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Research report

# Frontoparietal theta stimulation causally links working memory with impulsive decision making

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ABSTRACT

Delaying gratification in value-based decision making is canonically related to activation in the dorsolateral prefrontal cortex (dlPFC), but past research neglected that the dlPFC is part of a larger frontoparietal network. It is therefore unknown whether the dlPFC causally implements delay of gratification in concert with posterior parts of the frontoparietal network rather than in isolation. Here, we addressed this gap by testing the effects of frontoparietal theta synchronization and desynchronization on impulsive decision making using transcranial alternating current stimulation (tACS). Healthy participants performed an intertemporal choice task and a 3-back working memory task while left frontal and parietal cortices were stimulated with a 5 Hz theta frequency at in-phase (synchronization), anti-phase (desynchronization), or sham tACS. We found frontoparietal in-phase theta tACS to improve working memory performance, while in the decision task anti-phase tACS was associated with more impulsive choices and stronger hyperbolic discounting of future rewards. Overall, our findings suggest that future-oriented decision making might causally rely on synchronous activation in a frontoparietal network related to working memory.
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## 1. Introduction

The ability to delay gratification is a hallmark of individual success and psychological health (Baumeister, 2002; Bickel et al., 2019; Daugherty & Brase, 2010). A large body of evidence ascribes the dorsolateral prefrontal cortex (dlPFC) a central role for resisting immediate rewards in order to achieve long-term goals (Figner et al., 2010; McClure, Laibson, Loewenstein, & Cohen, 2004; Wesley & Bickel, 2014). As the dlPFC is part of the frontoparietal control network (Domenech, Redouté, Koechlin, & Dreher, 2018; Vincent, Kahn, Snyder, Raichle, & Buckner, 2008), it seems implausible to assume that dlPFC implements patience in intertemporal decisions in isolation rather than in concert with posterior regions like posterior parietal cortex (PPC). However, the majority of previous neural studies, and brain stimulation research in particular (Yang, Mauer, Vollm, & Khalifa, 2020; Yang, Vollm,

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& Khalifa, 2018), focused on the dlPFC either in isolation or in interaction with the neural reward system. Therefore, it remains unknown whether delaying gratification causally requires the dlPFC to synchronize activity with PPC.

Synchronous firing in dlPFC and PPC was already shown to play an important role for working memory processes, which in turn are hypothesized to contribute to delay of gratification (Hofmann, Schmeichel, & Baddeley, 2012). Synchronous, in-phase stimulation of dlPFC and PPC with transcranial alternating current stimulation (tACS) in the theta band enhanced working memory functioning, while desynchronous, out-of-phase stimulation impaired it (Alekseichuk, Pabel, Antal, & Paulus, 2017; Polania, Nitsche, Korman, Batsikadze, & Paulus, 2012; Violante et al., 2017). This suggests a causal role of functional coupling between dlPFC and PPC for working memory processes (thought there might be gender differences in the relative recruitment of dlPFC and PPC; see Hill, Laird, and Robinson (2014)). Importantly, working memory has been linked to patience in intertemporal choice, as working memory processes may allow maintaining abstract information like the value of long-term rewards in mind during intertemporal decisions. In particular, representations of the value of long-term rewards in working memory are considered as less concrete than immediately available outcomes (Fujita, 2011; Stillman et al., 2017), such that delay of gratification crucially relies on the strength of these value representations in working memory. Behavioral and neural findings support this link between delay of gratification and working memory: Behaviorally, working memory capacity predicts patience in intertemporal choice (Hofmann et al., 2012), and in the brain the neural correlates of working memory and intertemporal choice were found to strongly overlap (Jimura, Chushak, Westbrook, & Braver, 2018; Wesley & Bickel, 2014). We therefore hypothesized that strengthening value representations in working memory via synchronization versus desynchronization of frontoparietal activity promotes choices of long-term rewards.

To test our hypotheses, we aimed to synchronize and desynchronize theta band oscillations in dlPFC and PPC with tACS while participants performed a working memory and an intertemporal decision task. We expected to replicate previous findings that frontoparietal synchronization, relative to desynchronization, enhances working memory performance. We furthermore predicted that synchronization versus desynchronization of frontoparietal theta oscillations increases preferences for delayed over immediate rewards in the intertemporal decision task. This would provide evidence for a causal involvement of frontoparietal synchronization in delay of gratification and neurally link future-oriented intertemporal decisions to working memory functioning.

## 2. Methods

### 2.1. Participants

30 healthy volunteers (mean age = 24 years, sd = 2.88, 15 female, 15 male) were recruited through the participant pool of the Munich Experimental Laboratory for Economic and Social Sciences (MELESSA) at the Ludwig Maximilian University Munich, Germany. The sample size was determined with an apriori power analysis (power = 80%, alpha = 5%) assuming an effect size of Cohen's $d = .47$ from a previous study investigating the effect of phase synchronization on working memory (Alekseichuk et al., 2017). Volunteers were screened for counterindications to tACS prior to participation. Written informed consent was provided by all volunteers before the start of the experiment. Participants received a fixed compensation of 20 euros and an additional bonus depending on their decisions in the decision making task (see below). The study was approved by the local ethics committee of the psychology department at the University of Munich.

### 2.2. Stimuli and task design

*Working memory task*. Participants performed a 3-back working memory task. During the task, participants viewed a sequence of letters, and each letter was presented on the screen for 1.5 s (inter-stimulus interval: 1.5 sec; Fig. 1A). Stimuli were present in white (size: approx. 2° visual angle) against a grey background. The task was to indicate whether the letter currently displayed on the screen was identical with the letter presented 3 trials before (target stimulus). Participants had to indicate their responses before the start of the next trial. A block of the 3-back task with 40 trials included a total of 6 target stimuli. Participants were instructed to press the space button only if the current letter was a target.

*Intertemporal choice task*. Participants performed an intertemporal choice task where they chose between two monetary rewards that were available at different points in time: a smaller-sooner (SS) reward, which they obtained at the end of the experimental session (delay = 0 days), and a larger-later (LL) reward, which was delivered at a later date (Fig. 1B. The SS reward ranged from .5 to 4.5 euro in steps of .5 euro (9 levels), the LL was fixed at 5 euro and was delivered after 5–180 days (administered delays: 5, 10, 20, 50, 90, or 180 days). The two options were presented randomly on the left and right side of the screen and participants were asked to indicate their choice by pressing the left or right arrow key for the option on the left and right screen side, respectively, on a standard keyboard. Participants had 4 s to indicate their choice. After each decision, a fixation cross appeared on the screen for the remaining time of the 4 s, then the next trial started.

