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Lateral prefrontal cortex and self-control in intertemporal choice

Bernd Figner[1,2], Daria Knoch[3], Eric J Johnson[1,4], Amy R Krosch[1,5], Sarah H Lisanby[6], Ernst Fehr[7] & Elke U Weber[1,2,4]

Disruption of function of left, but not right, lateral prefrontal cortex (LPFC) with low-frequency repetitive transcranial magnetic stimulation (rTMS) increased choices of immediate rewards over larger delayed rewards. rTMS did not change choices involving only delayed rewards or valuation judgments of immediate and delayed rewards, providing causal evidence for a neural lateral-prefrontal cortex–based self-control mechanism in intertemporal choice.

Every day we make decisions that trade off short-term and long-term consequences. In such intertemporal choices between sooner-smaller and later-larger rewards, humans and other animals exhibit impatience, particularly if immediate rewards are available[1]. Steep discounting of delayed rewards has been implicated in suboptimal behaviors, such as insufficient saving for retirement, substance abuse and nonresponse to climate change. The neural basis of intertemporal choice is still intensively debated, with three recent neural accounts: single-valuation[2], dual-valuation[3] and self-control. The first two reflect important functional magnetic resonance imaging studies of intertemporal choice. The third is based only on indirect evidence from functional magnetic resonance imaging[4–6] and rTMS[7] studies; to the best of our knowledge, no study has provided causal evidence to investigate self-control mechanisms in intertemporal choice.

The three accounts mostly agree on the brain regions involved (ventral striatum, medial-prefrontal cortex, posterior cingulate cortex and lateral-prefrontal cortex (LPFC)) but differ substantially on the specifics (**Supplementary Text**). Both the single- and dual-valuation accounts assume that the choice of an option is a direct result of the comparison of their valuations, without additional intervening processes such as self-control. In contrast, the self-control account assumes that a tempting option (an immediate sooner-smaller reward) might be valued more highly than an alternative (a delayed later-larger reward) but that the later-larger reward might still be chosen as a result of intervening self-control processes. The (dorsal) LPFC has been implicated in self-control[6–8], making it a prime target for a brain stimulation study.

Transient disruption of LPFC with rTMS therefore provides a crucial test for the need of a self-control component in intertemporal choice models. Both dual- and single-valuation accounts predict that whatever effect LPFC disruption might have on choice should be reflected in option valuations, as choice follows directly from valuation. In contrast, the self-control account predicts that choice can be influenced without altering valuation (**Supplementary Text**).

To test for the LPFC's involvement in intertemporal self-control processes, we applied to each of 52 participants a 15-min train of 1-Hz low-frequency rTMS to either the left or right LPFC (left and right rTMS groups) or sham rTMS (sham control group) (**Supplementary Methods**). Participants completed three tasks (**Supplementary Figs. 1** and **2**). The first was a choice task of 36 binary choices between sooner-smaller and later-larger options (18 now trials with immediate sooner-smaller rewards and 18 not-now trials in which both the sooner-smaller and the later-larger rewards were delayed), with the relative differences in sooner-smaller/later-larger magnitudes ranging from small (the later-larger reward was 0.5% larger than the sooner-smaller reward) to large (the later-larger reward was 75% larger than the sooner-smaller reward). The second was a valuation task, in which

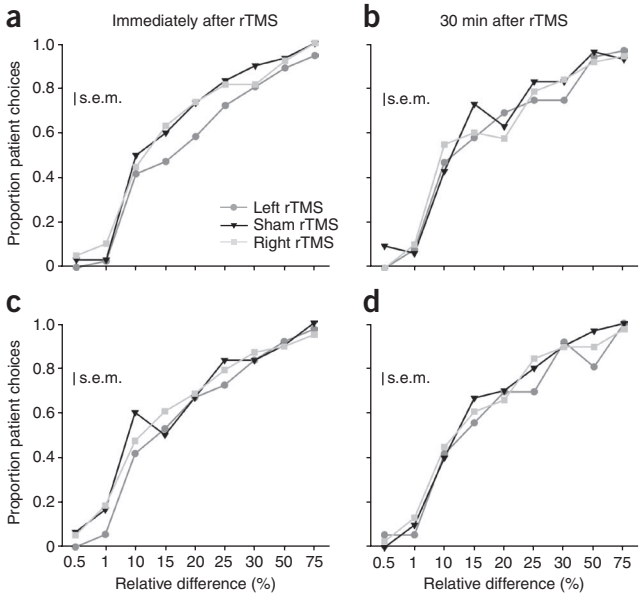

Figure 1 Proportion of patient choices (later-larger) as a function of the relative difference between magnitude of sooner-smaller and later-larger. Lines indicate the proportion of later-larger choices for left, right and sham rTMS groups. (**a**) Now trials in TA1. (**b**) Now trials in TA2. (**c**) Not-now trials in TA1. (**d**) Not-now trials in TA2. The largest s.e.m. for difference left versus sham in each panel is shown.

