token represented by a yellow cross (X) was hidden behind one random box out of the six. Participants had to guess the color of the box (blue or pink) hiding the token. The probability of the token being hidden behind a specific color was calculated by the color distribution of the boxes. One out of five different payoffs was randomly picked for each color as the reward for correct guess (5, 25, 50, 75, and 100 points) if that color ended up hiding the token.

Participants received the corresponding reward if the correct color was guessed and did not receive anything otherwise. The task had 250 trials with a duration of approximately 20 min, in which 125 unique trials with all possible combinations of probabilities and payoffs were presented twice randomly. In each session, participants played the task three times, once during each stimulation condition.

Using this task, it is possible to evaluate different behavioral-dependent variables. The analyses focused on the level of risk taken by participants, which was calculated as the chosen option payoff standard deviation in each trial type (a detailed calculation follows in the statistical analyses section). In addition to the level of risk, we evaluated participants' value, probability scores, and response times. These additional dependent variables are analyzed aiming a deeper comprehension of risk-taking behavior, to help disentangling the factors that might lead to behavioral changes. Here, Value stands for the average payoff chosen by the participant across the two repetitions of a same trial type, independent of the probability associated to those payoffs (see also example on Section 2.7.3). Probability scores are scores from −2 (probability of 1/6) to 2 (probability 5/6) indicating participants' choices of probabilities in each trial independent of the associated payoffs. These scores are again averaged across the two repetitions of each trial type. Response time refers to the time between stimulus presentation and response, again averaged between the two presentations of each trial. Detailed explanations of each variable follow in the statistical analyses, Section 2.7).

2.4. Compensation

One trial was selected at the end of each session for choice-related payoffs. This was implemented in the following way: each participant could freely select one task repetition between 1 and 3 and then use an online random number generator to randomly select a trial. Each point gained in the task was converted to €0.1 in their final payment. Participants were informed about their earnings from each session right after the respective session; all payments were made after the whole experiment was concluded (session 2). After session 2, participants received both a fixed show-up fee (€7.5 or an academic credit named SONA point per hour), and the choice-dependent payoffs from both sessions. Participants were compensated with vouchers that could be spent online or at local retailers; the average compensation was €40 (minimum: €5 (+5 SONA points); maximum: €60).

2.5. Transcranial alternating current stimulation (tACS)

Partly replicating the stimulation protocol used by Dantas et al. (2021), we targeted the left DLPFC (F3, based on the international 10–20 EEG system) and right DLPFC (F4, based on the international 10–20 EEG system) using an HD tACS setup composed of a small circular electrode (diameter: 2.1 cm; thickness: 2 mm) and a large rubber ring tACS electrode (outer diameter: 11 cm; inner diameter: 9 cm; thickness: 2 mm) (neuroConn, Ilmenau, Germany) fixed using conductive gel (Ten20 conductive Neurodiagnostic electrode paste, WEAVER and company, Aurora, CO, USA) and keeping the electrode impedance below 15 kΩ (Dantas et al., 2021c). HD tACS was applied in a single-blinded fashion using a neuroConn DC-stimulator (neuroConn, Ilmenau, Germany) set at 6.5 Hz frequency (theta-range stimulation) and two different intensities: 1.5 mA (as used in Dantas et al., 2021) and 3.0 mA (both peak-to-peak).

The stimulation, which lasted on average for 20 min, was delivered during the task. During sham tACS, the stimulation was ramped up for 30 s and ramped down immediately after. Breaks of around five minutes (including three minutes of EEG recording) were taken between different stimulation protocols. The simulations of the different protocols were modeled using SimNIBS (Thielscher et al., 2015) and are shown in Fig. 3.

2.6. Electroencephalography (EEG)

To record prefrontal theta-band power, EEG electrodes were positioned on F1, F5, F2, F6, FZ, and FpZ (according to the 10–20 international EEG system). We recorded EEG immediately before and immediately after each of the three blocks of task and stimulation. Each

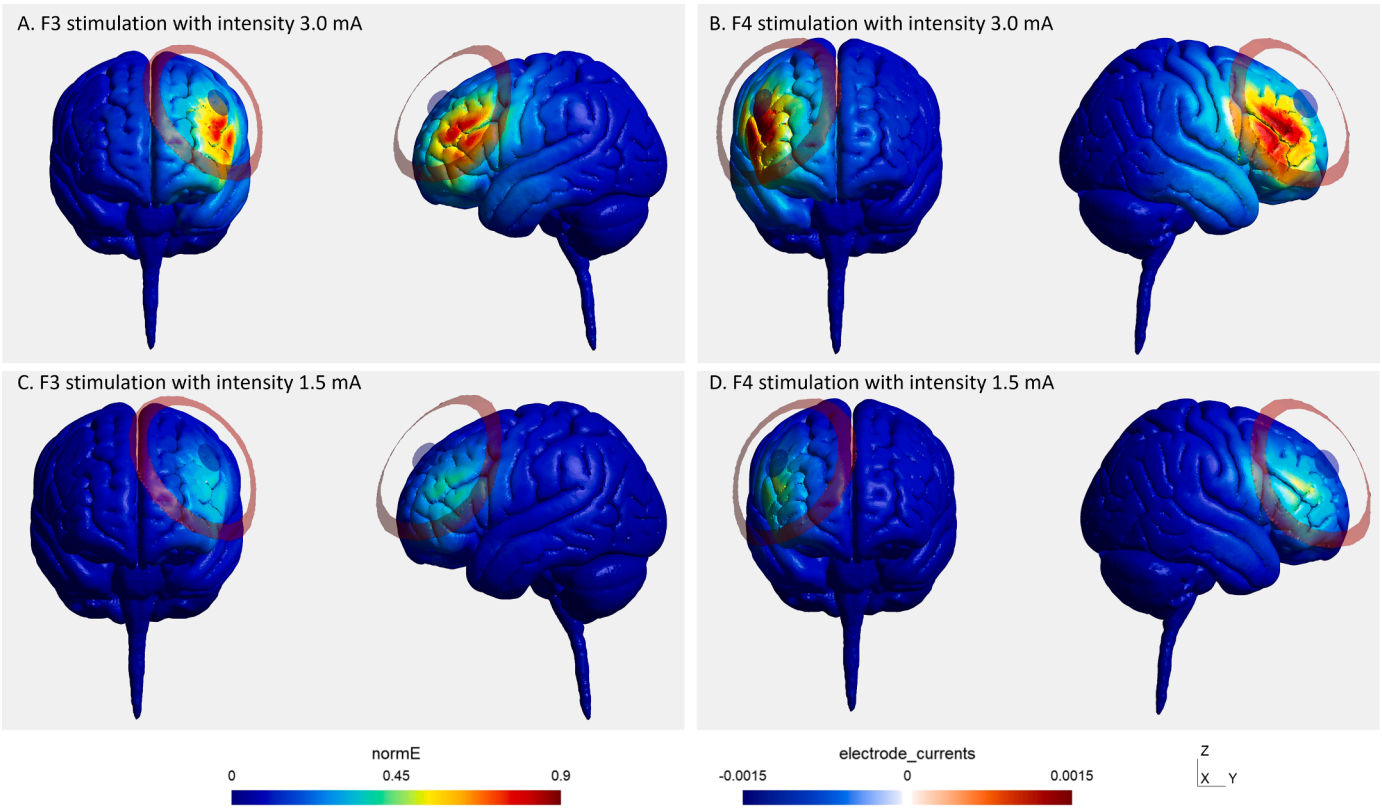

Fig. 3. SimNIBS HD tACS simulation. Simulations using 3.0 mA (A and B) and 1.5 mA (C and D) intensities. A and C show the front and left views of the stimulation made at F3. B and D show the front and right views of the stimulation made at F4. The colors stand for the normalized electric field (0–0.9), red areas indicate higher .

EEG measurement lasted three minutes, and participants were asked to avoid any movement and stay relaxed with their eyes closed.

The BrainAmp Standard EEG amplifier and BrainVision Recorder software (BrainProducts GmbH, Munich, Germany) were used for data recording (DC: 200 Hz; sampling rate: 500 Hz). The electrode impedance was kept below 15 kΩ. The data were preprocessed (offline) using the FieldTrip toolbox (Oostenveld et al., 2011; Popov et al., 2018) and custom MATLAB scripts, during which the EEG recordings were low-pass filtered in the analog domain (cutoff frequency: 250 Hz) and digitized (sampling rate: 1000 Hz). A notch filter (50 Hz) was used to remove electrical noise and demean the data over the full dataset. The data were segmented into 90 trials of two seconds each. To exclude trials with high variance and excessive noise, variance analyses and visual inspection were performed.

The EEG data were preprocessed using a fast Fourier transformation with hanning tapers and output frequencies between 1 Hz and 20 Hz with FieldTrip (Oostenveld et al., 2011). Afterwards, we used custom MATLAB ("MATLAB R2018b," 2018) scripts to average the data's power spectra for the pre-stimulation and each one of the measurements after the three stimulation protocols per session. We defined the theta-band to be between 5 Hz and 8 Hz, with 1.5 Hz above and 1.5 Hz below the stimulation frequency (6.5 Hz). The theta power was then analyzed per channel by comparing the data obtained after the different stimulation protocols with the pre-stimulation measurement.

2.7. Statistical analyses

The data collected and codes used are available at https://data.mendeley.com/datasets/3ys3kw9mf6, thus ensuring the transparency of our findings and facilitating their reproducibility. The behavioral data were preprocessed using custom MATLAB scripts (Mathworks Inc., Massachusetts, USA). We analyzed four behavioral-dependent variables — Risk, Probability scores, Value, and response time—and the EEG data. The statistical analyses were conducted using custom R scripts (R Core team, 2015).

2.7.1. Risk

We first calculated the level risk in each participant's chosen option per trial. During each MGT trial, participants were asked to choose a color, blue or pink, where X represents the payoff associated with the chosen color. Each color has a probability p of hiding a token. By guessing the color that hides the token correctly, participant can win a payoff x, which can be equal to X if the participant guesses the color correctly or zero otherwise. This means that this specific trial i would have an expected value E of xp or $E(X_i) = xp$. To calculate participants' risk-taking, we calculated the trial's level of variation (Tobler et al., 2007), where the variance of payoffs from choosing color X in trial i is given by the following equation:

$$Var(X_i) = \sum p(x - E(X_i))^2. \quad (1)$$

From the variance, we calculated the trial's standard deviation as the square root of the trial's variance. The resulting score is our measure of risk-taking (e.g., Myerson, 2005) behavior and the main dependent variable, which, from now on, is referred to as "Risk."

$$Risk_i = SD_i = \sqrt{Var(X_i)} \quad (2)$$

As each unique trial was presented twice during a complete MGT, we averaged the results of both repetitions for each participant in each MGT trial ($Risk_i = (Risk_{i1} + Risk_{i2})/2$, where i represents the 125 unique trials per participant per condition. Note that we took average between two repetitions to get the trial-level measure of risk and also our subsequent measures of probability scores, value and response time. Hence, for each participant, $Risk_i$ is calculated, for $i = 1$ to 125, indicating that each participant has 125 Risk measurements per task repetition. The task is repeated once per condition, for each of the three stimulation

intensities (sham, 1.5 and 3 mA) and 2 repetitions by side (left and risk DLPFC), meaning 6 repetitions in total.