### 2.3. tACS protocol

We applied tACS using a 4-channel tDCS stimulator (DC-Stimulator MC, neuroConn, Ilmenau, Germany). As in Biel, Sterner, Roll, and Sauseng (2022), we employed a high-definition 2 × 1 electrode set up. For the dlPFC we placed the active electrode over position F3 and the reference electrodes over positions Fz and F7 according to the international 10–20 system. For the PPC, the active electrode was placed over electrode position P3 and the reference electrodes over electrode positions Pz and P7. We used square rubber electrodes (3 × 3 cm), which were attached to the participants' head with the Ten20 conductive paste (Ten20 EEG Conductive Paste, Weaver and Company) and were kept steady throughout the session using fixation bandages. We performed current modeling using the Simnibs 2.1 toolbox (Saturnino et al., 2019,

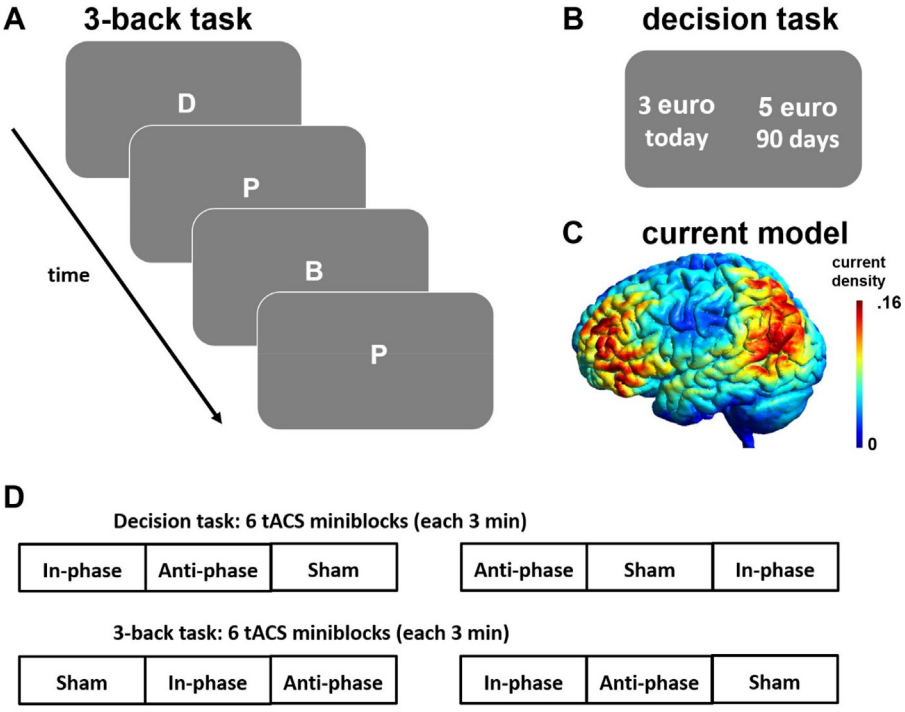


**Fig. 1 – Experimental procedures. (A) In the 3-back working memory task, participants had to decide whether the currently presented letter is identical with the letter presented three trials before, requiring them to constantly maintain and update information in their working memory. (B) In the intertemporal decision task, participants made choices between smaller-sooner (e.g., 3 euro delivered today) and larger-later (e.g., 5 euro after 90 days) rewards. (C) Participants performed these tasks while undergoing in-phase (synchronizing), anti-phase (desynchronizing), or sham tACS over the left prefrontal and parietal cortex. We placed 3 × 3 cm central electrodes over F3 and P3, which were surrounded by reference electrodes at Fz, F7, Pz, and P7. Stimulation intensity was 1.5 mA peak-to-peak (frequency = 5 Hz). Current flow simulations were performed with Simnibs 2.1 (Saturnino et al., 2019, pp. 3–25). (D) Participants performed six miniblocks for each task. The order of tACS conditions in the miniblocks was counterbalanced across participants.**

pp. 3–25), which suggested that this electrode set up led to strong and focal electrical fields in dlPFC and PPC, while stimulation effects between the two areas were negligible (Fig. 1C). We stimulated participants in three conditions: synchronization (in-phase theta band (5 Hz) stimulation of dlPFC and PPC), desynchronization (anti-phase theta band stimulation of the two areas), and sham with a current strength of 1.5 mA peak-to-peak.

### 2.4. *Procedure*

Participants performed the 3-back and the intertemporal choice task in three tACS conditions: frontoparietal synchronization, desynchronization, and sham (within-subject design). The intertemporal choice task included a total of 180 trials (60 trials per tACS condition), and the working memory task a total of 240 trials (80 per tACS condition). The tasks were administered in counterbalanced order and were performed in 12 miniblocks (2 per task and tACS condition; Fig. 1D). At the start of each miniblock, participants were stimulated with tACS for 30 s (current ramp-up: 5 s) without performing the task, followed by 120 s of task performance under stimulation. At the end of each miniblock, participants indicated whether they experienced any discomfort or flickering sensations due to the stimulation on a rating scale ranging from 0 (not at all) to 10 (very strongly). Note that we observed no significant effects of in-phase or anti-phase tACS on stimulation-induced discomfort, both $P > .15$, or flickering, both $P > .30$. In the sham condition, the current was ramped down prior to task performance. Participants had a 30 s task- and stimulation-free break between the miniblocks to minimize potential carry-over effects between stimulation blocks (Christian, Kapetaniou, & Soutschek, 2023; Moisa, Polania, Grueschow, & Ruff, 2016; Soutschek, Moisa, Ruff, & Tobler, 2021).

At the end of the experiment, participants filled in demographic questionnaires and were debriefed. For the payment, one trial from the intertemporal choice task was randomly selected and implemented: if the participant had chosen the SS option in that trial, the corresponding amount was added as bonus to the standard compensation, whereas if they chose the LL option 5 euro were sent to them on the corresponding date via mail.

