Frontopolar theta oscillations link metacognition with prospective decision making

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Prospective decision making considers the future consequences of actions and therefore requires agents to represent their present subjective preferences reliably across time. Here, we test the link of frontopolar theta oscillations to both metacognitive ability and prospective choice behavior. We target these oscillations with transcranial alternating current stimulation while participants make decisions between smaller-sooner and larger-later monetary rewards and rate their choice confidence after each decision. Stimulation designed to enhance frontopolar theta oscillations increases metacognitive accuracy in reports of subjective uncertainty in intertemporal decisions. Moreover, the stimulation also enhances the willingness of participants to restrict their future access to short-term gratification by strengthening the awareness of potential preference reversals. Our results suggest a mechanistic link between frontopolar theta oscillations and metacognitive knowledge about the stability of subjective value representations, providing a potential explanation for why frontopolar cortex also shields prospective decision making against future temptation.
Beliefs about our economic preferences guide our behavior no less than these preferences themselves: For example, only if we are aware of our health goals and our weakness for chocolate may we avoid the sweets shelf in the supermarket. How precisely we can gauge our preferences is determined by our metacognitive abilities, which appear crucial for successful behavioral control given their contributions to symptoms of several psychiatric disorders. In value-based choice, our metacognitive abilities allow us to judge how confident we are in our preferences. While numerous studies investigated how such economic preferences are represented in the brain, less is known about the neural mechanisms that guide value-based decision making by metacognitive judgments of preferences. The psychological literature conceptualizes metacognition as a construct that allows explaining the accuracy of introspective confidence reports, but for a long time it has been debated whether metacognition represents also a natural kind at the neural level. Previous research has documented a correlative link between metacognition in value-based choice and activity in the frontopolar cortex (FPC), but it remains unclear whether this FPC activity indeed causally contributes to choice-related confidence or whether it just relates to confidence without any behavioral implications. To decide whether FPC activity constitutes a functionally relevant neural substrate of metacognition, rather than just a correlate of behaviors associated with metacognition, it is necessary to show that modulating FPC excitability changes metacognitive confidence reports. Previous brain stimulation studies on perceptual decision making have yielded the puzzling finding that FPC disruption improves rather than disrupts metacognitive readout of confidence, challenging theoretical accounts associating FPC activation with better metacognition. Thus, it remains a matter of controversial debate what role FPC activity plays for representing metacognitive judgments and using them to guide behavior.

In particular, it is unclear how exactly prospective decision making—choices that concern future outcomes—relies on metacognitive awareness of preferences as encoded by the FPC. In the current example, knowing about their individual personal tendency to eat chocolate even though this runs counter to long-term health goals is an individual’s awareness of preferences as encoded by the FPC. In the current example, knowing about their individual personal tendency to eat chocolate even though this runs counter to long-term health goals indicates whether an individual can reliably forecast future decisions or task performance. If FPC activity constitutes a neural substrate for metacognition, theta-tACS over FPC should improve metacognition in both retrospective judgments and prospective decision making. We, therefore, assessed the impact of FPC tACS on (1) a confidence accuracy task measuring metacognition as the accuracy of retrospective confidence judgments and (2) a task measuring metacognition as the capacity to assess the risk of preference reversal in prospective self-control decisions about whether to restrict one’s access to future temptations. Lastly, because prospective self-control represents only an implicit indicator of metacognition, we also tested the hypothesis that higher metacognitive skills quantified by explicit retrospective confidence judgments predict better prospective self-control, as posited by formal models of precommitment.

Here, we show that enhancing FPC theta-band oscillations improves both metacognitive accuracies in retrospective judgments concerning intertemporal decision making and the willingness to restrict the access to temptations when anticipating preference reversals. This deepens our understanding of the neural basis of metacognition and suggests a neural link between metacognition and prospective decision-making.