Therefore, for example, when comparing condition a, where the participant received Sham stimulation over the right DLPFC to condition b, where they received right DLPFC 1.5 mA stimulation, an increase in $Risk_i$ shows that in trial i participants who chose a safer option during condition a opted for a riskier option in condition b; meaning that participants chose the option with higher payoff standard deviation in condition b than in condition a.

These results were analyzed at the group level by fitting a linear mixed model (LMM) to predict risk-taking behavior (Risk), with session (sessions 1 and 2), side (stimulation site left and right DLPFC), condition (sham, 1.5 mA, and 3 mA) and their interaction (side*condition) as factors (formula: Risk ~ session + side + condition + side*condition, estimated using REML and nlminb optimizer), and using a first-order autoregressive covariance structure (AR1), with Bonferroni correction for multiple comparisons. The remaining possible interactions were excluded from the model, as they were not significant and did not improve the model's fit. The model included participant per trial as a random effect accounting for the individual differences in participant's responses to the different trials presented during the task execution. The fit of all models was compared based on their Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC).

The post hoc analyses also included the number of stimulation exposures (StimExp, 0, 1, or 2) and session (1 or 2) as factors in a LMM (estimated using REML and nlminb optimizer) to predict Risk (formula: Risk ~ session + side + condition + StimExp + session * condition + session * StimExp + side * condition) and used a first-order autoregressive covariance structure (AR1). Again, the model included participant per trial as a random effect. The analyses presented normally distributed residuals and showed no heteroscedasticity, and no observations were removed as outliers.

2.7.2. Probability scores

Replicating the analyses used by Dantas et al. (2021), we calculated probability scores indicating the probability of winning associated with the color chosen by the participants in each trial of the MGT. This approach, similar to what was used in several previous studies (Boggio et al., 2010a, 2010b; Fecteau et al., 2007b; Knoch et al., 2006), considered a positive score if the winning probability was below 50 % and a negative score if it was above 50 %, with scores ranging from −1 to +1 (Fecteau et al., 2007c, 2007a; Minati et al., 2012; Rogers et al., 1999). Aiming to conduct a more detailed analysis of a participant's choices of probabilities, we classified the choices into a scale ranging from −2 to 2, where options with 1/6 probabilities received a score of 2 and options with probabilities of 2/6 received a score of 1 and so on (Dantas et al., 2021b). These probability scores can be seen in Appendix 2.

Previous studies interpreted positive scores as indication of risk proneness and negative scores as indication of risk aversion (Boggio et al., 2010a, 2010b; Fecteau et al., 2007b; Knoch et al., 2006). Nevertheless, choosing options with low probability might be optimal in the case of higher expected values (Bhatia, 2014). Take for example a choice between an outcome of 100 points with a probability of 1/6 and the outcome of 5 points with probability of 5/6. In this case, the choice of a lower probability is optimal. Therefore, we interpret the probability scores as pure indicators of the probabilities chosen by the participant, without inferring their risk-taking behavior from this measure alone.

The statistical analyses were done by fitting a LMM (estimated using REML and nlminb optimizer) to predict the effects of session, side, condition, and the interaction between side and condition on participants' probability scores (formula: Prob ~ session + side + condition + side*condition) and using a first-order autoregressive covariance structure (AR1), with Bonferroni correction for multiple comparisons. The remaining interactions were excluded for not being significant and not improving the model's fit, analyzed based on the models' AIC and BIC. Again, participant per trial was used as a random effect. The analyses presented normally distributed residuals and showed no heteroscedasticity. No observations were removed as outliers.

2.7.3. Value

The value of a trial is the size of reward associated with the chosen option in a trial in the MGT. Value was computed independently of the option's winning probabilities and simply captures whether subjects are attracted by larger pay-offs. For example, in a trial offering two options where blue offers a payoff of 5 points with a probability of 1/6 and pink offers a 5/6 probability of a payoff of 25 points, the choice of blue in the two repetitions of the trial would yield a value of 5, choosing pink in both repetitions would yield a Value of 25 and a participant that chooses blue in one repetition and pink in the other would end up with a Value of 15 (5 + 25/2) for this specific trial.

Value data were analyzed using an LMM (estimated using REML and the nlminb optimizer). We fitted the model to predict the effects of session, side, condition, and the interaction side*condition on Value (formula: Value ~ session + side + condition + side*condition), with Bonferroni correction for multiple comparisons. The model included participant per trial as a random effect. Again, the analyses presented normally distributed residuals and showed no heteroscedasticity. There were no outliers.

2.7.4. Response time

Response time (RT) was calculated as the time difference between the trial onset and the participants' finger press on the keyboard. Unlike the other dependent variables analyzed, the data on participants' response time included outliers. We used custom R scripts to remove observations outside 1.5 times the interquartile range above the upper quartile and below the lower quartile (R Bloggers, 2011). A total of 1598 observations (of different participants) were removed, leaving 20,152 observations.

Afterwards, we fitted an LMM (estimated using REML and nlminb optimizer) to predict RT. Session, side, condition, and its interactions were used as factors (formula: RT ~ session + side + condition + session * side + session * condition + condition * side + session * side * condition), with Bonferroni correction for multiple comparisons. Participant per trial was included as a random effect. The final analyses presented normally distributed residuals and showed no heteroscedasticity.

2.7.5. EEG data

For the EEG analyses, we fitted a LMM (estimated using REML and nlminb optimizer) to predict the theta power in each of the electrodes (F1, F2, F5, F6, FZ, and FpZ), with side (left and right), stimulation condition (sham, 1.5 mA, and 3 mA), and their interaction (side*condition) as factors (formula: theta-power ~ condition + side + condition * side) and used a compound symmetry covariance structure with Bonferroni correction for multiple comparisons. The model included participant per trial as a random effect.

Considering the findings in the literature regarding the correlation between frontal theta-band asymmetry and risk-taking behavior (Dantas et al., 2021b; Gianotti et al., 2009; Sela et al., 2012), we ran further analyses including the levels of frontal theta-band asymmetry (AsymPre) into our model (formula: Risk ~ AsymPre + side + condition + AsymPre * side + AsymPre * condition + side * condition). Again, we included participant per trial as a random effect and Bonferroni correction for multiple comparisons. In this step, we investigated whether the resting-state frontal theta-band asymmetry, measured before task and stimulation, could help predict risk-taking behavior. We estimated participants' frontal theta-band asymmetry by calculating the difference in theta power measured by averaging the right hemisphere (F2 and F6) minus the left hemisphere (F1 and F5) (Gianotti et al., 2009).

To further investigate the relationship between resting state and

frontal theta-power, we also included the average theta-power estimated in the right (AVRIGHTPRE, averaging F2PRE and F6PRE), left (AVLEFTPRE, averaging F1PRE and F5PRE), and midline (AVMIDLINEPRE, averaging FZPRE and FpZPRE) before the stimulation or task as factors in a mixed model to predict Risk (formula: Risk ~ AVLEFTPRE + AVRIGHTPRE + AVMIDLINEPRE + SESSION + side + condition + AVLEFTPRE * AVRIGHTPRE + condition * side + AVLEFTPRE * condition + AVRIGHTPRE *condition + AVMIDLINEPRE * condition). The remaining possible interactions were excluded from the model, as they were not significant and did not improve the model's fit, analyzed based on the models' AIC and BIC. The model included participant per trial as a random effect and Bonferroni correction for multiple comparisons. No covariance structure was used.

The final step of our analyses is a series of Pearson correlation analyses including Risk and the EEG measurements before stimulation and task, aiming to achieve a better understanding of the relationship between frontal theta-power and risk-taking behavior.

3. Results

3.1. Behavioral results

In this section, we present the main behavioral results of our experiment. The detailed statistical methodology can be found in the Statistical Analyses section. Means and standard deviations of each dependent variable are reported in Appendix 3.

3.1.1. Main results: risk

When analyzing the effects of both stimulation intensities over the left hemisphere on risk-taking behavior, the LMM analysis showed a statistically significant and positive conditional effect of both 1.5 (beta = 0.23, 95 % CI [0.03, 0.42], t(21,714) = 2.31, $p = 0.021$) and 3 mA (beta = 0.35, 95 % CI [0.03, 0.42], t(21,714) = 3.51, $p < 0.001$) theta-band tACS compared to sham. Thus, risk-taking behavior increased after both 1.5 mA and 3 mA tACS over the left DLPFC (F3).

To evaluate the effect of both stimulation intensities over the right hemisphere on risk-taking behavior, we analyzed the interaction between side (right) and intensity (sham, 1.5 mA, and 3 mA), again compared to sham. The LMM analysis showed a non-significant and negative conditional effect of 1.5 mA tACS (beta = −0.27, 95 % CI [−0.55, 6.52e-03], t(21,714) = −1.91, $p = 0.056$) and a significant negative conditional effect of the interaction between 3 mA stimulation and the right side (beta = −0.50, 95 % CI [−0.80, −0.20], t(21,714) = −3.27, $p = 0.001$), compared to baseline (sham). Hence, risk-taking behavior was significantly reduced only after the 3 mA theta-band tACS over the right DLPFC (F4).

We did not find significant effects of session (beta = −0.08, 95 % CI [−0.29, 0.13], t(21,714) = −0.76, $p = 0.450$) or stimulation side, comparing sham over left DLPFC to sham over right DLPFC (beta = 0.10, 95 % CI [−0.16, 0.37], t(21,714) = 0.76, $p = 0.448$). This means that participants had no significant differences in risk-taking behavior between the sessions. Further, there was no difference in their behavior due to the simple placement of the stimulation setting over the right or left hemispheres (without active stimulation). Full statistical report is available in Appendix 4.

As we saw a significant increase in risk-taking behavior after left 1.5 mA (and 3 mA) stimulation, we ran post hoc analyses by adding the amount of exposure to stimulation as a factor. These analyses accounted for the possibility of spillover effects of stimulation, considering that participants were stimulated twice (plus sham) within one session. The full report of these post hoc analyses is available in Appendix 5. Of note, we observed a significant reduction of risk-taking behavior as the amount of exposure to stimulation increased (beta = −0.36, 95 % CI [−0.55, −0.16], t(21,710) = −3.61, $p < 0.001$), and a replication of the findings of Dantas et al. (2021), with a significant reduction in risk-taking behavior after left 1.5 mA stimulation (beta = −0.50, 95 % CI [−0.79, −0.20], t(21,710) = −3.31, $p < 0.001$) (Fig. 4).