### 2.5. *Statistical analysis*

In the *3-back task*, we analyzed tACS effects on reaction times and the sensitivity index d' (difference between z-transformed hits and false alarms: $Z_{hits}$ minus $Z_{false\ alarms}$ (Soutschek & Tobler, 2020; Westbrook, Kester, & Braver, 2013)) with repeated measures ANOVAs and paired-samples *t*-tests.

We Bonferroni-corrected the *P*-values of the *t*-tests for the number of post-hoc tests ($p_{corrected} = P \times 3$).

In the *intertemporal choice task*, we performed both model-free and model-based analyses. Model-based analyses of hyperbolic discounting quantify the influence of delay in reward delivery on value computations during intertemporal choice (Laibson, 1997), thereby providing insights into latent variables underlying observable choice behavior. The notion that frontoparietal coupling promotes delay of gratification predicts that tACS should affect both model-free and model-based measures of future-oriented decision making. Testing for model-free and model-based stimulation effects therefore allowed assessing the robustness of our findings, such that it was not necessary to correct for multiple comparisons here (Gelman, Hill, & Yajima, 2012). For the model-free analysis, we used generalized linear mixed models (GLMMs) implemented via the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2014). We regressed binary choices (0 = SS option, 1 = LL option) on predictors for tACS (synchronization versus sham and desynchronization versus sham), amount of SS reward, and delay of LL reward:

$$\begin{aligned}\mathrm{P(LL\ choice)} = {} & \mathrm{b_0} + \mathrm{b_1} \times \mathrm{tACS_{synchronization}} + \mathrm{b_2} \\ & \times \mathrm{tACS_{desynchronization}} + \mathrm{b_3} \times \mathrm{Reward} + \mathrm{b_4} \times \mathrm{Delay}\end{aligned}$$

All continuous variables were z-standardized, and all fixed-effect predictors were also modelled as random slopes in addition to participant-specific random intercepts. As control variables of no interest, we added random slopes for stimulation-induced discomfort and flickering. Due to the binary nature of the dependent variable, we assumed a binomial distribution with a logit link. All model assumptions (constant and normally distributed errors) were fulfilled. Conditional $R^2$ was .86. We also computed Bayes factors quantifying the evidence for the alternative relative to the null hypothesis ($BF_{10}$) following the approach described by Wagenmakers (2007).

Note that we performed the apriori power analysis for the working memory task due to the lack of an available effect size specifically for tACS effects in intertemporal choice. Moreover, power calculations for GLMM are based on simulations and commonly require the availability of empirical data. However, when we performed a posthoc power analysis for the GLMM on intertemporal choice (assuming the same effect size as for the 3-back task) with the SIMR package in R, the power with a sample of 30 participants was 78%. This suggests that the study was sufficiently powered to detect significant tACS effects in the GLMM on intertemporal choice.

For the model-based analysis, we fitted hyperbolic discount functions to the choice data in a hierarchical Bayesian fashion using the JAGS software package (Plummer, 2003). We assumed that the subjective value of delayed rewards can be described by a canonical hyperbolic discount function (Frederick, Loewenstein, & O'Donoghue, 2002; Laibson, 1997):

$$SV_{LL} = \frac{LL\ reward\ magnitude}{1 + delay \times exp\left(k_{sham} + dummy_{in} \times k_{in} + dummy_{anti} \times k_{anti}\right)}$$

Where $k_{sham}$ represents the hyperbolic discount factor (log-transformed to facilitate parameter estimation) under sham, whereas $k_{in}$ and $k_{anti}$ indicate the shift in hyperbolic discounting under synchronization (in-phase) and desynchronization (anti-phase), respectively, compared to sham. Subjective values were fitted to binary choices with a softmax link function including an inverse temperature parameter β as measure of choice consistency:

$$P(LL\ choice) = \frac{1}{1 + \exp(-\beta \times (SV_{LL} - SV_{SS}))}$$
$$\beta = \beta_{sham} + dummy_{in} \times \beta_{in} + dummy_{anti} \times \beta_{anti}$$

We fitted parameters both on the group and the individual level by assuming that individual parameters are normally distributed around the group means. To estimate the models, we used non-informative uniform priors and two chains with 25,000 iterations (10,000 burn-in samples). For all group parameters $\hat{R}$ was ≤1.01, indicating model convergence. For statistical inference, we checked whether 95% highest-density interval (HDI) of the group-level posterior distributions included zero. We computed Bayes factors $BF_{10}$ with the Savage–Dickey ratio (Wagenmakers, Lodewyckx, Kuriyal, & Grasman, 2010), estimating the density of prior and posterior distributions with the dlogspline function in R.

Lastly, we tested for correlations between individual discount factors and working memory performance (sensitivity d') under sham as well as for the difference between in-phase and anti-phase stimulation. We used non-parametric rank correlations (Spearman's rho) to minimize the influence of outliers on the correlation coefficients.

## 3. Results

### 3.1. Frontoparietal theta stimulation improves working memory performance

As manipulation check, we first assessed whether frontoparietal stimulation affected working memory performance. A repeated measures ANOVA revealed a significant effect of tACS on sensitivity d' as measure of performance accuracy in the n-back task (hits minus false alarms), $F(2, 58) = 8.27$, $P < .001$. Post-hoc tests suggest that d' was significantly increased under synchronization relative to sham, $t(29) = 3.59$, $p_{corrected} = .004$, Cohen's $d = .66$, and desynchronization, $t(29) = 3.59$, $p_{corrected} = .003$, Cohen's $d = .66$, whereas desynchronization showed no significant difference to sham, $t(29) = .08$, $p_{corrected} = 1$, Cohen's $d = .01$ (Fig. 2A). Reaction times in hit trials were not significantly altered by tACS, $F(2, 58) = 1.04$, $P = .36$. Thus, our results replicate previous findings on the causal involvement of frontoparietal synchronization in working memory (Alekseichuk et al., 2017; Polania et al., 2012).