Results

Thirty-seven participants received theta (5 Hz), control-gamma (80 Hz), and sham tACS over FPC (within-subject design) while performing a confidence accuracy task and a precommitment task. tACS non-invasively modulates brain rhythms in a frequency-specific manner, which allows establishing causal relationships between brain oscillations and behavior. The confidence accuracy task required participants to make choices between a smaller-sooner (SS) and a larger-later (LL) reward (e.g., 8 Swiss francs today versus 10 Swiss francs in 20 days). After each choice, participants indicated their confidence in having made the best decision given their own preferences. The precommitment task also required decisions between SS and LL rewards, and participants had to decide between a binding choice of the LL reward (e.g., 7 Swiss francs in 68 days, precommitment) or postponing the decision between the SS and LL reward (e.g., 7 Swiss francs in 28 days or 10 Swiss francs in 68 days). If they chose to postpone the decision, participants were re-contacted after the interval associated with the SS reward (28 days in the example) and had to make the final decision between the two options, with the delays adjusted for the elapsed time (in the example, 7 Swiss francs today versus 10 Swiss francs in 40 days). Thus, individuals who are aware that they may reverse their preference from the LL reward at the first choice to the SS reward in 28 days should prefer to precommit to the LL reward at the first choice opportunity. Note that anticipation of possible preference reversals requires metacognitive access to individual time preferences, such that participants with better metacognitive ability should choose the precommitment option more frequently when the risk of preference reversals increases.

Theta-tACS increases metacognitive sensitivity. Metacognitive awareness of economic preferences can be determined by
assessing an individual’s ability to reliably perceive uncertainty in the decision process. This uncertainty decreases with the difference in subjective value between the choice options, as expressed in the choices of the individual. Specifically, individuals with high metacognitive sensitivity report high levels of confidence when the decision uncertainty they reveal in their choices is low, and low confidence when revealed decision uncertainty is high. In contrast, agents with low metacognitive skills show no systematic relationship between confidence reports and revealed decision uncertainty.

To test our hypotheses, we first determined the subjective value of each choice option by fitting hyperbolic discount functions to the individual choice data, separately for each tACS condition (see “Methods”). Discount parameters \( k \) did not differ significantly between stimulation conditions, Wilcoxon rank-sum tests, all \( W < 651 \), all \( p > 0.72 \). Moreover, tACS did not affect mean confidence ratings, paired-samples \( t \) tests, all \( t < 1 \), all \( p > 0.67 \). Thus, there was no evidence that frontopolar stimulation changed time preferences or decision confidence per se. To assess whether tACS affects the relationship between confidence and decision uncertainty, we used a mixed generalized linear model (MGLM). Specifically, we regressed binary choices of LL vs. SS rewards in the confidence accuracy task on predictors for tACS (tACS\(_{\text{theta-sham}}\) and tACS\(_{\text{theta-gamma}}\), the signed difference in value (DV, with the subjective value of the LL reward given by the individual hyperbolic discount functions) between LL and SS rewards, confidence ratings, as well as the interactions between these predictors. We assessed how theta stimulation changes behavior relative to both sham tACS (tACS\(_{\text{theta-sham}}\)) and gamma tACS (tACS\(_{\text{theta-gamma}}\)) as an active control condition. The degree to which DV predicts choice is a measure of revealed decision uncertainty (with steeper logistic curves corresponding to lower decision uncertainty). Thus, the strength of the interaction between DV and confidence indicates metacognitive ability, i.e., how reliably an individual can track and report noise in the decision process. Overall, participants showed a significant DV x confidence interaction, \( \beta = 2.22, \ CI_{\text{bootstrap}} = [1.19–3.43] \), suggesting that they indeed had metacognitive access to their decision uncertainty while making intertemporal choices.