3.1.2. Probability scores

The analyses of probability scores showed a significant negative effect of session, indicating that participants chose significantly lower probabilities during session 2 (beta = −0.04, 95 % CI [−0.07, −0.02], t(21,714) = −3.87, $p < 0.001$) compared to session 1. Although there was a nearly significant positive effect of the 1.5 mA stimulation over the left hemisphere (beta = 0.02, 95 % CI [−1.40e-03, 0.04], t(21,714) = 1.83, $p = 0.067$), there were no significant effects of any of the stimulation conditions. Full statistical report is available in Appendix 6.

3.1.3. Value

Regarding Value, there were significant effects of both stimulation protocols over the right and left hemispheres. Stimulation over the left hemisphere led to a significant increase in Value. This effect was found for both intensity levels: 1.5 mA (beta = 0.49, 95 % CI [0.06, 0.92], t

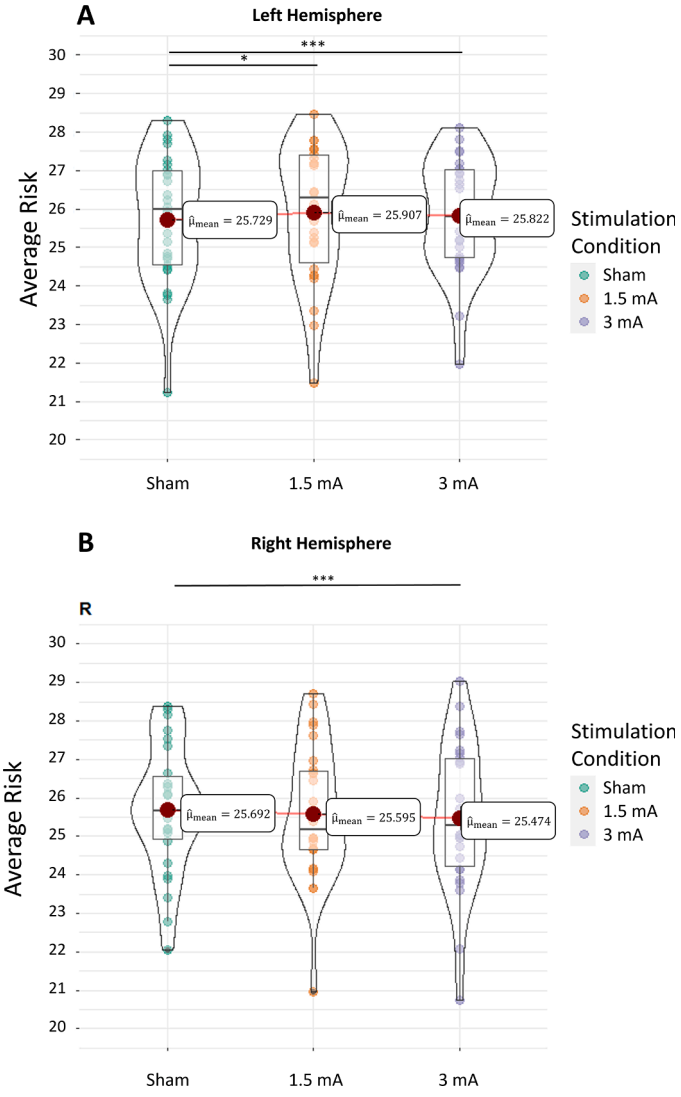

Fig. 4. Average risk-taking behavior by stimulation condition and hemisphere. The average risk-taking was estimated by averaging the standard deviations of each participant's choices in the 125 unique trials, across stimulation conditions (Sham in green, 1.5 mA in purple, and 3 mA in orange) over (A) the left DLPFC (left hemisphere) and (B) the right DLPFC (right hemisphere). The figure depicts the individual average risk-taking behavior (dots, ranging from 20.746 to 29.024), the group average by stimulation condition (bars), and the mean by stimulation condition (dark red marks). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

(21,714) = 2.23, p = 0.026) and 3 mA (beta = 0.78, 95 % CI [0.34, 1.23], t(21,714) = 3.44, p < 0.001) (Fig. 5).

The stimulation over the right hemisphere led to a significant reduction in Value only at 3 mA (beta = −1.11, 95 % CI [−1.79, −0.44], t(21,714) = −3.24, p = 0.001), and not at 1.5 mA stimulation (beta = −0.55, 95 % CI [−1.17, 0.07], t(21,714) = −1.74, p = 0.082). There were no significant effects of either session (beta = −0.23, 95 % CI [−0.69, 0.24], t(21,714) = −0.95, p = 0.342) or side (beta = 0.23, 95 % CI [−0.37, 0.83], t(21,714) = 0.75, p = 0.455) on Value. Full statistical report is available in Appendix 7.

3.1.4. Response time

Participants' response time was significantly lower in session 2 compared to session 1 (beta = −0.18, 95 % CI [−0.30, −0.05], t(20,111) = −2.74, p = 0.006). During session 1, both 1.5 mA (beta = −0.03, 95 % CI [−0.05, −0.02], t(20,111) = −4.20, p < 0.001) and 3 mA (beta = −0.02, 95 % CI [−0.04, −2.90e-03], t(20,111) = −2.31, p = 0.021) stimulation over the left hemisphere led to a significant reduction in RT. tACS over the right hemisphere in session 1 led to increases in RT, with similar effects during 1.5 mA (side right * intensity 1.5 mA, beta = 0.09, 95 % CI [0.07, 0.12], t(20,111) = 7.05, p < 0.001) and 3 mA (side right * intensity 3 mA, beta = 0.09, 95 % CI [0.07, 0.12], t(20,111) = 7.05, p < 0.001) stimulation (Fig. 6).

The interactions of the different stimulation conditions with the sessions were mainly significant. There was a significant positive effect of the 3 mA stimulation over the left hemisphere (session 2*intensity 3 mA, beta = 0.03, 95 % CI [2.97e-03, 0.05], t(20,111) = 2.19, p = 0.028), with non-significant changes in response time observed during 1.5 mA over the left hemisphere in session 2 (beta = 0.02, 95 % CI [−7.25e-03, 0.04], t(20,111) = 1.39, p = 0.165). The stimulation over the right hemisphere during session 2 yielded significant negative effects during both 1.5 mA (side right * intensity 1.5 mA * session 2, beta = −0.09, 95 % CI [−0.13, −0.06], t(20,111) = −5.06, p < 0.001) and 3 mA stimulation (side right * intensity 3 mA * session 2, beta = −0.10, 95 % CI [−0.14, −0.07], t(20,111) = −5.79, p < 0.001). Full statistical report is available in Appendix 8.

3.2. EEG results

3.2.1. Theta-band entrainment

To evaluate the potential entrainment effects, we compared theta-power levels before the task (resting state: eyes closed) with theta-power levels immediately after the task and stimulation (resting state: eyes closed). The estimated theta power was averaged for the left hemisphere (left, F1, and F5), right hemisphere (right, F2, and F6), and midline (midline, FZ, and FpZ). The analyses showed a significant or a nearly significant increase in theta power after left but not right tACS. This increase was not only limited to the left hemisphere but was also observed in the right hemisphere and midline. The results by side after left DLFPC tACS are depicted in Table 1, and the results after right DLPFC stimulation are detailed in Table 2 (the detailed results per electrode are available in Appendix 5).

3.2.2. Theta-power and risk-taking behavior

We first assessed whether resting-state frontal theta-band asymmetry significantly affected individual risk-taking behavior. The levels of theta-band asymmetry measured during resting state (before stimulation or task) did not significantly affect the levels of risk-taking behavior (beta = −4.05, 95 % CI [−8.93, 0.84], t(28) = −1.70, p = 0.101). Nevertheless, there was a significant effect of the interaction between resting-state frontal theta asymmetry and 1.5 mA stimulation over the left (but not right) hemisphere (beta = 1.43, 95 % CI [0.33, 2.53], t(21,712) = 2.55, p = 0.011), indicating a significant increase in risk-taking behavior.

Exploring this relationship in more detail, we added the average theta power measured over the right (AVRIGHTPRE, F2, and F6), left (AVLEFTPRE, F1, and F5), and midline electrodes (AVMIDLINEPRE, FZ, and FpZ) into the model to estimate the effects of such factors on risk-

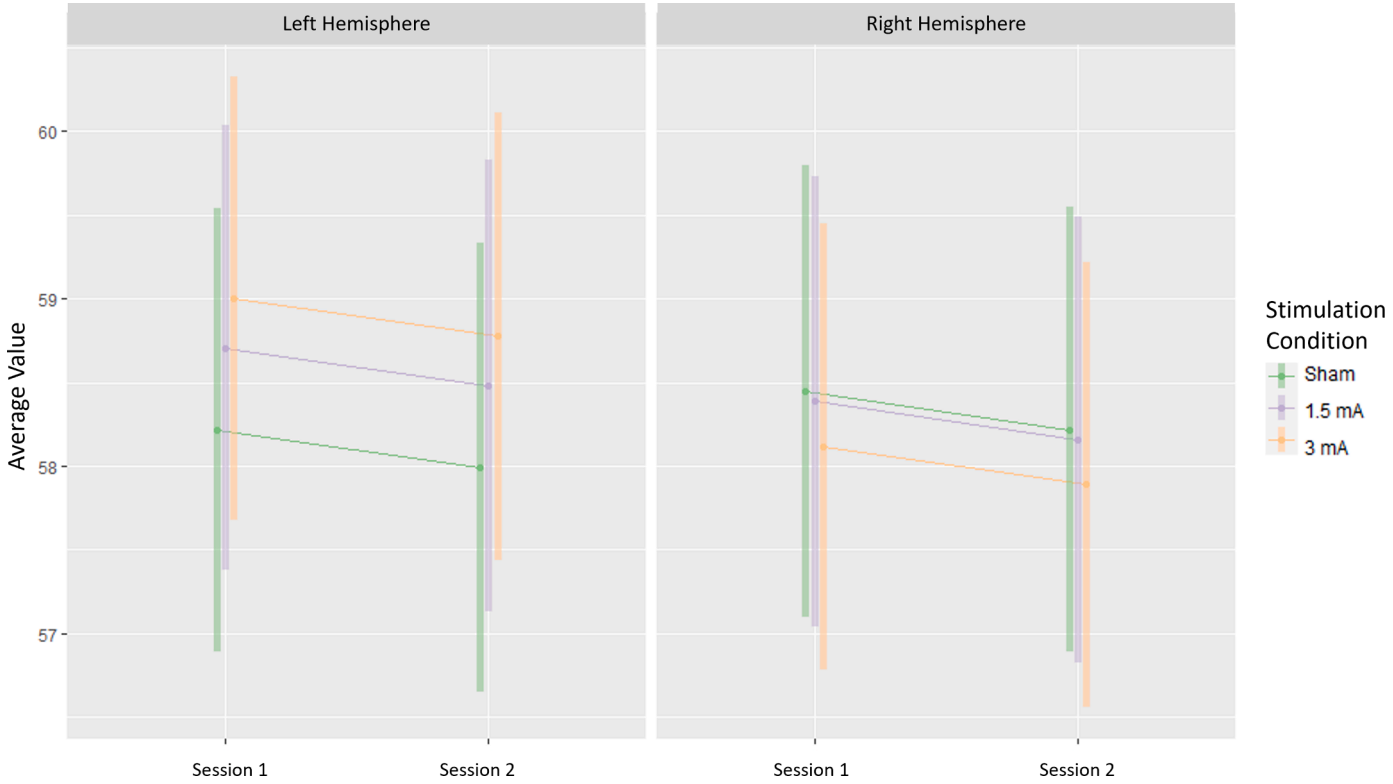

Fig. 5. Value by stimulation condition and hemisphere. The figure depicts participants' value, meaning the payoff associated to participants' chosen options independent of their probabilities. Value results are depicted per session (x axis), stimulation condition (lines), and hemisphere stimulated (left and right).