### 3.2. Frontoparietal anti-phase theta stimulation enhances impulsive decision making

Based on the hypothesized link between working memory and the ability to delay gratification, we next assessed stimulation effects on intertemporal decisions. A model-free GLMM revealed that – as to be expected – the probability of choosing the LL option decreased with increasing amounts of the SS reward, beta = −2.16, $CI_{95\%} = [-2.56, -1.76]$, $z = 10.52$, $P < .001$,

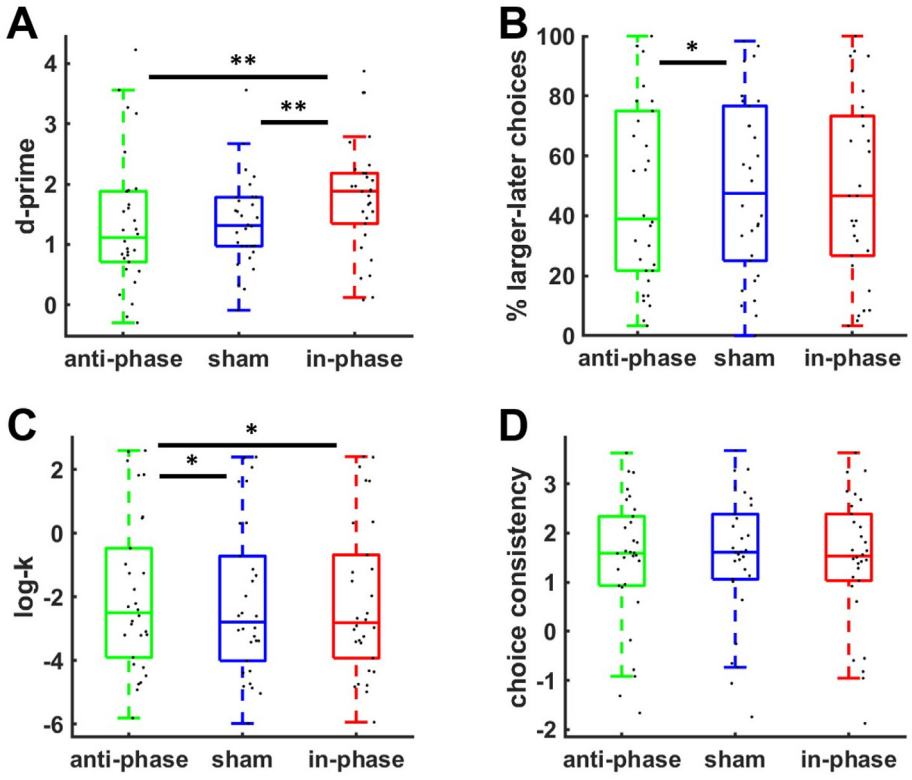


**Fig. 2 – (A) Frontoparietal in-phase theta stimulation significantly improved working memory performance (sensitivity d') compared to sham and anti-phase tACS. In the intertemporal decision task, anti-phase tACS resulted in (B) less choices of larger-later rewards and (C) stronger temporal discounting compared with sham tACS. (D) We observed no stimulation effects on choice consistency (inverse temperature). For illustration purpose, (C) and (D) show extracted individual parameter estimates from the hierarchical Bayesian model. Black dots indicate individual data points; asterisks indicate significant effects (*P < .05; **P < .01).**

$BF_{10} = 1.7 \times 10^{10}$, and with longer delays until LL reward delivery, beta = −1.85, $CI_{95\%}$ = [−2.34, −1.35], z = 7.30, P < .001, $BF_{10} = 1.8 \times 10^{6}$. While we observed no influence of synchronization relative to sham on choices, beta = .02, $CI_{95\%}$ = [−.36, .41], z = .12, P = .91, $BF_{10}$ = .37, theta desynchronization significantly reduced preferences for delayed rewards compared with sham, beta = −.30, $CI_{95\%}$ = [−.60, −.01], z = 2.04, P = .04, $BF_{10}$ = 2.09, though not compared with synchronization, beta = .09, $CI_{95\%}$ = [−.29, .46], z = .44, P = .66, $BF_{10}$ < .001 (Fig. 2B). This supports the hypothesized involvement of frontopolar theta coupling in intertemporal decision making.

The model-free results are corroborated by a model-based analysis of hierarchically estimated hyperbolic discount factors (Table 1). Desynchronization significantly increased hyperbolic discounting of delayed rewards, $HDI_{mean}$ = .20, $HDI_{95\%}$ = [.03, .36], $BF_{10}$ = 1.3, while synchronization showed no significant effects, $HDI_{mean}$ = .01, $HDI_{95\%}$ = [−.14, .17], $BF_{10}$ = .1. A direct comparison between synchronization and desynchronization suggested that desynchronization increased delay discounting also relative to theta synchronization, $HDI_{mean}$ = .18, $HDI_{95\%}$ = [.01, .34], $BF_{10}$ = 4.2 (Fig. 2C). There was no evidence for stimulation effects on choice consistency, as the inverse temperature parameter was unaffected by synchronization, $HDI_{mean}$ = −.05, $HDI_{95\%}$ = [−.23, .15], $BF_{10}$ = .6, or desynchronization, $HDI_{mean}$ = −.05, $HDI_{95\%}$ = [−.24, .15], $BF_{10}$ = .7 (Fig. 2D). Together, this provides converging evidence that anti-phase frontoparietal theta tACS increases impulsiveness in intertemporal choice.

**Table 1 – Results for the hierarchically estimated hyperbolic discount model. The parameters $k_{sham}$, $k_{in}$, $k_{anti}$ refer to the posterior distributions of the group-level log-transformed hyperbolic discount factors under sham, synchronization versus sham, and desynchronization versus sham, respectively, whereas $\beta_{sham}$, $\beta_{in}$ and $\beta_{anti}$ refer to the inverse temperature (choice consistency) parameter. Standard errors of the mean are in brackets.**

| Parameter | Mean | $HDI_{2.5\%}$ | $HDI_{97.5\%}$ |
|---|---|---|---|
| $k_{sham}$ | −1.92 (.55) | −2.97 | −.79 |
| $k_{in}$ | .01 (.08) | −.14 | .17 |
| $k_{anti}$ | .20 (.09) | .03 | .36 |
| $\beta_{sham}$ | 1.51 (.28) | .97 | 2.04 |
| $\beta_{in}$ | −.05 (.09) | −.23 | .15 |
| $\beta_{anti}$ | −.05 (.10) | −.24 | .15 |

Finally, based on studies suggesting a link between working memory and intertemporal decisions, we tested for the hypothesized correlation between working memory performance (sensitivity d') and delay discounting (individual parameter estimates log-k from hyperbolic discount model). The hypothesized link between working memory and intertemporal choice predicts significant correlations between sensitivity d' and log-k both under sham and between the tACS effects on these measures. Under sham, better working memory performance (d') was associated with weaker temporal discounting (log-k), Spearman's rho = −.39, $P = .02$, one-tailed (Fig. 3A). Moreover, the baseline-corrected influences of synchronization versus desynchronization on d' and log-k were correlated, Spearman's rho = −.34, $P = .03$, one-tailed (Fig. 3B): individuals with stronger working memory improvement under synchronization versus desynchronization showed also more future-oriented decisions (more negative log-ks) under synchronization versus desynchronization. This suggests a possible link between the tACS effects on working memory and decision making.

