Science Advances

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advances.sciencemag.org/cgi/content/full/2/10/e1600992/DC1

Supplementary Materials for

Brain stimulation reveals crucial role of overcoming self-centeredness in self-control

Alexander Soutschek, Christian C. Ruff, Tina Strombach, Tobias Kalenscher, Philippe N. Tobler

Published 19 October 2016, *Sci. Adv.* **2**, e1600992 (2016)
DOI: 10.1126/sciadv.1600992

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Supplementary Materials

SupplementaryResults

Models of hyperbolic temporal discounting with only k_{delay} as free parameter

In the current study, we estimated both the undiscounted reward value V_{delay} and the discount factor k_{delay} in the intertemporal decision task. This was done in analogy to hyperbolic models of social discounting and allowed us to disentangle TMS effects on the propensity to choose delayed rewards at minimal delays (reflected by V_{delay}) versus the discounting of delayed rewards with increasing temporal delay (indicated by k_{delay}). However, because temporal discounting is often analysed by hyperbolic models with a fixed intercept and only k_{delay} as free parameter, we tested the robustness of our findings by fitting the following hyperbolic function to the individual indifference values in the intertemporal decision task (equation 3)

$$\mathrm{SV}_{\mathrm{delay}} = 160/(1 + k_{\mathrm{delay}} \times D_{\mathrm{delay}}) \tag{3}$$

Contrary to equation 1, V_{delay} was fixed to 160 Swiss francs in this model, and only the discount factor k_{delay} was estimated. Based on our finding that TMS over pTPJ increases k_{delay} in hyperbolic models with free intercept, we tested the directed hypothesis (using one-tailed *t*-tests) that pTPJ, relative to TMS control sites, leads to higher log-transformed values of k_{delay} in hyperbolic models with fixed intercept as well. The data generally conformed with the hypothesis, but the steeper temporal discounting in the pTPJ TMS than the vertex TMS group reached only trend-level in Study 1, $t(41) = 1.32$, $p < 0.1$. In Study 2, we found that pTPJ TMS significantly increased temporal discounting relative to S1 TMS, $t(39) = 1.94$, $p < 0.05$, and tended to increase temporal discounting relative to vertex TMS, $t(36) = 1.32$, $p < 0.1$. This result pattern is consistent with our findings when both V_{delay} and k_{delay} were estimated. Importantly, when we compared model fits of the two-parameter model and the one-parameter model using the Akaike information criterion (AIC), the two-parameter model (AIC Study 1 = 88, Study 2 = 161) showed a better model fit (i.e., lower AIC) than the one-parameter model (AIC Study 1 = 131, Study 2 = 174), even though AIC penalizes for the number of free parameters. This suggests that a model with a free intercept fits the data clearly better than a model with fixed intercept and underlines the importance of distinguishing between the parameters V_{delay} and k_{delay}.

Quasi-hyperbolic models of temporal discounting

Besides hyperbolic models, “quasi-hyperbolic” functions have been applied to describe temporal discounting (31) (equation 4)

$$SV = \beta \times \delta^{D} \tag{4}$$

where SV is the subjective value of the discounted delayed reward and D indicates the temporal delay. The degree of temporal discounting is determined by both the parameters β and δ (“beta-delta model”), with β measuring an individual’s sensitivity to immediate rewards and δ indicating the discounting of delayed rewards for longer temporal delays. Based on our assumption that the pTPJ relates to encoding the value of future rewards, we expected pTPJ TMS to affect the δ rather than the β parameter. In Study 1, a 2 (Parameter) x 2 (TMS) mixed-measures ANOVA on the log-transformed δ and β parameters showed a significant Parameter x TMS interaction, $F(1, 41) = 4.59$, $p < 0.05$, partial $\eta^2 = 0.101$, suggesting differential TMS effects on δ and β. In line with our prediction, TMS over pTPJ, relative to vertex TMS, resulted in significantly larger log-transformed δ parameters, $t(41) = 2.18$, $p < 0.05$, one-tailed, whereas pTPJ TMS did not affect the log-transformed β parameter, $t < 1$, $p = 0.94$. Similarly, in Study 2 a mixed-measures ANOVA showed a marginally significant Parameter x TMS interaction, $F(2, 56) = 2.77$, $p = 0.07$, partial $\eta^2 = 0.090$. Again, TMS over pTPJ, relative to S1 or vertex TMS, only affected δ parameters, all $t > 1.75$, all $p < 0.05$, one-tailed, whereas we found no effect of pTPJ TMS on the β parameter, all $t < 1.23$, all $p > 0.23$. Thus, within the framework of the “quasi-hyperbolic” beta-delta model of temporal discounting, the pTPJ relates to the patient δ–system rather than the impulsive β–system. The model fit of the quasi-hyperbolic model (AIC Study 1 = 88, Study 2 = 158) was comparable to the model fit of the hyperbolic model with free intercept (AIC Study 1 = 88, Study 2 = 161).