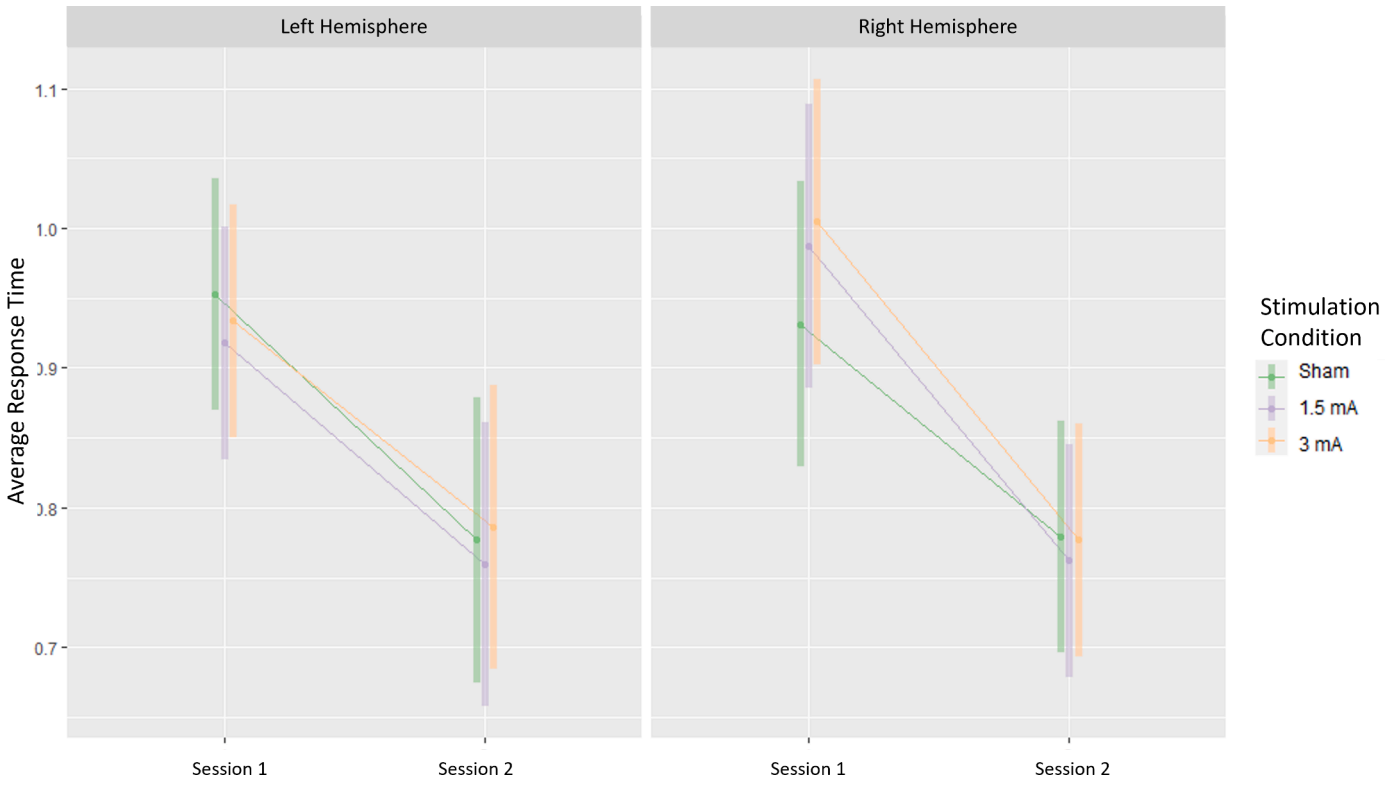

Fig. 6. Average response time by stimulation condition and hemisphere. The figure depicts the average response time per session (x axis), the stimulation condition (lines), and the hemisphere stimulated (left and right).

Table 1
Theta power measured after left DLPFC stimulation. Results compared to measurements in the resting state before stimulation and task.

Stimulation over the left DLPFC						
Average by side	**Condition**	**Estimates**	**std. Error**	**CI**	**p**	**df**
Left	SHAM	0.25	0.07	0.11 – 0.38	**0.001**	198
Left	1.5 mA	0.14	0.07	0.00 – 0.28	**0.045**	198
Left	3 mA	0.18	0.07	0.04 – 0.32	**0.01**	198
Right	SHAM	0.25	0.06	0.12 – 0.37	**<0.001**	198
Right	1.5 mA	0.15	0.06	0.02 – 0.27	**0.02**	198
Right	3 mA	0.19	0.06	0.07 – 0.31	**0.002**	198
Midline	SHAM	0.22	0.06	0.10 – 0.34	**<0.001**	198
Midline	1.5 mA	0.14	0.06	0.01 – 0.26	**0.029**	198
Midline	3 mA	0.17	0.06	0.05 – 0.29	**0.007**	198

Table 2
: Theta power measured after the right DLPFC stimulation. Results compared to measurements in the resting state before stimulation and task.

Stimulation over the right DLPFC						
Average by side	**Condition**	**Estimates**	**std. Error**	**CI**	**p**	**df**
Left	SHAM	−0.12	0.1	−0.32 – 0.08	0.243	198
Left	1.5 mA	−0.02	0.1	−0.22 – 0.19	0.882	198
Left	3 mA	−0.01	0.1	−0.21 – 0.19	0.928	198
Right	SHAM	−0.13	0.09	−0.30 – 0.05	0.152	198
Right	1.5 mA	0	0.09	−0.18 – 0.17	0.957	198
Right	3 mA	−0.01	0.09	−0.19 – 0.17	0.92	198
Midline	SHAM	−0.09	0.09	−0.27 – 0.09	0.309	198
Midline	1.5 mA	0.02	0.09	−0.16 – 0.20	0.856	198
Midline	3 mA	0.04	0.09	−0.14 – 0.22	0.671	198

taking behavior. The results of this analysis showed a reduction in risk-taking behavior from session 1 to session 2 (beta = −0.31, 95 % CI [−0.44, −0.18], t(21,708) = −4.79, $p < 0.001$). We also found a negative effect of the interaction between resting-state theta-power measured on the right and left hemispheres, meaning that this interaction led to reductions in risk-taking behavior and is statistically significant and negative (beta = −1.12, 95 % CI [−1.83, −0.41], t(25) = −3.24, $p = 0.002$). This indicates that participants' resting-state theta-power significantly affects their risk-taking behavior. Again, we observed a significant effect of the interaction between the right side and stimulation at 3 (beta = −0.38, 95 % CI [−0.69, −0.08], t(21,708) = −2.48, $p = 0.013$). Furthermore, we observed a significant effect of the interaction between the theta-power measured before the stimulation in the right hemisphere and 1.5 mA stimulation, which led to increased risk-taking behavior (beta = 1.99, 95 % CI [0.06, 3.91], t(21,708) = 2.02, $p = 0.044$), indicating that the stimulation effects are state-dependent. Appendix 6 presents the full results of this analysis.

To study the correlation between risk-taking behavior and the levels of baseline theta-power (before task and execution), we performed a correlation analysis between the average resting-state frontal theta-power (measured in the left, middle, and right hemispheres) and participants' risk-taking behavior. These correlation analyses show

significant negative correlations between risk-taking behavior and the average frontal theta-power in the left ($r = -0.03$, 95 % CI [−0.04, −0.02], $t(21,748) = -4.57$, $p < 0.001$) and right ($r = -0.04$, 95 % CI [−0.05, −0.02], $t(21,748) = -5.23$, $p < 0.001$) hemispheres. We also evaluated the correlation between resting-state frontal theta-band frontal asymmetry (right–left average theta-power) and risk-taking behavior, which was again negative and significant ($r = -0.02$, 95 % CI [−0.04, −0.01], $t(21,748) = -3.47$, $p = 0.024$). However, the correlation coefficients indicate that the correlation between frontal left and right resting-state theta-power is stronger than the correlation obtained between resting-state frontal asymmetry and risk-taking behavior. Overall, our results indicate a significant negative correlation between resting-state frontal theta-power measured before task/stimulation and participants' risk-taking behavior.

4. Discussion

Several EEG studies have shown a correlation between frontal theta-band power and risk-taking behavior (Gianotti et al., 2009; Knoch et al., 2006; Massar et al., 2014, 2012; Schiller et al., 2014; Schmidt et al., 2019, 2018). Although the functional relevance of this theta-band power in risk-taking behavior has been studied, evidence from studies that experimentally modulated this oscillatory frequency band using NIBS is sparse and inconsistent. To investigate the functional relationship between frontal theta-band activity and risk-taking behavior, we utilized a within-subject design with single-blinded sham control and combined EEG-HD tACS application (6.5 Hz) to the left and right DLPFC during the execution of the MGT (Dantas et al., 2021b). EEG was recorded before and immediately after task execution and stimulation. Our design also included two stimulation intensities: 1.5 mA and 3 mA.

4.1. Behavioral results

As initially hypothesized, the behavioral results confirm the functional relevance of frontal theta-band activity and the modulation of risk-taking behavior. Our findings indicate that tACS over the left DLPFC led to significant monotonical increases in risk-taking behavior, which can be seen as the estimated betas reported in the results section. These results show an increase in choices of higher risk (standard deviation of payoffs) by 0.23 during 1.5 mA stimulation, and 0.35 during 3 mA stimulation, both compared to the average Risk observed during Sham.

Opposite effects were observed during right hemisphere stimulation, with a non-significant reduction of risk-taking behavior. While a non-significant decrease of −0.27 standard deviations was observed during 1.5 mA right DLPFC stimulation, a significant reduction of −0.50 standard deviations in the participants' choices was observed during 3 mA stimulation.

Such results represent a significant increase in risk-taking behavior during left theta-band tACS (1.5 mA and 3 mA) and significant reduction of risk-taking behavior during high intensity (3 mA) but not low intensity (1. 5 mA) right DLPFC theta-band tACS. These findings indicate that frontal theta-band activity plays a functional role in decision-making under risk, that it plays an important part in the electrophysiological mechanism involved in the processing and modulation of this type of behavior (Gianotti et al., 2009; Massar et al., 2014, 2012; Studer et al., 2013).