## 4. Discussion

Frontoparietal theta coupling plays an important role in working memory functioning, but little is known about its contribution to value-based decision making. Here, we show that anti-phase frontoparietal theta tACS enhances the discounting of delayed rewards, suggesting a causal role of frontoparietal coupling for intertemporal choice. Because in-phase versus anti-phase frontoparietal tACS also improved working memory performance, replicating previous findings (Alekseichuk et al., 2017; Biel et al., 2022; Polania et al., 2012), our findings suggest overlapping neural mechanisms to underlie working memory and intertemporal decision making. This is further evidenced by significant correlations between working memory performance and delay discounting. Taken together, our results suggest that frontoparietal theta coupling may causally underlie both working memory and decision processes.

By highlighting the importance of synchronized brain network activity, our findings go beyond current neural models of intertemporal decision making: Previous research ascribed the dlPFC a role for encoding long-term goals and for modulating the subjective value of rewards in the brain's reward system (Hare, Hakimi, & Rangel, 2014; Smith, Monterosso, Wakslak, Bechara, & Read, 2018; van den Bos, Rodriguez, Schweitzer, & McClure, 2014; Wesley & Bickel, 2014). However, this perspective neglected that the dlPFC is part of a frontoparietal control network (Vincent et al., 2008), making it reasonable to assume that the dlPFC implements future-oriented decisions not in isolation but in interaction with the parietal cortex. In fact, past studies provided evidence for PPC activation during intertemporal decisions (Boettiger et al., 2007; Rodriguez, Turner, Van Zandt, & McClure, 2015) or also more ventral parts of the parietal cortex (Soutschek, Moisa, Ruff, & Tobler, 2020; Soutschek, Ruff, Strombach, Kalenscher, & Tobler, 2016), but evidence for dlPFC-PPC connectivity during decision making was lacking so far. Our findings fill this gap by showing that the dlPFC's influence on intertemporal choice requires synchronization with lateral PPC. Note that one previous study provided evidence for a causal involvement of medial (rather than lateral) frontoparietal synchronization for value-based decision making, positing that the network performs value-to-action transformations communicated from the PFC to the PPC to translate values into actions (Polania, Moisa, Opitz, Grueschow, & Ruff, 2015). We assume that the lateral network identified in the current study may play a similar role in intertemporal choice: dlPFC-PPC synchronization may promote the transfer of information about delayed reward values encoded in dlPFC to the PPC, where the values are assigned to action options (Sugrue, Corrado, & Newsome, 2004). As caveat, we note that the current findings provide no insights into the directionality of the information flow between dlPFC and PPC. Nevertheless, our results highlight that the dlPFC contributes to value-based choice as part of a frontoparietal network, going beyond prevalent views in the literature (Smith et al., 2018; Wesley & Bickel, 2014; Yang et al., 2018).

The influence of frontoparietal tACS on decision making moreover appears to be related to working memory processes. Consistent with past research (Hofmann et al., 2012), better working memory performance was associated with less impulsive decision making, and the stimulation effects on delay discounting co-varied with tACS-induced working

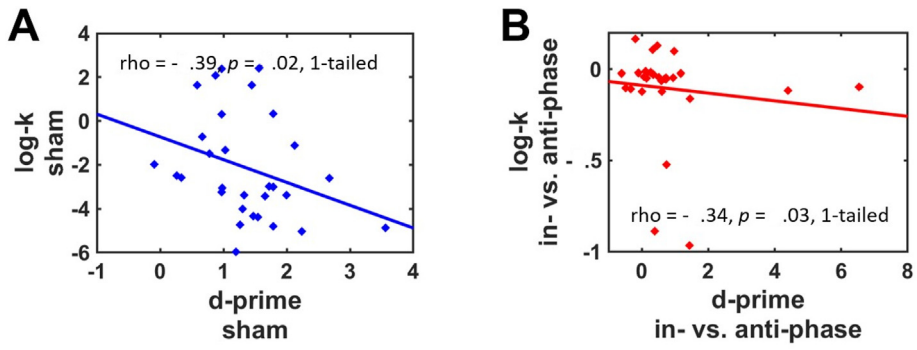


**Fig. 3 – Correlations between working memory performance (sensitivity d') and log-transformed discount parameters (A) under sham and (B) under synchronization versus desynchronization (baseline-corrected). Note that statistical inferences are based on non-parametric tests to account for the skewedness of the parameter distributions.**

memory improvements. Delaying gratification is thought to require the representation of the value of long-term rewards (which are less concrete than immediately available outcomes (Fujita, 2011; Stillman et al., 2017)) in working memory (Jimura et al., 2018; Smith et al., 2018; Wesley & Bickel, 2014). As a caveat, we note that the 3-back task showed effects of in-phase, but not anti-phase stimulation, whereas the intertemporal decision task was affected only by anti-phase, not in-phase tACS. While this result pattern was not expected apriori, we might explain it by differences in the difficulty of the employed tasks: In the rather demanding 3-back task, participants benefitted from strengthening fronotoparietal coupling through in-phase tACS. In the intertemporal decision task, in contrast, value representations encoded in the frontoparietal network might already have been sufficiently strong under sham such that they could not further be strengthened by in-phase tACS. In any case, our findings provide neural support for theoretical accounts on the role of working memory for delay of gratification by suggesting a link between frontoparietal coupling in working memory and intertemporal decision making.