In line with our hypothesis, the ability to report decision uncertainty was significantly increased under theta tACS, both relative to sham tACS, tACS\(_{\text{theta-sham}}\) x DV x confidence, \( \beta = 2.57, \ CI_{\text{bootstrap}} = [1.32–4.34] \), and gamma tACS, tACS\(_{\text{theta-gamma}}\) x DV x Confidence, \( \beta = 1.39, \ CI_{\text{bootstrap}} = [0.37–2.80] \) (Fig. 2 and Table 1). We note that this result pattern was robust to controlling for potential tACS effects on confidence (which were non-significant, as shown above) by subtracting the mean confidence rating in each tACS condition from confidence scores (tACS\(_{\text{theta-sham}}\) x DV x Confidence, \( \beta = 2.38, \ CI_{\text{bootstrap}} = [1.44–4.06] \); tACS\(_{\text{theta-gamma}}\) x DV x Confidence, \( \beta = 1.36, \ CI_{\text{bootstrap}} = [0.38–2.81] \)). An additional MGLM assessing specifically differences between gamma and sham tACS showed a significant tACS\(_{\text{gamma-sham}}\) x DV x Confidence interaction, \( \beta = 1.14, \ CI_{\text{bootstrap}} = [0.31–2.24] \). This may point to some frequency-unspecific stimulation effects. Importantly, however, the effects of theta tACS were significantly stronger than those of gamma tACS, demonstrating specific effects of theta tACS. Individual coefficients (Fig. 2D) suggest that variation in metacognitive sensitivity was larger under theta compared with sham and gamma tACS. This pattern might result from variation in the degree of alignment between individual frontopolar theta rhythms and the applied stimulation frequency of 5 Hz, or from individual differences in the general susceptibility to brain stimulation factors which add to the variation in baseline metacognitive sensitivity. This suggests interesting hypotheses for future experiments that may directly manipulate these factors. Irrespective of these considerations, our present results show that stimulation designed to enhance frontopolar theta oscillations indeed improves the ability to track objective decision uncertainty, supporting the view that these oscillations constitute a causal neural mechanism enabling metacognition of value-based choice processes.

**Theta tACS increases sensitivity to benefits of commitment.** Having established that frontopolar theta tACS improves metacognition, we next asked whether participants apply metacognitive knowledge to restrict their access to temptations in the precommitment task. Metacognitively sophisticated individuals should...
increasingly prefer to precommit as the risk of preference reversals increases, i.e., the more they switch to preferring the SS over the LL reward at the final choice even though they preferred the LL over the SS option initially. To assess how tACS changes this willingness to precommit with increasing risk of preference reversals, we regressed binary choices in the precommitment task on predictors for tACS (tACS\_theta-sham and tACS\_theta-gamma), the signed value difference between the LL and SS reward at the first choice instance (DV\_initial), Preference-reversal risk (DV\_final − DV\_initial), and the interaction terms. DV\_initial and DV\_final were again computed based on the individual hyperbolic discount functions. The variable Reversal risk captured the increase of the subjective value of the SS relative to the LL reward at the final choice in case of choice postponement (i.e., for the second choice; DV\_final) compared with the initial (current) choice (DV\_initial), thus measuring the risk of preference reversals for each combination of reward options (Reversal risk for a given option: DV\_final − DV\_initial). Again in line with our hypotheses, theta tACS increased the sensitivity of precommitment choices to potential preference reversals relative to sham, tACS\_theta-sham × Reversal risk, beta = 2.05, CI\_bootstrap = [0.04–6.24] (Fig. 3A, B and Table 2); this effect was stronger when participants currently preferred the LL over SS reward and might thus reverse their preference from the LL to the SS reward at the time of the final choice, tACS\_theta-sham × DV\_initial × Reversal risk, beta = 2.02, CI\_bootstrap = [0.45–4.20]. Also relative to gamma control stimulation, theta tACS increased sensitivity to preference reversal particularly when the LL option was currently preferred over the SS option, tACS\_theta-gamma × DV\_initial × Reversal risk, beta = 2.79, CI\_bootstrap = [0.15–6.48], even though the lower-level tACS\_theta-gamma × Reversal risk interaction was not significant, beta = −0.08, CI\_bootstrap = [−2.40 to 2.82]. A further analysis testing for differences between gamma and sham tACS provided no evidence for potential influences of gamma tACS on precommitment (all confidence intervals contained zero). Taken together, our findings show that FPC theta oscillations motivate precommitment decisions in particular during high risk of preference reversals.