When looking at participants' choices of probabilities, we did not find any effects of tACS, which is in line with the findings of Dantas et al. (2021). However, our results show a significant shift toward choosing lower probabilities from Session 1 to Session 2. This shift toward choosing options with lower probabilities can signal an increase in risk proneness over time due to a higher familiarization with the task (Chuang and Schechter, 2015; Dion and Miller, 1971). However, this increase was not reflected in participants' risk-taking behavior. Further studies are needed to investigate this effect of time on probability choices.

Participants' Value, on the other hand, was significantly higher during the left hemisphere tACS (high and low intensity) compared to sham. When stimulating the left DLPFC, Value increased significantly, with an increase of 0.49 points during 1.5 mA stimulation and 0.78 points during 3 mA stimulation. An effect in the opposite direction was observed during right DLPFC stimulation, with a nonsignificant decrease of −0.55 points in Value during 1.5 mA stimulation and a significant decrease of −1.11 points during 3 mA stimulation.

This effect was in the same direction as the effects observed in risk-taking behavior. Again, in line with these effects, tACS to the right DLPFC led to a significant reduction in Value. However, the reduction in Value was observed only during high-intensity tACS. Considering our use of the standard deviation of the chosen option as a measure of risk associated with the option (which accounts for both probabilities and values), the observed results indicate that the changes in risk-taking behavior were mainly driven by the changes in payoff size (our Value measure) sensitivity. These results are in line with previous studies, indicating that a lower sensitivity to value is associated with reduced risk-taking behavior (Boggio et al., 2010a, 2010b; Dantas et al., 2021b; Fecteau et al., 2007a; Gilmore et al., 2018; Levasseur-Moreau and Fecteau, 2012).

The effects of tACS on response times were session-dependent. In session 1, left DLPFC tACS (1.5 mA or 3 mA) led to significant decreases in response time, while right DLPFC stimulation (1.5 or 3 mA) led to increases in response time. In session 2, response times were generally faster, and the direction of the stimulation effects was the opposite of what was observed in session 1. During session 2, left hemisphere stimulation (3 mA) resulted in increases in response time, while right hemisphere stimulation (1.5 mA or 3 mA) led to reductions. These findings indicate that, at baseline, theta-band tACS over the right hemisphere increases response time. However, when the task is repeated in session 2 and the participant has faster responses, this same protocol will potentialize these "natural" responses, leading to steeper decreases in response times. The opposite logic seems to apply to left hemisphere stimulation. This proposed mechanism can, however, only be speculated, and more research is necessary to better understand the effect of frontal theta-band tACS on response time during risky decision-making.

4.2. EEG results

The electrophysiological data were analyzed to evaluate the possible oscillatory entrainment of theta-band tACS. The comparison between the frontal theta-power recorded during three minutes immediately before and after the stimulation and task showed a significant increase in theta-power after sham stimulation. These findings indicate that theta-power increases as a response to the decision-making task, which is in line with the EEG literature on risk-taking behavior, according to which frontal theta-band activity increases when exposed to risky choice environments (Christie and Tata, 2009; Pinner and Cavanagh, 2017; Schmidt et al., 2018).

When comparing the active stimulation protocols, after left DLPFC tACS, at 1.5 mA or 3 mA, we observed a general increase in left, right, and midline theta-power. No significant electrophysiological aftereffects were observed after the right DLPFC tACS.

4.2.1. Stimulation intensity

Recent studies have questioned the cortical reach of low-intensity transcranial electric stimulation (tES). They have indicated that the low intensities commonly used in studies, such as 1 mA or 1.5 mA, are not sufficient to reach the cortex, considering the electric resistance created by the scalp [25,35,36]. We therefore tested the effect of a lower and a higher-intensity tACS on risk-taking.

According to our findings, lower-intensity tACS may in some cases not be enough to consistently induce behavioral effects (Sela et al., 2012; Wischnewski and Compen, 2022a). For example, while both 1.5 mA and 3 mA left prefrontal cortex stimulation significantly increased

risk-taking behavior and frontal theta-power (compared to sham), we did not find significant changes in risk-taking behavior during right hemisphere stimulation at 1.5 mA intensity. These null results are in line with Sela et al. (2012), where no behavioral changes were observed after 1 mA right DLPFC peak-to-peak stimulation. Nevertheless, the stimulation of the right DLPFC with 3 mA tACS in our study led to a significant reduction in risk-taking behavior. Hence, it might be necessary to use higher tACS intensities to robustly find behavioral responses (Antal et al., 2017; Asamoah et al., 2019; Bland and Sale, 2019; Widge, 2018). These results indicate that a possible reason for inconsistent results in behavioral responses can be the use of low-intensity stimulation protocols (Alekseichuk et al., 2022; Reato et al., 2013; Schutter, 2016).

While electrophysiological theta-band tACS aftereffects are often not found (Bland and Sale, 2019; Dantas et al., 2021b), recent studies have detected significant changes in theta-power with the use of intrahemispheric montage (Wischnewski and Compen, 2022b) or by applying tACS at individual theta-power (Aktürk et al., 2022; Zhang et al., 2022). In our study, left hemisphere tACS led to significant increases in theta-power, with higher (albeit not significantly different) estimated increases after 3 mA stimulation than after 1.5 mA tACS.

There were no significant changes in theta-power after right tACS, although we saw a decrease in risk taking behavior after 3 mA right DLPFC stimulation. While one might argue that a higher tACS intensity may be required for significant electrophysiological aftereffects in general, the question remains as to why this seems to be the case after right, but not left, hemispheric stimulation. Thus, further studies investigating the effect of different stimulation intensities on different stimulation sites are needed.

4.3. Interhemispheric stimulation

We were able to show behavioral effects after right and left theta-band tACS, with a significant increase in risk-taking behavior after left DLPFC tACS (both 1.5 and 3 mA) and a significant reduction in risk-taking behavior after right stimulation (3 mA only). These changes in risk-taking behavior confirm that different hemispheres have different roles in this electrophysiological mechanism, since the stimulation of each hemisphere induced behavioral changes in opposite directions, which is in line with previous findings (Gianotti et al., 2009; Goel et al., 2007; Li et al., 2019; Schiller et al., 2014).

However, although side of stimulation seems to play a key role in the modulation of risk-taking behavior, the results indicate that the relationship between frontal theta-power in each hemisphere and the modulation of risk-taking behavior is not simply derived from the levels of frontal theta-band asymmetry, as suggested by Gianotti et al. (2009) (Gianotti et al., 2009).

Consistent with Gianotti et al. (2009), we observed a significant negative correlation between risk-taking behavior and frontal theta-band asymmetry, which indicates that higher frontal theta-band asymmetry was correlated with lower levels of risk-taking behavior. However, our results revealed that the negative correlations between frontal theta-power and risk-taking behavior were also significant and stronger than the correlation observed between frontal asymmetry and risk-taking behavior. These findings indicate that frontal theta-power during resting state is also a strong indicator of individual risk proneness, and that this is independent of right–left theta power asymmetry.

Moreover, resting-state frontal asymmetry did not significantly affect risk-taking behavior when included as a factor in our analyses, while the interaction between theta-power measured on the right and left hemisphere had a significant negative effect on risk-taking behavior. These findings indicate that the frontal theta-power significantly affects risk-taking behavior, and that the relative difference between hemispheres (asymmetry) does not.

4.4. State-dependent effects

As previously mentioned, we found significant effects of resting-state theta-power on risk-taking behavior. Specifically, when adding the average left, right, and midline resting-state theta-power to our LMM to evaluate the effects of such factors on risk-taking behavior, we saw that the interaction between average theta-power in the right and left hemispheres led to significant negative effect on risk-taking behavior. This means that the higher theta power in both the right and left DLPFC the lower risk-taking behavior, in our experimental conditions.

The same analyses showed significant effects of right DLPFC 3 mA stimulation, which again reduced participants' risk-taking behavior. However, the left hemisphere stimulation effect was dependent on participants' resting-state frontal theta-power. We only observed significant results when the left hemisphere stimulation (at 1.5 mA) interacted with the resting-state theta-power measured in the right hemisphere, which yielded significant increases in risk-taking behavior. We also added resting-state frontal theta-band asymmetry (left–right theta-power) as a factor to our LMM, and this factor did not significantly affect participants' risk-taking behavior. However, again, the interaction between frontal theta-band asymmetry and left 1.5 mA tACS yielded significant increases in risk-taking behavior.

These findings suggest that the effects of theta-band tACS are potentially state-dependent, implying that although the involvement of theta-band activity in the modulation of risk-taking behavior is clear, the direction of the results observed after theta-band tACS in risk-taking behavior potentially depends on the participants' baseline frontal theta-power. Nevertheless, since our experimental design does not include a full EEG set, it is not possible to reliably attribute these measurements to specific brain areas.

The post hoc behavioral analyses provided further evidence of state dependence. Despite aligning with Sela et al. (2012), where left DLPFC theta-band tACS increased risk-taking behavior, the current results differed from those reported by Dantas et al. (2021). Further analyses revealed that longer exposure to stimulation resulted in reduced risk-taking behavior. Additionally, left hemisphere stimulation at 1.5 mA led to significant reductions in risk-taking behavior (in line with Dantas et al., 2021), while non-significant effects were observed at 3 mA tACS when controlling for the amount of stimulation exposure. However, the behavioral effects of right hemisphere stimulation were not affected by adding these factors in the model.

While our design aimed at controlling for spillover effects by having short breaks between the different stimulation conditions, it is possible that the sequence of stimulation protocols and/or the repetition of the task could account for the observed differences in effect direction. Therefore, further research is needed to disentangle the effects of the task and stimulation.

Another limitation of our study is the lack of assessment for the potential levels of discomfort across the different stimulation protocols. Although tACS is thought to be rather comfortable for the participants (Bikson et al., 2016), different sensorial stimulation comparing the 1.5 mA and 3 mA stimulation cannot be discarded and should be explored in future studies.

Overall, our findings confirm the relevance of frontal theta-band activity in risk-taking behavior [20,68]. Our results further indicate that, based on EEG data, it is possible to estimate an individual's risk proneness, which is a relatively simple method independent of a specific task. More importantly, we contribute to the field of decision neuroscience and advance our knowledge of the underlying neural processes of risk-taking behavior. Our study adds to the current literature by highlighting the importance of a specific oscillatory pattern in the processing of a complex behavior such as decision-making under risk.