While our finding that in-phase frontoparietal tACS improves working memory functioning is in line with previous evidence (Alekseichuk et al., 2017; Biel et al., 2022; Polania et al., 2012), other studies observed no influence of in-phase theta tACS (Hosseinian, Yavari, Kuo, Nitsche, & Jamil, 2021; Jones, Arciniega, & Berryhill, 2019; Röhner et al., 2018). This might be explained by differences in the applied theta frequency (Jones et al., 2019), the electrode setup (Hosseinian et al., 2021), or differences in task difficulty (Röhner et al., 2018). It is worth noting that past tDCS/tACS studies often provided mixed or inconsistent results (Horvath, Forte, & Carter, 2015a; 2015b), but recent meta-analyses suggest significant stimulation effects in various domains of cognition, including working memory (Grover, Fayzullina, Bullard, Levina, & Reinhart, 2023; Lee, Lee, & Kang, 2023). The heterogeneity of stimulation effects might be related to differences in the employed stimulation protocols, including factors such as electrode positioning, electrode size, and current intensity. To maximize the robustness of our stimulation effects, we employed a high-definition electrode setup (to prevent a diffuse current flow through the brain) and a current intensity within the recommended optimal range (Ehrhardt, Filmer, Wards, Mattingley, & Dux, 2021). Moreover, a limitation of tACS is that its influence on cognition can be confounded with transcutaneous stimulation of peripheral nerves (Asamoah, Khatoun, & Mc Laughlin, 2019) or of the retina (Schutter, 2016; Schutter & Hortensius, 2010). In our view, however, it seems unlikely that the current results can be explained by such peripheral stimulation effects. This is because we observed significant differences between in-phase and anti-phase tACS on both tasks, whereas peripheral effects should be similar for in-phase and anti-phase stimulation (because in both conditions the DLPFC and the PPC are stimulated with a theta frequency). Lastly, a limitation of the current study is that we did not directly assess frontoparietal coupling via electrophysiological recordings during task performance. While previous evidence suggests that frontoparietal phase-dependent theta tACS can indeed modulate frontoparietal theta coupling (Alekseichuk et al., 2017; Feher, Nakataki, & Morishima, 2022; Hu et al., 2022), the current data do not allow concluding that the observed stimulation effects on behavior can be explained via changes in frontoparietal coupling. Combining tACS with electrophysiological recording, following approaches described in previous studies (Haslacher et al., 2023, 2024), would therefore further have strengthened our conclusions.

Taken together, our results show that frontoparietal theta coupling causally contributes to intertemporal decision making. This provides a network perspective on the contribution of the neural control system to decision making, overcoming the focus of past research on the DLPFC in isolation (or in interaction with the subcortical reward system). Given the prevalence of impulsive decision making in several clinical disorders (W. K. Bickel, Koffarnus, Moody, & Wilson, 2014; Monterosso, Piray, & Luo, 2012; Stutzer & Meier, 2015; Volkow & Baler, 2015), these findings may contribute to the development of more effective neural treatments of impulsiveness.

## Funding and competing interests

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## CRediT authorship contribution statement

**Georgia E. Kapetaniou:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Gizem Vural:** Writing – review & editing, Investigation. **Alexander Soutschek:** Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

## Data availability statement

The raw data underlying the reported reports are publicly available on the Open Science Framework (OSF; https://osf.io/j872n/).

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## Scientific transparency statement

DATA: All raw and processed data supporting this research are publicly available: https://osf.io/j872n/

CODE: All analysis code supporting this research is publicly available: https://osf.io/j872n/

MATERIALS: All study materials supporting this research are publicly available: https://osf.io/j872n/

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the supplementary data to the online version of this article.

## Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2025.02.012.

## REFERENCES


Alekseichuk, I., Pabel, S. C., Antal, A., & Paulus, W. (2017). Intrahemispheric theta rhythm desynchronization impairs working memory. *Restorative Neurology and Neuroscience, 35*(2), 147–158. https://doi.org/10.3233/RNN-160714

Asamoah, B., Khatoun, A., & Mc Laughlin, M. (2019). tACS motor system effects can be caused by transcutaneous stimulation of peripheral nerves. *Nature communications, 10*(1), 266.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme 4. *arXiv preprint arXiv:1406.5823*.

Baumeister, R. F. (2002). Yielding to temptation: Self-control failure, impulsive purchasing, and consumer behavior. *Journal of consumer research, 28*(4), 670–676.

Bickel, W. K., Athamneh, L. N., Basso, J. C., Mellis, A. M., DeHart, W. B., Craft, W. H., et al. (2019). Excessive discounting of delayed reinforcers as a trans-disease process: Update on the state of the science. *Current Opinion in Psychology, 30*, 59–64.

Bickel, W. K., Koffarnus, M. N., Moody, L., & Wilson, A. G. (2014). The behavioral- and neuro-economic process of temporal discounting: A candidate behavioral marker of addiction. *Neuropharmacology, 76*(Pt B), 518–527. https://doi.org/10.1016/j.neuropharm.2013.06.013

Biel, A. L., Sterner, E., Roll, L., & Sauseng, P. (2022). Modulating verbal working memory with fronto-parietal transcranial electric stimulation at theta frequency: Does it work? *The European Journal of Neuroscience,* 55(2), 405–425. https://doi.org/10.1111/ejn.15563

Boettiger, C. A., Mitchell, J. M., Tavares, V. C., Robertson, M., Joslyn, G., D'Esposito, M., et al. (2007). Immediate reward bias in humans: Fronto-parietal networks and a role for the catechol-O-methyltransferase 158(Val/Val) genotype. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience, 27*(52), 14383–14391. https://doi.org/10.1523/JNEUROSCI.2551-07.2007

Christian, P., Kapetaniou, G. E., & Soutschek, A. (2023). Causal roles of prefrontal and temporo-parietal theta oscillations for inequity aversion. *[Social Cognitive and Affective Neuroscience Electronic Resource]*. , Article nsad061. https://doi.org/10.1093/scan/nsad061

Daugherty, J. R., & Brase, G. L. (2010). Taking time to be healthy: Predicting health behaviors with delay discounting and time perspective. *Personality and Individual Differences, 48*(2), 202–207.