Little involvement of pTPJ in attentional reorienting

In study 2, we also considered alternative cognitive mechanisms that could in principle explain the common effects of pTPJ TMS on intertemporal and interpersonal decision-making. In particular, previous studies have related the TPJ to attentional reorienting (11, 12). As temporal delays and social distances were presented as horizontal number lines in study 1, pTPJ TMS may have reduced the number of patient and prosocial choices by impairing the reorientation of attention from the immediate or selfish reward options (presented in the centre of the screen) to the long temporal delays or high social distances (appearing on the right side of the screen). This is because TMS over the right TPJ (albeit at a more anterior part of the TPJ than targeted here) has been shown to impair reorienting attention from a distractor to a target presented to the right of the distractor (11,12). Note that attentional reorienting may be related to more anterior parts of the TPJ, whereas we applied TMS over a more posterior subregion thought to be involved in social cognition (13). Nevertheless, we controlled for this alternative explanation in Study 2 in two ways: first, we counterbalanced across subjects whether the temporal/social distances and the immediate/selfish reward options were presented on the left or right side of the screen. Thus, even if pTPJ TMS had impaired the reorientation of attention from the left to the right screen side (11), it would not have selectively biased attention to the immediate and selfish reward options. Second, as further test of whether the TMS effects on decisions in the intertemporal and the interpersonal tasks are due to TMS effects on attentional reorienting, we included the factor screen side (selfish/immediate option on left side and distances on right side vs. selfish/immediate option on right side and distances on left side) into our ANOVA. If pTPJ TMS impaired the reorientation of attention from the left to the right screen side, we should observe an interaction between TMS effects and spatial stimulus arrangement. However, neither the main effect of screen side nor any interaction between stimulus arrangement and TMS showed a significant result (all $F < 1.31$, all $p > 0.25$). Thus, TMS effects on attentional reorienting cannot explain the observed findings.

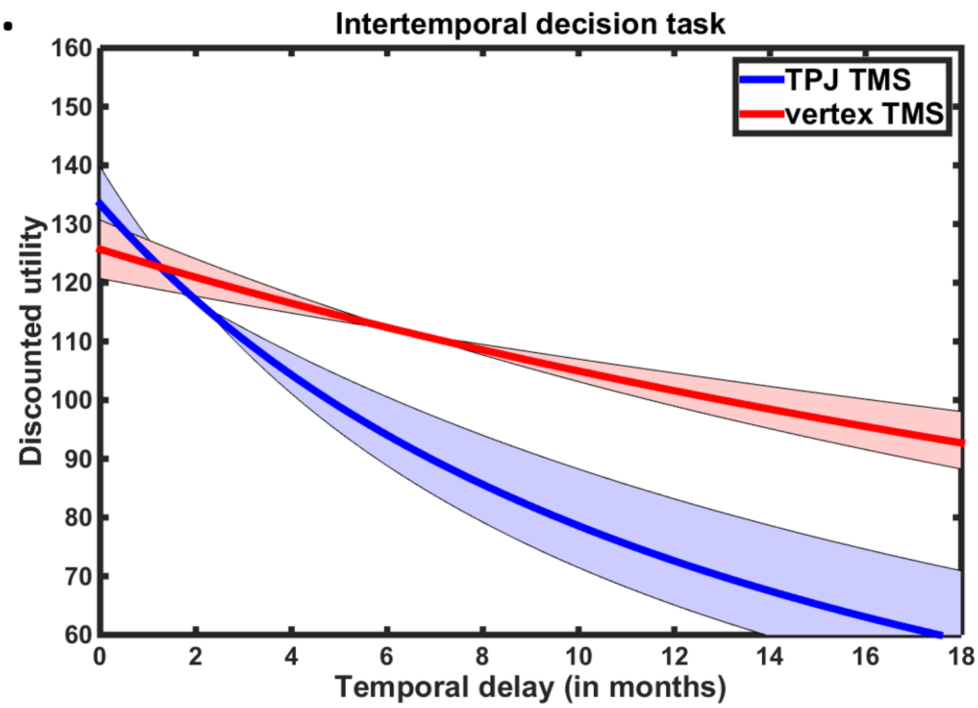
Little involvement of pTPJ in number line processing