Lastly, we tested whether metacognitive awareness of preference-based choice uncertainty (as measured in the confidence accuracy task) predicts the willingness to make binding LL reward choices in the precommitment task. Formal models of prospective decision-making propose that metacognitive awareness of one’s economic preferences should motivate voluntary self-restriction when the risk of preference reversals is high.\(^{12,16}\) Consistent with the predictions of theoretical accounts, individual estimates of metacognitive sensitivity (individual coefficients for DV × Confidence interaction under sham) significantly correlated with the propensity to precommit with increasing reversal risk (individual coefficients for Reversal risk), r = 0.61, p < 0.001 (Fig. 3C). We also tested whether low decision
confidence (indicated by participants’ mean confidence ratings) predicts higher willingness to precommit, as low confidence might be associated with a high general likelihood of changing one’s mind. Contrary to this proposal, there was a positive instead of negative correlation between confidence and precommitment, $r = 0.33$, $p = 0.05$, suggesting that individuals with low confidence avoided precommitment to LL rewards and preferred to postpone decisions instead. Lastly, also the strength of tACS effects on metacognition ($tACSt_{\text{theta-sham}} \times DV \times \text{Confidence}$) significantly predicted the impact of tACS on precommitment ($tACSt_{\text{theta-sham}} \times Reversal \text{ risk}$), $r = 0.56$, $p < 0.001$ (Fig. 3D).

Taken together, these findings support our hypothesis that agents with better metacognitive awareness of their time preferences show increased willingness to restrict their access to temptations to avoid preference reversals.

**Discussion**

For consistent (i.e., rational in the economic sense) decision-making, humans need to reliably represent their preferences. Here, we examined the causal neural mechanisms that implement metacognitive awareness of economic preferences and their impact on behavior. First, we show that stimulation designed to enhance frontopolar theta oscillations facilitates precommitment decisions as well. Thus, we improved metacognitive sensitivity under theta relative to sham tACS predicts stronger effects of frontopolar theta tACS on the sensitivity to the risk of preference reversals.

**Table 2 Results of MGLM explaining choices (1 = precommit, 0 = postpone decision) in the precommitment task.**

| Regressor | Beta    | 95% CI Bootstrap |
|-----------|---------|-----------------|
| Intercept | 1.33    | [-1.02 to 3.98] |
| $DV_{\text{initial}}$ | 3.06    | [1.85 to 4.66]  |
| Reversal risk | 1.40    | [-0.70 to 3.61] |
| $tACSt_{\text{theta-sham}}$ | 0.55    | [-0.28 to 2.86] |
| $tACSt_{\text{theta-gamma}}$ | -2.03   | [-4.12 to 0.52] |
| $DV_{\text{initial}} \times Reversal risk$ | -1.84   | [-3.76 to 0.12] |
| $DV_{\text{initial}} \times tACSt_{\text{theta-sham}}$ | 0.74    | [-0.22 to 2.90] |
| $DV_{\text{initial}} \times tACSt_{\text{theta-gamma}}$ | 0.09    | [-1.27 to 2.19] |
| Reversal risk $\times tACSt_{\text{theta-sham}}$ | 2.05    | [0.04 to 6.24]  |
| Reversal risk $\times tACSt_{\text{theta-gamma}}$ | -0.08   | [-2.40 to 2.82] |
| $DV_{\text{initial}} \times Reversal risk \times tACSt_{\text{theta-sham}}$ | 2.02    | [0.45 to 4.20]  |
| $DV_{\text{initial}} \times Reversal risk \times tACSt_{\text{theta-gamma}}$ | 2.79    | [0.15 to 6.48]  |

...theoretical models, agents with higher metacognitive sensitivity showed the strongest sensitivity to precommitment demands under sham. Improved metacognitive sensitivity under theta relative to sham tACS predicts stronger effects of frontopolar theta tACS on the sensitivity to the risk of preference reversals.