[1]Center for Decision Sciences and [2]Department of Psychology, Columbia University, New York, New York, USA. [3]Social and Affective Neuroscience, Department of Psychology, University of Basel, Basel, Switzerland. [4]Graduate School of Business, Columbia University, New York, New York, USA. [5]Department of Psychology, New York University, New York, New York, USA. [6]Division of Brain Stimulation and Therapeutic Modulation, Columbia University, New York, New York, USA. [7]Institute for Empirical Research in Economics, University of Zurich, Zurich, Switzerland. Correspondence should be addressed to B.F. (bf2151@columbia.edu).

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Table 1 Left, right and sham rTMS group: frequencies for combinations of actual choices versus valuation-implied preferences of sooner-smaller and later-larger in now trials immediately after rTMS train

Valuation-implied preference	Actual choice					
	Left rTMS		Right rTMS		Sham rTMS	
	Sooner-smaller	Later-larger	Sooner-smaller	Later-larger	Sooner-smaller	Later-larger
Sooner-smaller	34	6	33	16	30	12
Later-larger	12	48	6	45	8	50

Numbers represent the percentages of sooner-smaller/later-larger combinations for actual choices versus preferences derived from valuations. The left rTMS group exhibited an increased number of impulsive, compared with self-controlled preference reversals (12% versus 6%) and the right and the sham rTMS groups exhibited an increased number of self-controlled, compared with impulsive, preference reversals (right, 16% versus 6%; sham, 12% versus 8%).

participants rated the attractiveness of 12 single options taken from the choice set. The third was a choice-titration task (because choice titrations showed the same results as the choice task, they are described only in the **Supplementary Data Analysis**). Each task was administered twice, immediately after the rTMS train (task administration 1, TA1) and again 30 min later (task administration 2, TA2), after rTMS effects were expected to have dissipated[9]. We compared data both between the rTMS groups and within groups across the two task administrations.

The self-control account predicts LPFC disruption to specifically increase impatient choice for immediate rewards (that is, now trials), as they are particularly tempting and require the most self-control, most strongly for intermediate relative differences, as subjective discounted values of sooner-smaller and later-larger are close, resulting in increased temptation and choice conflict. We found significant differences for left versus sham and left versus right groups for now trials of TA1 ($P = 0.006$ and 0.008, respectively; **Fig. 1a**). All other comparisons were nonsignificant (TA1 now trials sham versus right, all TA1 not-now comparisons; **Fig. 1b**; all TA2 now and not-now comparisons; $P = 0.08$–0.99; **Fig. 1c**,**d**). This between-groups comparison was replicated by a within-groups comparison. In addition, both analyses indicated that the left rTMS effects in TA1 were significantly stronger for now than for not-now trials (between-groups, left versus sham and left versus right, $P = 0.002$ and 0.003; within-groups, $P = 0.037$).

As expected, the rTMS effect was particularly strong for now trials with intermediate relative differences in reward magnitudes. The left rTMS effects in TA1 now trials were significantly stronger for intermediate than for small and large relative differences, as confirmed by both the within ($P = 0.005$) and between ($P = 0.01$) comparisons (**Fig. 1a**).

In contrast, valuations of single options showed no effect of either rTMS or task administration in both analyses ($P = 0.15$–0.90; **Supplementary Figs. 3–5**). However, valuation showed the same sensitivity to the reward magnitude and time of delivery (both $P < 0.001$). Because the independence of valuation from the effects of rTMS is crucial for the self-control account, we conducted follow-up analyses to corroborate these results and rule out alternative explanations, such as lower diagnostic sensitivity or statistical power of the valuation task and decay of the rTMS effect (**Supplementary Data Analysis**).

Finally, we examined reversals between the preferences implicit in the valuation task and the choices in TA1 now trials. The two valuation accounts predict no systematic preference reversals between valuations and choices. The self-control account predicts that intact self-control leads to increased numbers of self-controlled preference reversals in which the later-larger reward is chosen although the immediate sooner-smaller reward is valued more highly, but that temporarily impaired self-control produces an increase in impulsive preference reversals (the sooner-smaller reward is chosen despite higher valuation of the later-larger reward). Our results were consistent with self-control predictions (self-controlled preference reversals, $P < 0.001$; impulsive preference reversals, $P = 0.034$; **Table 1**, **Supplementary Figures 6** and **7** and **Supplementary Table 1**).