As a second alternative explanation for the observed TMS effects, we considered that parts of the inferior parietal cortex in proximity to the TPJ relate to number processing (26). Indeed, TMS of the right inferior parietal cortex was found to impair the recognition of numbers on a number line (26). Thus, as both social distance and temporal delay were indicated by number lines, pTPJ TMS might have distorted social distance and temporal delay information. Note that number line processing may be related to more dorsal and medial parts, whereas we applied TMS over a more ventral and lateral subregion. Nevertheless, we tested the effects of pTPJ TMS on a numerical line estimation task (26) to assess whether TMS at the same pTPJ region that increased temporal and social discounting also affected number line processing.

To address this possibility, we assessed subjects' ability to recognize a number, on scales that ranged from 0 to 180 or from 0 to 100 (in analogy to the temporal delays 0-180 and the social distances 0-100). For each subject, we calculated the mean difference (in percent) between the estimated number and the true number. We found no TMS effects on performance in this task ($F < 1$, $p = 0.70$; fig. S3). Thus, the effects of pTPJ TMS on temporal and social discounting do not reflect distortions of the numerical representations of temporal and social distance.

Figures

A.



B.

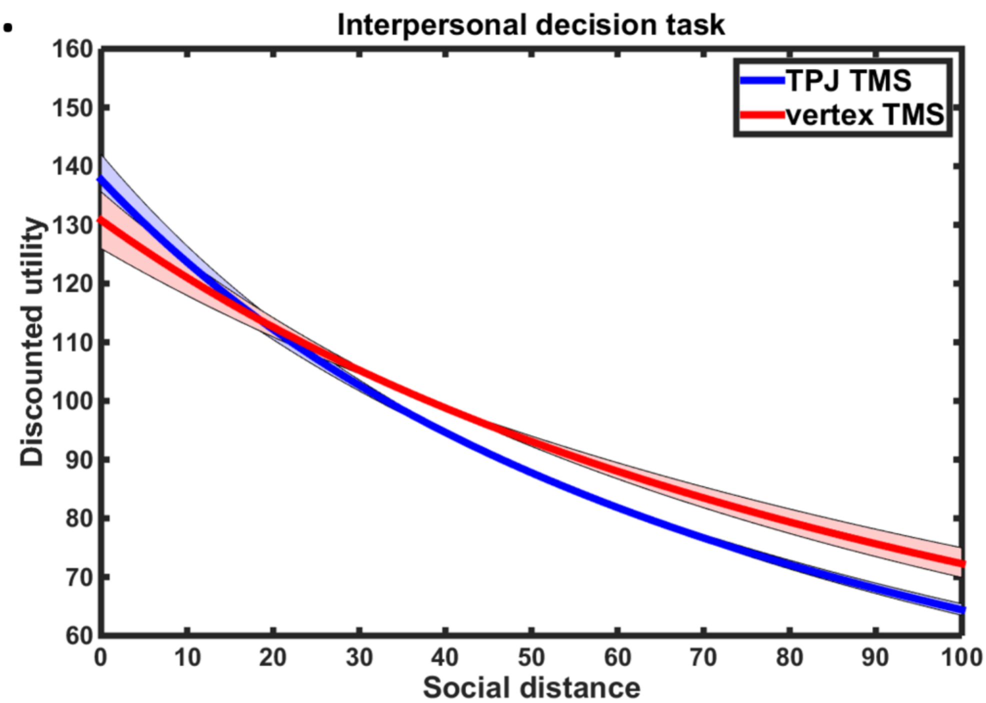
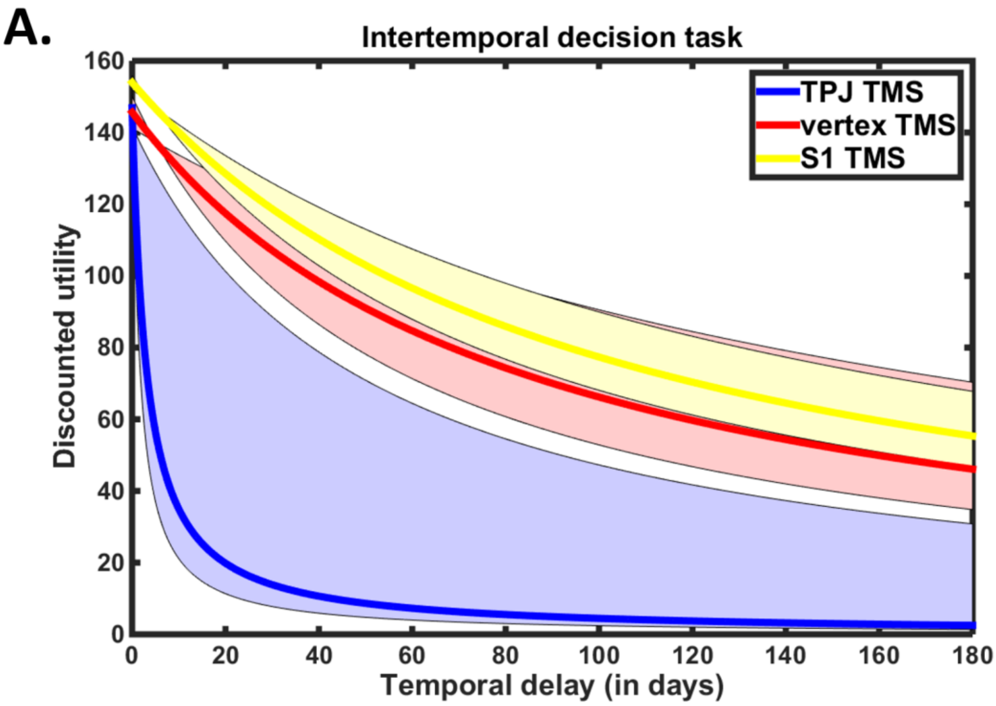


fig. S1. Fit of two-parameter hyperbolic discount functions [$SV_{delay} = V_{delay}/(1 + k_{delay} \times D_{delay})$; $SV_{social} = V_{social}/(1 + k_{social} \times D_{social})$] in Study 1. Mean discount functions for (**A**) the intertemporal decision task and (**B**) the interpersonal decision task, separately for the pTPJ TMS and the vertex TMS groups. Shaded areas represent standard error of the mean.