Domenech, P., Redouté, J., Koechlin, E., & Dreher, J.-C. (2018). The neuro-computational architecture of value-based selection in the human brain. *Cerebral Cortex, 28*(2), 585–601.

Ehrhardt, S. E., Filmer, H. L., Wards, Y., Mattingley, J. B., & Dux, P. E. (2021). The influence of tDCS intensity on decision-making training and transfer outcomes. *Journal of Neurophysiology, 125*(2), 385–397. https://doi.org/10.1152/jn.00423.2020

Feher, K. D., Nakataki, M., & Morishima, Y. (2022). Phase-synchronized transcranial alternating current stimulation-induced neural oscillations modulate cortico-cortical signaling efficacy. *Brain Connectivity, 12*(5), 443–453. https://doi.org/10.1089/brain.2021.0006

Figner, B., Knoch, D., Johnson, E. J., Krosch, A. R., Lisanby, S. H., Fehr, E., et al. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature neuroscience, 13*(5), 538–539.

Frederick, S., Loewenstein, G., & O'Donoghue, T. (2002). Time discounting and time preference: A critical review. *Journal of Economic Literature, 40*, 350–401.

Fujita, K. (2011). On conceptualizing self-control as more than the effortful inhibition of impulses. *Personality and Social Psychology Review: An Official Journal of the Society for Personality and Social Psychology, Inc, 15*(4), 352–366. https://doi.org/10.1177/1088868311411165

Gelman, A., Hill, J., & Yajima, M. (2012). Why we (usually) don't have to worry about multiple comparisons. *Journal of research on educational effectiveness, 5*(2), 189–211.

Grover, S., Fayzullina, R., Bullard, B. M., Levina, V., & Reinhart, R. M. (2023). A meta-analysis suggests that tACS improves cognition in healthy, aging, and psychiatric populations. *Science translational medicine, 15*(697), Article eabo2044.

Hare, T. A., Hakimi, S., & Rangel, A. (2014). Activity in dlPFC and its effective connectivity to vmPFC are associated with temporal discounting. *The Florida Nurse, 8*, 50. https://doi.org/10.3389/fnins.2014.00050

Haslacher, D., Cavallo, A., Reber, P., Kattein, A., Thiele, M., Nasr, K., … Soekadar, S. R. (2024). Working memory enhancement using real-time phase-tuned transcranial alternating current stimulation. *Brain Stimulation, 17*(4), 850–859.

Haslacher, D., Narang, A., Sokoliuk, R., Cavallo, A., Reber, P., Nasr, K., … Soekadar, S. R. (2023). In vivo phase-dependent enhancement and suppression of human brain oscillations by transcranial alternating current stimulation (tACS). *Neuroimage, 275*, Article 120187.

Hill, A. C., Laird, A. R., & Robinson, J. L. (2014). Gender differences in working memory networks: A BrainMap meta-analysis. *Biological psychology, 102*, 18–29.

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends Cogn Sci, 16*(3), 174–180. https://doi.org/10.1016/j.tics.2012.01.006

Horvath, J. C., Forte, J. D., & Carter, O. (2015a). Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: A systematic review. *Neuropsychologia, 66*, 213–236. https://doi.org/10.1016/j.neuropsychologia.2014.11.021

Horvath, J. C., Forte, J. D., & Carter, O. (2015b). Quantitative review finds No evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS). *Brain Stimulation, 8*(3), 535–550. https://doi.org/10.1016/j.brs.2015.01.400

Hosseinian, T., Yavari, F., Kuo, M. F., Nitsche, M. A., & Jamil, A. (2021). Phase synchronized 6 Hz transcranial electric and magnetic stimulation boosts frontal theta activity and enhances working memory. *Neuroimage, 245*, Article 118772. https://doi.org/10.1016/j.neuroimage.2021.118772

Hu, Z., Samuel, I. B. H., Meyyappan, S., Bo, K., Rana, C., & Ding, M. (2022). Aftereffects of frontoparietal theta tACS on verbal working memory: Behavioral and neurophysiological analysis. *IBRO Neurosci Rep, 13*, 469–477. https://doi.org/10.1016/j.ibneur.2022.10.013

Jimura, K., Chushak, M. S., Westbrook, A., & Braver, T. S. (2018). Intertemporal decision-making involves prefrontal control mechanisms associated with working memory. *Cerebral Cortex, 28*(4), 1105–1116. https://doi.org/10.1093/cercor/bhx015

Jones, K. T., Arciniega, H., & Berryhill, M. E. (2019). Replacing tDCS with theta tACS provides selective, but not general WM benefits. *Brain Research, 1720*, Article 146324. https://doi.org/10.1016/j.brainres.2019.146324

Laibson, D. (1997). Golden eggs and hyperbolic discounting. *Quarterly Journal of Economics, 112*(2), 443–477. https://doi.org/10.1162/003355397555253

Lee, T. L., Lee, H., & Kang, N. (2023). A meta-analysis showing improved cognitive performance in healthy young adults with transcranial alternating current stimulation. *NPJ Sci Learn, 8*(1), 1. https://doi.org/10.1038/s41539-022-00152-9

McClure, S. M., Laibson, D. I., Loewenstein, G., & Cohen, J. D. (2004). Separate neural systems value immediate and delayed monetary rewards. *Science, 306*(5695), 503–507. https://doi.org/10.1126/science.1100907

Moisa, M., Polania, R., Grueschow, M., & Ruff, C. C. (2016). Brain network mechanisms underlying motor enhancement by transcranial entrainment of gamma oscillations. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience, 36*(47), 12053–12065. https://doi.org/10.1523/JNEUROSCI.2044-16.2016

Monterosso, J., Piray, P., & Luo, S. (2012). Neuroeconomics and the study of addiction. *Biological Psychiatry, 72*(2), 107–112. https://doi.org/10.1016/j.biopsych.2012.03.012

Plummer, M. (2003). JAGS: A program for analysis of Bayesian graphical models using gibbs sampling. In *Paper presented at the Proceedings of the 3rd international workshop on distributed statistical computing*.