5. Conclusion

This study aimed to investigate the relationship between frontal

theta-band activity power and risk-taking behavior using tACS at 6.5 Hz. A single-blinded, sham-controlled, within-subject design was used, and risk-taking behavior was measured using the MGT. Stimulation was applied over the left and right DLPFC at 1.5 mA and 3 mA. The results showed that left hemisphere stimulation led to an increase in risk-taking behavior compared to sham, which was also reflected as significant overall increases in frontal theta-power. Right hemisphere stimulation led to a reduction in risk-taking behavior only at a higher intensity of 3 mA; no EEG aftereffects were found. The effect of the stimulation was modulated by the resting-state theta-power as well as the amount of exposure to the stimulation. These findings suggest that lateralized oscillatory patterns play a crucial role in processing complex behaviors such as decision-making under risk and could potentially be utilized in clinical settings to diagnose and intervene in cases involving patients with abnormal risk-taking behaviors.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Scribendi AI in order to check the manuscript's grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take (s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Aline M. Dantas: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alexander T. Sack:** Resources, Supervision, Writing – review & editing. **Elisabeth Bruggen:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Peiran Jiao:** Supervision, Writing – review & editing. **Teresa Schuhmann:** Methodology, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

I have shared the data in Mendeley Data, which is reported in the manuscript.

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We acknowledge the valuable contributions of our participants, colleagues, and students who supported our data collection.

Appendix 1. EEG and stimulation setting

See Fig. A1

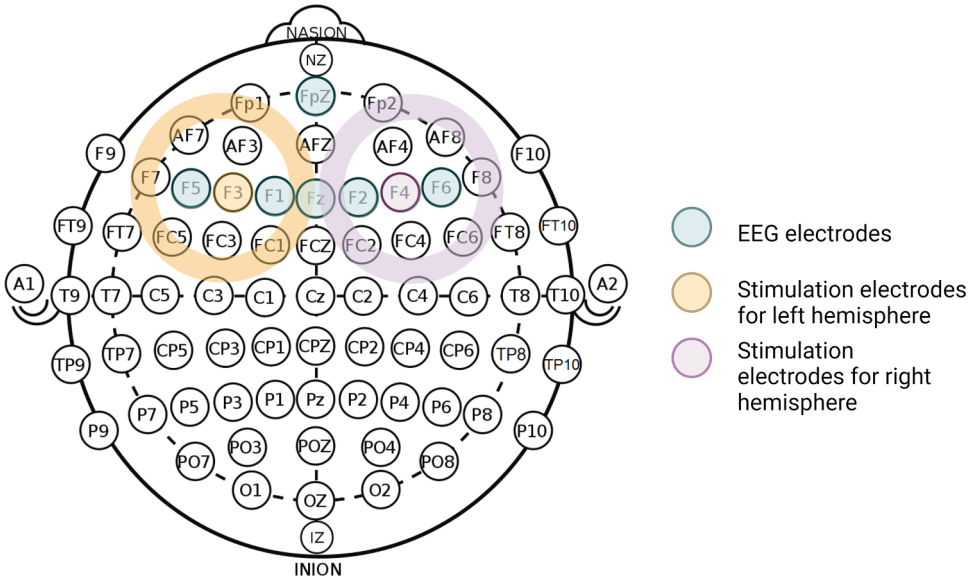

Fig. A.1. – EEG and stimulation settings.

The EEG settings were kept constant across sessions, with FpZ, FZ, F1, F2, F5 and F6 electrodes (blue) placed around the stimulation sites. In each session participants received either stimulation over the left hemisphere (yellow) or over the right hemisphere (purple).

Appendix 2. Probability Scores

Higher scores indicate that participants chose the trials with lower probabilities, while lower scores indicate that participants chose higher probabilities.

Pink	Blue	Choice	Probability
5	1	Blue	2
1	5	Pink	2
4	2	Blue	1
2	4	Pink	1
3	3	Pink	0
3	3	Blue	0
4	2	Pink	−1
2	4	Blue	−1
5	1	Pink	−2
1	5	Blue	−2

Appendix 3. Behavioral means and standard deviations

Dependent variable	*Mean*	*sd.*
Risk-taking behavior	25.73139	14.6133
Value	58.45785	31.8285
Probability scores	−0.9655617	0.9341396
Response Time	0.8439086	0.3448412

Appendix 4. Effects of stimulation protocols on Risk-taking behavior – Statistical report

	Risk-taking behavior				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
(Intercept)	25.66	0.29	25.09 – 26.23	**<0.001**	21,714
SESSION 2	−0.08	0.11	−0.29 – 0.13	0.45	21,714
SIDER	0.1	0.14	−0.16 – 0.37	0.448	21,714
1.5 mA	0.23	0.1	0.03 – 0.42	**0.021**	21,714
3 mA	0.35	0.1	0.16 – 0.55	**<0.001**	21,714
SIDE Right: 1.5 mA	−0.27	0.14	−0.55 – 0.01	0.056	21,714
SIDE Right: 3 mA	−0.5	0.15	−0.80 – −0.20	**0.001**	21,714
Random Effects					
σ^2	211.49				
$\tau_{00\ PARTICIPANT}$	0.96				
Observations	21,750				
Marginal R^2 / Conditional R^2	0.000 / 0.005				
AIC	147,184.282				

Risk-taking behavior								
SIDE	*COND.*	*SESSION*	*contrast*	*Estim.*	*SE*	*df*	*t.ratio*	*p.value*
Left	Sham	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.9739
Right	Sham	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.974
Left	1.5 mA	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.9739
Right	1.5 mA	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.974
Left	3 mA	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.974
Right	3 mA	.	SESSION 2 - SESSION 1	−0.08	0.106	21,714	−0.755	0.974
.	Sham	1	Right - Left	0.1032	0.1359	21,714	0.759	0.9732
.	Sham	2	Right - Left	0.1032	0.1359	21,714	0.759	0.9732
.	1.5 mA	1	Right - Left	−0.1663	0.1391	21,714	−1.195	0.8093
.	1.5 mA	2	Right - Left	−0.1663	0.1391	21,714	−1.195	0.8092
.	3 mA	1	Right - Left	−0.3955	0.1318	21,714	−3	**0.0201**
.	3 mA	2	Right - Left	−0.3955	0.1318	21,714	−3	**0.0204**
Left	.	1	1.5 mA - Sham	0.2258	0.0977	21,714	2.311	0.1388
Left	.	1	3 mA - 1.5 mA	0.1291	0.0982	21,714	1.314	0.7345
Left	.	2	1.5 mA - Sham	0.2258	0.0977	21,714	2.311	0.1384
Left	.	2	3 mA - 1.5 mA	0.1291	0.0982	21,714	1.314	0.7346
Right	.	1	1.5 mA - Sham	−0.0437	0.097	21,714	−0.451	0.9983
Right	.	1	3 mA - 1.5 mA	−0.1001	0.0996	21,714	−1.005	0.9036
Right	.	2	1.5 mA - Sham	−0.0437	0.097	21,714	−0.451	0.9983
Right	.	2	3 mA - 1.5 mA	−0.1001	0.0996	21,714	−1.005	0.9035

Degrees-of-freedom method: containment.
P value adjustment: mvt method for 20 tests.

Risk-taking behavior							
SESSION	*SIDE*	*Condition*	*emmean*	*SE*	*df lo*	*wer.CL up*	*per.CL*
1	Left	Sham	25.7	0.292	29	24.8	26.6
2	Left	Sham	25.6	0.295	29	24.7	26.5
1	Right	Sham	25.8	0.297	29	24.8	26.7
2	Right	Sham	25.7	0.293	29	24.8	26.6
1	Left	1.5 mA	25.9	0.293	29	25	26.8
2	Left	1.5 mA	25.8	0.297	29	24.9	26.7
1	Right	1.5 mA	25.7	0.297	29	24.8	26.6
2	Right	1.5 mA	25.6	0.293	29	24.7	26.6
1	Left	3 mA	26	0.291	29	25.1	26.9
2	Left	3 mA	25.9	0.295	29	25	26.9
1	Right	3 mA	25.6	0.294	29	24.7	26.5
2	Right	3 mA	25.5	0.293	29	24.6	26.5

Confidence level used: 0.95.
Conf-level adjustment: bonferroni method for 12 estimates.

Appendix 5. Post hoc analyses on the effects of repeated stimulation on risk-taking behavior

See Fig. A2

Our results indicate a significant reduction of risk-taking behavior from session 1 to session 2 (beta = −0.56, t(21,710) = −2.52, $p = 0.012$). A significant increase in risk-taking behavior was observed due to left hemisphere stimulation in the first session both with intensity 1.5 mA (beta = 0.55, t(21,710) = 4.28, $p < 0.001$) and 3 mA (beta = 0.52, t(21,710) = 4.11, $p < 0.001$).

Our results show a significant negative effect of the amount of exposure to stimulation (beta = −0.36, t(21,710) = −3.61, $p < 0.001$), indicating a reduction on risk-taking behavior as the amount of exposure to stimulation increases. We also observed a significant positive effect of the interaction between exposure to stimulation and session (beta = 0.30, t(21,710) = 2.21, $p = 0.027$).

In these analyses, the interaction between left 1.5 mA stimulation and session 2 led to a significant reduction in risk-taking behavior (beta = −0.50, t(21,710) = −3.31, $p < 0.001$), replicating the findings of Dantas et al. (2021). The 3 mA stimulation did not yield a significant effect (beta = −0.10, t(21,710) = −0.59, $p = 0.556$). As observed in our initial analyses, there was a significant reduction in risk-taking behavior during right side 3 mA stimulation (beta = −0.59, t(21,710) = −3.71, $p < 0.001$), while the effects of the right side 1.5 mA stimulation were still not significant (beta = −0.25, t(21,710) = −1.79, $p = 0.074$).