In line with theoretical models, agents with higher metacognitive sensitivity showed the strongest sensitivity to precommitment demands under sham. Improved metacognitive sensitivity under theta relative to sham tACS predicts stronger effects of frontopolar theta tACS on the sensitivity to the risk of preference reversals.
Our findings support this view, which is compatible with FPC’s proposed position at the top of a hierarchy of control processes. It may receive a readout of confidence signals from VMpFC or DLpFC. Indeed, theta oscillations have been related to decision-making processes in DLpFC and VMpFC, and prefrontal theta was shown to reflect both objective choice difficulty and self-reported confidence. Theta oscillations might thus enable the FPC to synchronize with these regions and metacognitively access decision-related information like choice difficulty encoded in the theta frequency. It is worth noting that the FPC was related to metacognition in both value-based and perceptual decision making, supporting a domain-general role in mediating between confidence representations and action planning. Our findings support domain generality by linking FPC to metacognition in both retrospective and prospective value judgments.

We note that besides metacognition the FPC has also been related to other functions that might promote precommitment and future-oriented behavior, for example representing predictive cognitive maps or integrating interoceptive signals into goal-directed behavior. The FPC’s precise role in cognition is still controversially debated, and it is currently unclear how different views can be integrated. In the context of the current study, however, it seems most parsimonious to explain the stimulation effects on precommitment via the FPC’s role for metacognition, given the FPC’s well-established role for metacognition in the literature as well as the importance of metacognition for precommitment. We also note that due to the relatively low spatial specificity of tACS, we cannot rule out that the observed results reflect stimulation effects on brain regions adjacent to FPC, including the dorsomedial prefrontal cortex, VMpFC, and DLpFC. However, our current findings provide no evidence for tACS effects on confidence ratings or the degree of hyperbolic discounting, aspects of behavior that have been linked to VMpFC and DLpFC. Thus, stimulation effects on FPC provide a more parsimonious account of our data, but it remains to be seen whether the stimulation effects concern local activity or coherence of FPC communication with other brain regions. Finally, it is worth mentioning that our experimental design did not include an active control region, which further underlines that we cannot draw strong conclusions regarding the local specificity of the observed stimulation effects.

While our data reinforce theoretical assumptions on the FPC’s role for metacognition, they may appear in conflict with previous stimulation studies reporting that disrupting FPC functioning with transcranial magnetic stimulation (TMS) improved, rather than impaired, metacognition in perceptual decision making. However, TMS over FPC is commonly perceived as rather aversive by participants, and these studies did not statistically control for tACS-induced discomfort (see below). The study was approved by the ethics committee of Canton Zurich.

Methods

Participants. A total of 38 volunteers (Mage = 22.9 years, range = 19–31, 17 females) participated in this within-subject study. The sample size was determined with a power analysis (alpha = 5%, two-tailed, power = 80%) based on our previous tDCS study on precommitment. One participant terminated prematurely due to tACS-induced side effects (dizziness). The data of this participant were therefore discarded from the analyses. All volunteers gave informed written consent before participating. They received a fixed compensation of 70 Swiss francs plus a performance-dependent bonus (see below). The study was approved by the ethics committee of Canton Zurich.

Stimuli and task design

Confidence accuracy task. To determine metacognitive awareness of their economic preferences, participants performed a monetary intertemporal choice task (programmed in Matlab using the Cogent toolbox). In each trial, they chose between an immediate reward (0–10 Swiss francs) and a delayed reward (100 days later). Participants were then required to indicate the perceived accuracy of their choice after the 100-day delay (as a percentage from 0% to 100%). We used this delayed feedback procedure to make the decision and the reported confidence converge for the purposes of our analysis. At the end of the experiment, participants indicated the tDCS-induced discomfort, whether they perceived the discomfort as annoying during the tACS, as well as whether the discomfort or flickering affected their task performance on Likert scales from 1 to 9. The mean ratings reported for discomfort and flickering were 4.1 and 5.6, respectively, but participants reported only low to moderate disturbing influences during tACS (mean = 3.4) and flickering (mean = 2.9) on task performance. In order to control for any influences of tACS-induced irritations on task performance, we added the individual ratings for the impact of discomfort and...
flickering on task performance as control variables to all statistical models. For the payment, one trial of the two tasks was randomly selected and the corresponding amount was paid out after the associated delay. In case a trial of the precommitment task was chosen where participants had decided to postpone the decision, they were re-contacted 28 days after the experimental session and had to make a final choice between the SS and LL option. If participants chose an option to be paid out after the experiment (either in the confidence accuracy or in the precommitment task), the given amount was sent to the participant via mail.