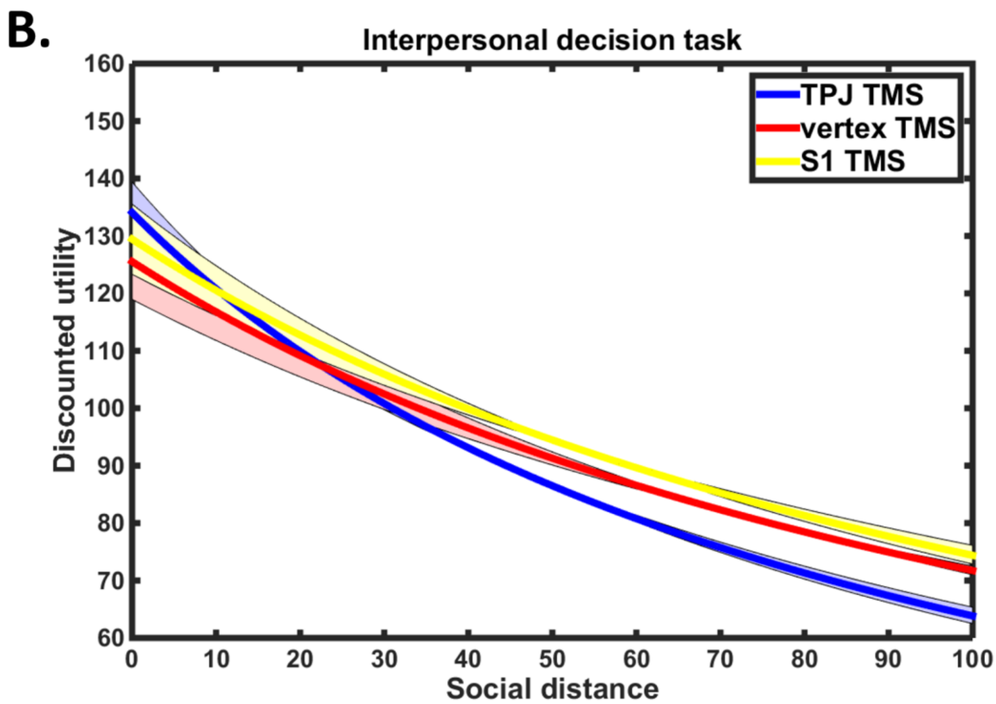
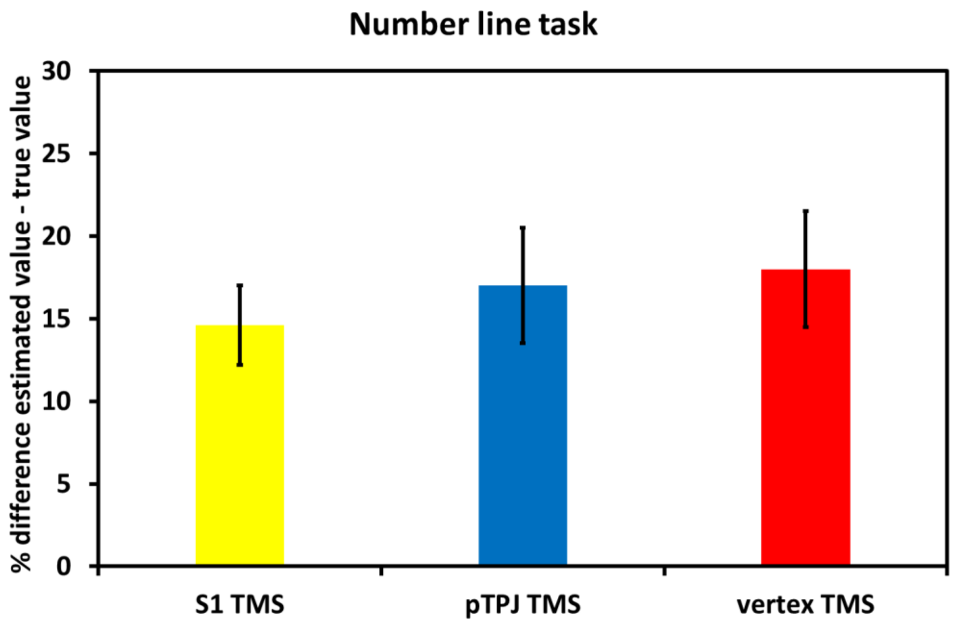


fig. S2. Fit of two-parameter hyperbolic discount functions [$SV_{delay} = V_{delay} / (1 + k_{delay} \times D_{delay})$; $SV_{social} = V_{social}/(1 + k_{social} \times D_{social})$] in Study 2. Mean discount functions for (**A**) the intertemporal decision task and (**B**) the interpersonal decision task, separately for the pTPJ TMS, S1 TMS, and the vertex TMS groups. Shaded areas represent standard error of the mean.



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