Polania, R., Moisa, M., Opitz, A., Grueschow, M., & Ruff, C. C. (2015). The precision of value-based choices depends causally on fronto-parietal phase coupling. *Nature Communications, 6*, 8090. https://doi.org/10.1038/ncomms9090

Polania, R., Nitsche, M. A., Korman, C., Batsikadze, G., & Paulus, W. (2012). The importance of timing in segregated theta phase-coupling for cognitive performance. *Current Biology: CB, 22*(14), 1314–1318. https://doi.org/10.1016/j.cub.2012.05.021

Röhner, F., Breitling, C., Rufener, K. S., Heinze, H.-J., Hinrichs, H., Krauel, K., et al. (2018). Modulation of working memory using transcranial electrical stimulation: A direct comparison between TACS and TDCS. *The Florida Nurse, 12*, 761.

Rodriguez, C. A., Turner, B. M., Van Zandt, T., & McClure, S. M. (2015). The neural basis of value accumulation in intertemporal choice. *The European Journal of Neuroscience, 42*(5), 2179–2189. https://doi.org/10.1111/ejn.12997

Saturnino, G. B., Puonti, O., Nielsen, J. D., Antonenko, D., Madsen, K. H., Thielscher, A. J. B., et al. (2019). *SimNIBS 2.1: A comprehensive pipeline for individualized electric field modelling for transcranial brain stimulation*.

Schutter, D. J. (2016). Cutaneous retinal activation and neural entrainment in transcranial alternating current stimulation: A systematic review. *Neuroimage, 140*, 83–88. https://doi.org/10.1016/j.neuroimage.2015.09.067

Schutter, D. J., & Hortensius, R. (2010). Retinal origin of phosphenes to transcranial alternating current stimulation. *Clinical Neurophysiology, 121*(7), 1080–1084. https://doi.org/10.1016/j.clinph.2009.10.038

Smith, B. J., Monterosso, J. R., Wakslak, C. J., Bechara, A., & Read, S. J. (2018). A meta-analytical review of brain activity associated with intertemporal decisions: Evidence for an anterior-posterior tangibility axis. *Neuroscience and Biobehavioral Reviews, 86*, 85–98. https://doi.org/10.1016/j.neubiorev.2018.01.005

Soutschek, A., Moisa, M., Ruff, C. C., & Tobler, P. N. (2020). The right temporoparietal junction enables delay of gratification by allowing decision makers to focus on future events. *Plos Biology, 18*(8), Article e3000800. https://doi.org/10.1371/journal.pbio.3000800

Soutschek, A., Moisa, M., Ruff, C. C., & Tobler, P. N. (2021). Frontopolar theta oscillations link metacognition with prospective decision making. *Nature Communications, 12*(1), 3943. https://doi.org/10.1038/s41467-021-24197-3

Soutschek, A., Ruff, C. C., Strombach, T., Kalenscher, T., & Tobler, P. N. (2016). Brain stimulation reveals crucial role of overcoming self-centeredness in self-control. *Sci Adv, 2*(10), Article e1600992. https://doi.org/10.1126/sciadv.1600992

Soutschek, A., & Tobler, P. N. (2020). Causal role of lateral prefrontal cortex in mental effort and fatigue. *Hum Brain Mapp, 41*(16), 4630–4640. https://doi.org/10.1002/hbm.25146

Stillman, P. E., Lee, H., Deng, X., Unnava, H. R., Cunningham, W. A., & Fujita, K. (2017). Neurological evidence for the role of construal level in future-directed thought. *[Social Cognitive and Affective Neuroscience Electronic Resource], 12*(6), 937–947. https://doi.org/10.1093/scan/nsx022

Stutzer, A., & Meier, A. N. (2015). Limited self-control, obesity, and the Loss of Happiness. *Health Econ*. https://doi.org/10.1002/hec.3227

Sugrue, L. P., Corrado, G. S., & Newsome, W. T. (2004). Matching behavior and the representation of value in the parietal cortex. *Science, 304*(5678), 1782–1787. https://doi.org/10.1126/science.1094765

van den Bos, W., Rodriguez, C. A., Schweitzer, J. B., & McClure, S. M. (2014). Connectivity strength of dissociable striatal tracts predict individual differences in temporal discounting. *The Journal of Neuroscience: the Official Journal of the Society for Neuroscience, 34*(31), 10298–10310. https://doi.org/10.1523/JNEUROSCI.4105-13.2014

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. *Journal of Neurophysiology, 100*(6), 3328–3342.

Violante, I. R., Li, L. M., Carmichael, D. W., Lorenz, R., Leech, R., Hampshire, A., … Sharp, D. J. (2017). Externally induced frontoparietal synchronization modulates network dynamics and enhances working memory performance. *Elife, 6*. https://doi.org/10.7554/eLife.22001

Volkow, N. D., & Baler, R. D. (2015). NOW vs LATER brain circuits: Implications for obesity and addiction. *Trends in neurosciences, 38*(6), 345–352.

Wagenmakers, E. J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review, 14*(5), 779–804.

Wagenmakers, E. J., Lodewyckx, T., Kuriyal, H., & Grasman, R. (2010). Bayesian hypothesis testing for psychologists: A tutorial on the Savage-Dickey method. *Cognitive Psychology, 60*(3), 158–189. https://doi.org/10.1016/j.cogpsych.2009.12.001

Wesley, M. J., & Bickel, W. K. (2014). Remember the future II: meta-analyses and functional overlap of working memory and delay discounting. *Biological Psychiatry*, *75*(6), 435–448. https://doi.org/10.1016/j.biopsych.2013.08.008

Westbrook, A., Kester, D., & Braver, T. S. (2013). What is the subjective cost of cognitive effort? Load, trait, and aging effects revealed by economic preference. *Plos One*, *8*(7), Article e68210. https://doi.org/10.1371/journal.pone.0068210

Yang, C. C., Mauer, L., Vollm, B., & Khalifa, N. (2020). The effects of non-invasive brain stimulation on Impulsivity in people with mental disorders: A systematic review and explanatory meta-analysis. *Neuropsychology Review*, *30*(4), 499–520. https://doi.org/10.1007/s11065-020-09456-2

Yang, C. C., Vollm, B., & Khalifa, N. (2018). The effects of rTMS on impulsivity in normal adults: A systematic review and meta-analysis. *Neuropsychology Review*, *28*(3), 377–392. https://doi.org/10.1007/s11065-018-9376-6