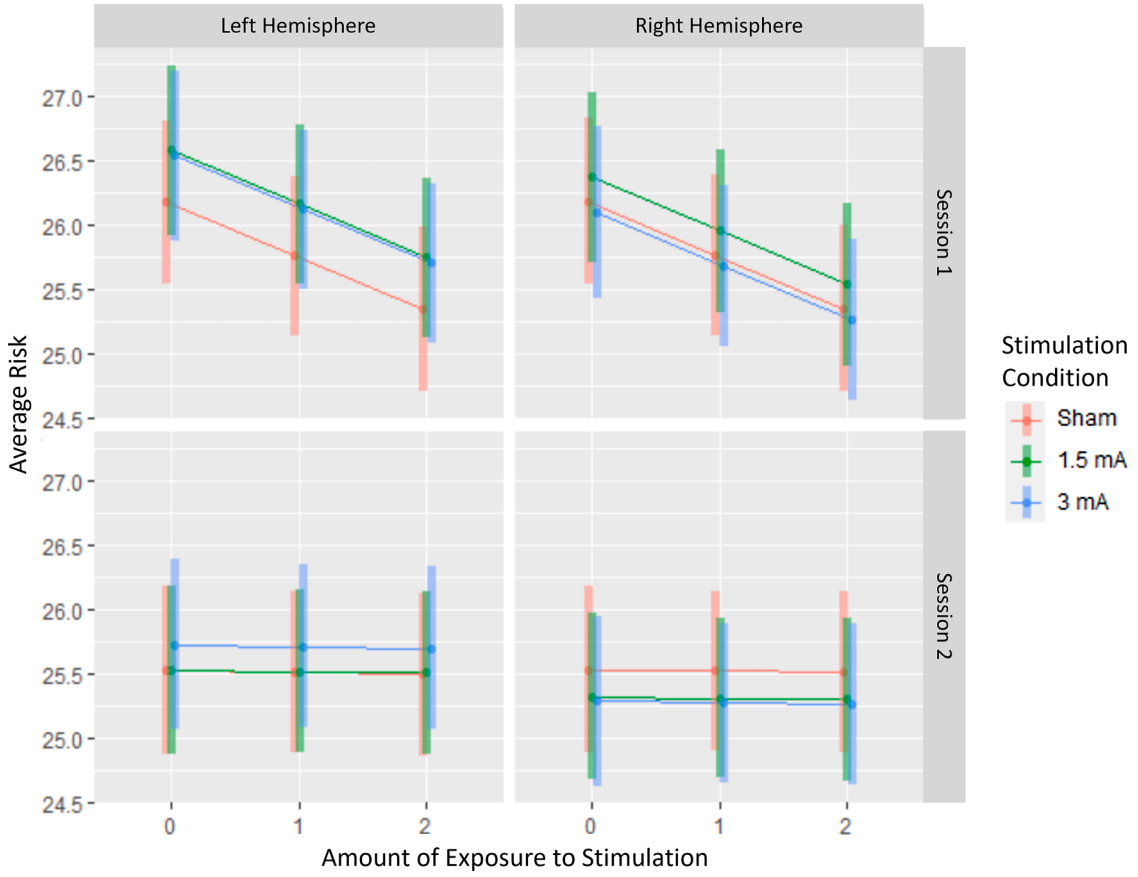

Fig. A.2. – Average risk-taking behavior by stimulation condition and amount of exposure to stimulation. Results are presented by session (vertical) and side (horizontal). The horizontal axis indicates the number of exposures to stimulation from zero to two.

Appendix 6. Effects of stimulation protocols on Probability scores – Statistical report

	Probability scores				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
(Intercept)	−0.92	0.03	−0.97 – −0.86	**<0.001**	21,714
SESSION 2	−0.04	0.01	−0.07 – −0.02	**<0.001**	21,714
SIDER	0.01	0.01	−0.02 – 0.04	0.695	21,714
1.5 mA	0.02	0.01	−0.00 – 0.04	0.067	21,714
3 mA	0.01	0.01	−0.02 – 0.03	0.525	21,714
SIDE Right: 1.5 mA	−0.01	0.02	−0.04 – 0.02	0.414	21,714
SIDE Right: 3 mA	−0.02	0.02	−0.05 – 0.02	0.382	21,714
Random Effects					
σ^2	0.88				
$\tau_{00\ PARTICIPANT}$	0.01				
ICC	0.02				
Observations	21,750				
Marginal R^2 / Conditional R^2	0.001 / 0.017				
AIC	45,609.135				

Probability Scores								
SIDE	*COND.*	*SESSION*	*contrast*	*estim.*	*SE*	*df*	*t.ratio*	*p.value*
Left	Sham	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0008**
Right	Sham	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0009**
Left	1.5 mA	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0008**
Right	1.5 mA	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0009**
Left	3 mA	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0009**
Right	3 mA	.	SESSION 2 - SESSION 1	−0.0437	0.0113	21,714	−3.869	**0.0008**
.	Sham	1	Right - Left	0.00584	0.0149	21,714	0.392	0.9992
.	Sham	2	Right - Left	0.00584	0.0149	21,714	0.392	0.9992
.	1.5 mA	1	Right - Left	−0.00732	0.0152	21,714	−0.48	0.9976
.	1.5 mA	2	Right - Left	−0.00732	0.0152	21,714	−0.48	0.9976
.	3 mA	1	Right - Left	−0.00934	0.0145	21,714	−0.645	0.9882
.	3 mA	2	Right - Left	−0.00934	0.0145	21,714	−0.645	0.9882
Left	.	1	1.5 mA - Sham	0.0205	0.0112	21,714	1.835	0.3697
Left	.	1	3 mA - 1.5 mA	−0.0132	0.0112	21,714	−1.175	0.8205
Left	.	2	1.5 mA - Sham	0.0205	0.0112	21,714	1.835	0.37
Left	.	2	3 mA - 1.5 mA	−0.0132	0.0112	21,714	−1.175	0.8205
Right	.	1	1.5 mA - Sham	0.00735	0.0111	21,714	0.661	0.9866
Right	.	1	3 mA - 1.5 mA	−0.01522	0.0114	21,714	−1.34	0.7169
Right	.	2	1.5 mA - Sham	0.00735	0.0111	21,714	0.661	0.9866
Right	.	2	3 mA - 1.5 mA	−0.01522	0.0114	21,714	−1.34	0.717

Degrees-of-freedom method: containment.
P value adjustment: mvt method for 20 tests.

Probability Scores							
SESSION	*SIDE*	*Condition*	*emmean*	*SE*	*df lo*	*wer.CL up*	*per.CL*
1	Left	Sham	−0.916	0.0266	29	−0.998	−0.833
2	Left	Sham	−0.959	0.0271	29	−1.044	−0.875
1	Right	Sham	−0.91	0.0272	29	−0.994	−0.825
2	Right	Sham	−0.954	0.0267	29	−1.037	−0.87
1	Left	1.5 mA	−0.895	0.0267	29	−0.978	−0.812
2	Left	1.5 mA	−0.939	0.0272	29	−1.024	−0.854
1	Right	1.5 mA	−0.903	0.0272	29	−0.987	−0.818
2	Right	1.5 mA	−0.946	0.0267	29	−1.029	−0.863
1	Left	3 mA	−0.908	0.0266	29	−0.991	−0.826
2	Left	3 mA	−0.952	0.027	29	−1.036	−0.868
1	Right	3 mA	−0.918	0.0269	29	−1.001	−0.834
2	Right	3 mA	−0.961	0.0268	29	−1.045	−0.878

Confidence level used: 0.95.
Conf-level adjustment: bonferroni method for 12 estimates.

Appendix 7. Effects of stimulation protocols on Value – Statistical report

	Value				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
(Intercept)	58.22	0.65	56.95 – 59.48	**<0.001**	21,714
SESSION 2	−0.23	0.24	−0.69 – 0.24	0.342	21,714
SIDER	0.23	0.31	−0.37 – 0.83	0.455	21,714
1.5 mA	0.49	0.22	0.06 – 0.92	**0.026**	21,714

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	Value				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
3 mA	0.78	0.23	0.34 – 1.23	**0.001**	21,714
SIDE Right: 1.5 mA	−0.55	0.32	−1.17 – 0.07	0.082	21,714
SIDE Right: 3 mA	−1.11	0.34	−1.79 – −0.44	**0.001**	21,714
Random Effects					
σ^2	998.17				
$\tau_{00\ PARTICIPANT}$	5.04				
Observations	21,750				
Marginal R^2 / Conditional R^2	0.000 / NA				
AIC	182,128.48				

Value								
SIDE	*COND.*	*SESSION*	*contrast*	*estim.*	*SE*	*df*	*t.ratio*	*p.value*
Left	Sham	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.9239
Right	Sham	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.9239
Left	1.5 mA	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.9239
Right	1.5 mA	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.9239
Left	3 mA	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.924
Right	3 mA	.	SESSION 2 - SESSION 1	−0.2265	0.238	21,714	−0.951	0.924
.	Sham	1	Right - Left	0.2287	0.306	21,714	0.748	0.9752
.	Sham	2	Right - Left	0.2287	0.306	21,714	0.748	0.9752
.	1.5 mA	1	Right - Left	−0.3225	0.313	21,714	−1.03	0.8931
.	1.5 mA	2	Right - Left	−0.3225	0.313	21,714	−1.03	0.8931
.	3 mA	1	Right - Left	−0.8848	0.297	21,714	−2.983	**0.0212**
.	3 mA	2	Right - Left	−0.8848	0.297	21,714	−2.983	**0.0214**
Left	.	1	1.5 mA - Sham	0.4902	0.22	21,714	2.227	0.1687
Left	.	1	3 mA - 1.5 mA	0.2928	0.221	21,714	1.323	0.7283
Left	.	2	1.5 mA - Sham	0.4902	0.22	21,714	2.227	0.1689
Left	.	2	3 mA - 1.5 mA	0.2928	0.221	21,714	1.323	0.7283
Right	.	1	1.5 mA - Sham	−0.0609	0.219	21,714	−0.279	0.9999
Right	.	1	3 mA - 1.5 mA	−0.2695	0.224	21,714	−1.202	0.8054
Right	.	2	1.5 mA - Sham	−0.0609	0.219	21,714	−0.279	0.9999
Right	.	2	3 mA - 1.5 mA	−0.2695	0.224	21,714	−1.202	0.8053

Degrees-of-freedom method: containment.
P value adjustment: mvt method for 20 tests.

Value							
SESSION	*SIDE*	*Condition*	*emmean*	*SE*	*df lo*	*wer.CL up*	*per.CL*
1	Left	Sham	58.2	0.647	29	56.2	60.2
2	Left	Sham	58	0.655	29	56	60
1	Right	Sham	58.4	0.658	29	56.4	60.5
2	Right	Sham	58.2	0.65	29	56.2	60.2
1	Left	1.5 mA	58.7	0.649	29	56.7	60.7
2	Left	1.5 mA	58.5	0.659	29	56.4	60.5
1	Right	1.5 mA	58.4	0.659	29	56.3	60.4
2	Right	1.5 mA	58.2	0.65	29	56.1	60.2
1	Left	3 mA	59	0.646	29	57	61
2	Left	3 mA	58.8	0.655	29	56.7	60.8
1	Right	3 mA	58.1	0.653	29	56.1	60.1
2	Right	3 mA	57.9	0.65	29	55.9	59.9

Confidence level used: 0.95.
Conf-level adjustment: bonferroni method for 12 estimates.