**TACS protocol.** We applied tACS using an 8-channel tDCS stimulator (DC-stimulator MC, neuroConn, Ilmenau, Germany). As previous studies suggest both metacognition and precommitment to be implemented by FPCs,14,18 we placed a smaller active 5 × 7 cm² electrode over electrode position Fpz and a larger 10 × 10 cm² electrode over CPz according to the international 10-20 system (Fig. 1D). Current modeling using the Simnibs 2.1 toolbox suggests that with this electrode setup current density is strongest in FPC while stimulation effects under the reference electrode are negligible. The electrodes were fixed to the participants’ heads by rubber straps. We used larger reference than active electrodes to minimize the stimulation effect at the vertex relative to the FPC site. We stimulated participants in the theta band (5 Hz) and gamma band (80 Hz) frequency with a current strength of 2 mA (peak-to-peak). The control frequency of 80 Hz was determined in pilot experiments to match the tACS-induced discomfort and phaseness between theta and control tACS. We note that phaseness appear to affect performance mainly in visual perception tasks40, and it seems much less likely that phaseness would affect (and in fact improve) value-based decision making, but we cannot logically rule out this possibility.

**Data analysis.** Data were analyzed with mixed generalized linear models (MGLMs) implemented in R using the lme4 package. The advantage of MGLMs over other statistical procedures is that MGLMs provide a better account of the full variance/covariance structure of the data, with binomially distributed binary dependent variables, compared to participant-specific aggregated approaches that neglect intra-individual variability on the trial level. In MGLMs statistical inferences are based on group-level fixed effect estimates while accounting for inter-individual variation via random effects. We assessed the significance of fixed effects by the 95% confidence intervals (CIbootstrap) determined via parametric bootstrap (implemented by the bootMer function in R), which provides more reliable results than p values based on Wald statistics. Importantly, our hypothesis that theta tACS improves metacognition is only supported by significant results for the comparisons between theta tACS and both sham tACS (passive control) and gamma tACS (as active control), and not by significant results for just one of these comparisons. Alpha correction for multiple comparisons was therefore not required41.

In the confidence accuracy task, we measured participants’ metacognitive awareness of their decision noise (uncertainty) following a previously described approach42. For that purpose, we first estimated each individual’s time preferences by fitting a hyperbolic discount function to the choices in the confidence accuracy task, separately for each tACS condition (Eq. 1):

\[
SV_{\text{LL}} = \frac{\text{LL reward magnitude}}{1 + k \times \text{delay}}
\]  

(1)

where \(SV_{\text{LL}}\) is the discounted subjective value of the LL reward option and \(k\) is a participant-specific constant that indicates the steepness of the discount function (discount factor). To translate subjective value into choices, we fitted a standard softmax function to each participant’s choices:

\[
P(\text{choice of LL option}) = \frac{1}{1 + e^{-r_{\text{LL}}(SV_{\text{LL}} - SV_{\text{SS}})}}
\]  

(2)

this function captures the likelihood of choosing the LL reward option as a function of the difference between the subjective value of the LL reward option (\(SV_{\text{LL}}\)) and the SS reward option (\(SV_{\text{SS}}\), with the inverse temperature parameter \(r_{\text{LL}}\) capturing the slope of the function, i.e., how strongly participants relied on this value difference for their choices. Individual parameters were estimated with a Bayesian approach (chains with 10,000 samples, the first 2000 samples were used as burn-in) using the 

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