Appendix 8. Effects of stimulation protocols on Response Time – Statistical report

	Response Time				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
(Intercept)	0.95	0.04	0.87 – 1.03	**<0.001**	20,111
SESSION2	−0.18	0.06	−0.30 – −0.05	**0.006**	20,111
SIDER	−0.02	0.06	−0.15 – 0.10	0.741	20,111
INTENSITYB	−0.03	0.01	−0.05 – −0.02	**<0.001**	20,111
INTENSITYC	−0.02	0.01	−0.04 – −0.00	**0.021**	20,111
SESSION2:SIDER	0.02	0.13	−0.23 – 0.27	0.853	20,111
SESSION2:INTENSITYB	0.02	0.01	−0.01 – 0.04	0.165	20,111
SESSION2:INTENSITYC	0.03	0.01	0.00 – 0.05	**0.028**	20,111
SIDER:INTENSITYB	0.09	0.01	0.07 – 0.12	**<0.001**	20,111
SIDER:INTENSITYC	0.09	0.01	0.07 – 0.12	**<0.001**	20,111

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	Response Time				
Predictors	*Estimates*	*std. Error*	*CI*	*p*	*df*
SESSION2:SIDER:INTENSITYB	−0.09	0.02	−0.13 – −0.06	**<0.001**	20,111
SESSION2:SIDER:INTENSITYC	−0.1	0.02	−0.14 – −0.07	**<0.001**	20,111
Random Effects					
σ^2	0.08				
$\tau_{00\ PARTICIPANT}$	0.03				
ICC	0.26				
Observations	20,152				
Marginal R^2 / Conditional R^2	0.070 / 0.311				
AIC	6207.563				

Response Time								
SIDE	*COND.*	*SESSION*	*contrast*	*estim.*	*SE*	*df*	*t.ratio*	*p.value*
Left	Sham	.	SESSION 2 - SESSION 1	−0.17594	0.06421	20,111	−2.74	0.0572
Right	Sham	.	SESSION 2 - SESSION 1	−0.15231	0.06427	20,111	−2.37	0.1533
Left	1.5 mA	.	SESSION 2 - SESSION 1	−0.15836	0.06426	20,111	−2.464	0.1209
Right	1.5 mA	.	SESSION 2 - SESSION 1	−0.22497	0.06424	20,111	−3.502	0.0046
Left	3 mA	.	SESSION 2 - SESSION 1	−0.14801	0.06421	20,111	−2.305	0.1791
Right	3 mA	.	SESSION 2 - SESSION 1	−0.22754	0.06425	20,111	−3.542	0.0039
.	Sham	1	Right - Left	−0.02122	0.06425	20,111	−0.33	1
.	Sham	2	Right - Left	0.00241	0.06423	20,111	0.038	1
.	1.5 mA	1	Right - Left	0.06921	0.06426	20,111	1.077	0.9426
.	1.5 mA	2	Right - Left	0.0026	0.06425	20,111	0.04	1
.	3 mA	1	Right - Left	0.07074	0.06425	20,111	1.101	0.9349
.	3 mA	2	Right - Left	−0.00878	0.06421	20,111	−0.137	1
Left	.	1	1.5 mA - Sham	−0.03488	0.00831	20,111	−4.197	0.0003
Left	.	1	3 mA - 1.5 mA	0.01589	0.00822	20,111	1.933	0.3887
Left	.	2	1.5 mA - Sham	−0.01729	0.00957	20,111	−1.808	0.4789
Left	.	2	3 mA - 1.5 mA	0.02624	0.00985	20,111	2.664	0.0705
Right	.	1	1.5 mA - Sham	0.05556	0.00978	20,111	5.682	<0.0001
Right	.	1	3 mA - 1.5 mA	0.01743	0.01009	20,111	1.727	0.5412
Right	.	2	1.5 mA - Sham	−0.0171	0.00822	20,111	−2.081	0.2927
Right	.	2	3 mA - 1.5 mA	0.01486	0.00802	20,111	1.851	0.4467

Degrees-of-freedom method: containment.
P value adjustment: mvt method for 20 tests.

Response Time							
SESSION	*SIDE*	*Condition*	*emmean*	*SE*	*df lo*	*wer.CL up*	*per.CL*
1	L	A	0.953	0.0406	29	0.826	1.079
2	L	A	0.777	0.0497	29	0.622	0.931
1	R	A	0.931	0.0498	29	0.777	1.086
2	R	A	0.779	0.0407	29	0.653	0.906
1	L	B	0.918	0.0407	29	0.791	1.044
2	L	B	0.759	0.0498	29	0.605	0.914
1	R	B	0.987	0.0498	29	0.832	1.142
2	R	B	0.762	0.0406	29	0.636	0.888
1	L	C	0.934	0.0406	29	0.807	1.06
2	L	C	0.786	0.0497	29	0.631	0.94
1	R	C	1.004	0.0498	29	0.85	1.159
2	R	C	0.777	0.0406	29	0.651	0.903

Confidence level used: 0.95.
Conf-level adjustment: bonferroni method for 12 estimates.

Appendix 9. EEG analyses. Theta power changes per electrode measured

Elect.	**Elect. Side**	**Stim. Side**	**Condition**	**Estimates**	**std. Error**	**CI**	**p**	**df**
F1	left	left	RESTING STATE (Baseline)	−0,34	0,14	−0,62 – −0,06	**0,016**	198
F1	left	left	SHAM	0,25	0,07	0,10 – 0,39	**0,001**	198
F1	left	left	1,5 mA	0,15	0,07	0,00 – 0,30	**0,047**	198
F1	left	left	3 mA	0,18	0,07	0,04 – 0,33	**0,013**	198
F1	left	right	RESTING STATE	−0,05	0,08	−0,20 – 0,10	0,519	198
F1	left	right	SHAM	−0,1	0,11	−0,31 – 0,11	0,345	198
F1	left	right	1,5 mA	0	0,11	−0,22 – 0,21	0,981	198
F1	left	right	3 mA	0	0,11	−0,21 – 0,21	0,996	198
F5	left	left	RESTING STATE (Baseline)	0,13	0,14	−0,15 – 0,41	0,353	198
F5	left	left	SHAM	0,24	0,07	0,11 – 0,38	**0,001**	198
F5	left	left	1,5 mA	0,13	0,07	−0,01 – 0,27	**0,065**	198
F5	left	left	3 mA	0,17	0,07	0,04 – 0,31	**0,013**	198

(*continued on next page*)

(*continued*)

Elect.	Elect. Side	Stim. Side	Condition	Estimates	std. Error	CI	p	df
F5	left	right	RESTING STATE	0,03	0,07	−0,11 – 0,17	0,678	198
F5	left	right	SHAM	−0,14	0,1	−0,34 – 0,06	0,171	198
F5	left	right	1,5 mA	−0,03	0,1	−0,23 – 0,17	0,786	198
F5	left	right	3 mA	−0,02	0,1	−0,21 – 0,18	0,881	198
F2	right	left	RESTING STATE (Baseline)	−0,4	0,14	−0,67 – −0,12	**0,005**	198
F2	right	left	SHAM	0,25	0,06	0,13 – 0,38	**<0,001**	198
F2	right	left	1,5 mA	0,15	0,06	0,02 – 0,27	**0,025**	198
F2	right	left	3 mA	0,18	0,06	0,05 – 0,30	**0,006**	198
F2	right	right	RESTING STATE	0,06	0,07	−0,07 – 0,19	0,352	198
F2	right	right	SHAM	−0,16	0,09	−0,34 – 0,03	0,093	198
F2	right	right	1,5 mA	−0,01	0,09	−0,20 – 0,17	0,883	198
F2	right	right	3 mA	−0,02	0,09	−0,20 – 0,16	0,822	198
F6	right	left	RESTING STATE (Baseline)	0,15	0,14	−0,12 – 0,42	0,272	198
F6	right	left	SHAM	0,24	0,07	0,11 – 0,37	**<0,001**	198
F6	right	left	1,5 mA	0,14	0,07	0,01 – 0,27	**0,035**	198
F6	right	left	3 mA	0,2	0,06	0,07 – 0,32	**0,003**	198
F6	right	right	RESTING STATE	−0,11	0,07	−0,24 – 0,02	0,104	198
F6	right	right	SHAM	−0,1	0,09	−0,29 – 0,08	0,265	198
F6	right	right	1,5 mA	0	0,1	−0,18 – 0,19	0,96	198
F6	right	right	3 mA	0,01	0,09	−0,17 – 0,20	0,879	198
FpZ	midline	left	RESTING STATE (Baseline)	0,32	0,14	0,05 – 0,60	**0,022**	198
FpZ	midline	left	SHAM	0,22	0,07	0,09 – 0,35	**0,001**	198
FpZ	midline	left	1,5 mA	0,14	0,07	0,01 – 0,27	**0,039**	198
FpZ	midline	left	3 mA	0,18	0,07	0,05 – 0,31	**0,007**	198
FpZ	midline	right	RESTING STATE	−0,03	0,07	−0,16 – 0,11	0,703	198
FpZ	midline	right	SHAM	−0,11	0,1	−0,30 – 0,08	0,254	198
FpZ	midline	right	1,5 mA	−0,02	0,1	−0,21 – 0,17	0,839	198
FpZ	midline	right	3 mA	0,02	0,1	−0,17 – 0,21	0,857	198
FZ	midline	left	RESTING STATE (Baseline)	−0,44	0,13	−0,70 – −0,18	**0,001**	198
FZ	midline	left	SHAM	0,22	0,07	0,09 – 0,35	**0,001**	198
FZ	midline	left	1,5 mA	0,12	0,07	−0,01 – 0,26	0,072	198
FZ	midline	left	3 mA	0,14	0,07	0,01 – 0,27	**0,033**	198
FZ	midline	right	RESTING STATE	−0,03	0,07	−0,17 – 0,12	0,714	198
FZ	midline	right	SHAM	−0,08	0,1	−0,27 – 0,11	0,426	198
FZ	midline	right	1,5 mA	0,05	0,1	−0,15 – 0,25	0,604	198
FZ	midline	right	3 mA	0,07	0,1	−0,12 – 0,26	0,477	198

Appendix 10. Effects of resting state theta power on Risk

Predictors	Estimates	std. Error	CI	p	df
(Intercept)	26.24	0.36	25.53 – 26.94	<0.001	21,730
AVLEFTPRE	2.95	2.20	−1.36 – 7.26	0.180	21,730
AVRIGHTPRE	−2.89	3.16	−9.08 – 3.30	0.360	21,730
AVMIDLINEPRE	−0.46	3.28	−6.88 – 5.97	0.889	21,730
Session [2]	−0.31	0.06	−0.44 – −0.18	<0.001	21,730
Side [Right]	−0.04	0.11	−0.26 – 0.18	0.711	21,730
1.5mA	0.14	0.12	−0.10 – 0.39	0.237	21,730
3 mA	0.16	0.12	−0.08 – 0.39	0.188	21,730
AVLEFTPRE × AVRIGHTPRE	−1.12	0.37	−1.84 – −0.39	0.002	21,730
SIDE [R]: 1.5mA	−0.18	0.16	−0.49 – 0.12	0.238	21,730
SIDE [R]: 3 mA	−0.38	0.15	−0.69 – −0.08	0.013	21,730
AVLEFTPRE: 1.5mA	−0.56	0.69	−1.91 – 0.80	0.420	21,730
AVLEFTPRE: 3 mA	−0.52	0.68	−1.85 – 0.81	0.444	21,730
AVRIGHTPRE: 1.5mA	1.98	0.98	0.06 – 3.91	0.044	21,730
AVRIGHTPRE: 3 mA	0.47	0.98	−1.45 – 2.38	0.634	21,730
AVMIDLINEPRE: 1.5mA	−1.73	1.03	−3.76 – 0.29	0.093	21,730
AVMIDLINEPRE: 3 mA	0.26	1.01	−1.73 – 2.25	0.798	21,730

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