In summary, we found that transient disruption of the left, but not right, LPFC by rTMS led to increased choosing of immediately available rewards. No effects were found for trials involving only delayed rewards or 30 min after rTMS, when rTMS effects had worn off. In contrast, no effects were found for valuation. We also found a twofold preference reversal pattern of differences in self-controlled and impulsive preference reversals that was predicted by the self-control account.

Taken together, our results indicate that the left LPFC is a crucial neural substrate for self-control processes in intertemporal choice. Our results are consistent with several possible neural implementations of how the LPFC exerts self-control in intertemporal choice, which should be investigated in the future. Possible implementations might work via the modulation of activity in valuation regions, via input into valuation areas, via differential influence of attention given to magnitude versus timing of rewards or via a more direct influence on choice, such as the inhibition of a prepotent response (that is, the tempting immediate sooner-smaller reward)[6,8]. Regardless of their neural implementation, our results provide, to the best of our knowledge, the first causal evidence that self-control processes should be incorporated into existing neural models of intertemporal choice.

Note: Supplementary information is available on the Nature Neuroscience website.

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AUTHOR CONTRIBUTIONS

All of the authors designed the experiment and edited the manuscript. B.F. and A.R.K. conducted and analyzed the pilot studies. B.F. and D.K. collected the data. B.F., D.K., E.J.J. and E.U.W. analyzed the data and B.F., E.U.W. and E.J.J. prepared the manuscript.

COMPETING FINANCIAL INTERESTS

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SUPPLEMENTAL ONLINE MATERIALS

Lateral prefrontal cortex and self-control in intertemporal choice

Figner, B.[1,2*], Knoch, D.[3], Johnson, E. J.[1,4], Krosch, A. R.[1,5], Lisanby, S. H.[6], Fehr, E.[7], and Weber, E. U.[1,2,4]

[1]Center for Decision Sciences, Columbia University; [2]Department of Psychology, Columbia University; [3]Social and Affective Neuroscience, Department of Psychology, University of Basel; [4]Graduate School of Business, Columbia University; [5]Department of Psychology, New York University; [6]Division of Brain Stimulation and Therapeutic Modulation, Columbia University; [7]Institute for Empirical Research in Economics, University of Zurich.
(collaboration between Fehr and Weber labs)

*Bernd Figner (corresponding author)
Center for Decision Sciences and Department of Psychology
Columbia University
406 Schermerhorn Hall
1190 Amsterdam Avenue
NY 10027, New York, USA
Tel.: 1 212 854 6416 Fax: 1 212 854 3609
e-mail: bf2151@columbia.edu

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METHODS AND MATERIALS

Participants. Fifty-two right-handed men, ranging in age from 19 to 33 years, provided written informed consent to participate in the study that was approved by the local ethics committee. Recent studies have shown hemispherical specialization in function of lateral prefrontal cortex (LPFC), with only the *right* LPFC being causally implicated in self-control in social[1] and risky[2] choice, whereas recent fMRI studies on intertemporal choice[3-5] implicated the *left* LPFC. Therefore, we randomly assigned participants to receive a single 15-minute train of rTMS to either the left LPFC (*left* rTMS group; $n = 18$), the right LPFC (*right* rTMS group; $n = 19$), or sham stimulation (*sham* control group; $n = 15$). No participant had previously experienced transcranial magnetic stimulation or seen any of the tasks used in this study. Participants were screened for a history of psychiatric illness or neurological disorder. No participant experienced serious adverse effects or reported any scalp pain, neck pain, or headaches after the experiment.

Repetitive transcranial magnetic stimulation (rTMS). rTMS was administered to the LPFC for 15 minutes, before participants (all TMS naïve) participated in the intertemporal choice task, valuation task, and choice-titrator task, using a Magstim Rapid Magnetic Stimulator (Magstim, Winchester, MA) and a commercially-available figure-eight coil (70-mm diameter double-circle, air-cooled). Stimulation intensity was set at 54% of maximum stimulator output. The coil was held tangential to the participant's head, with the handle pointing rostrally. Participants received a single, 15-min, 1-Hz rTMS train (900 pulses) over either the left LPFC or right LPFC, or they received sham stimulation. The inclusion of these three treatment groups not only allows for the investigation of potential hemispheric specialization of the self-control functions of the LPFC, but is further important because it provides a control for the potential side effects of rTMS[6], such as scalp discomfort and other nonspecific effects. For example, if we find a behavioral effect of rTMS only in the left LPFC, but neither the right LPFC nor the sham control group, we can rule out that the behavioral effect was produced by rTMS side effects. For stimulation of the left and right dorsal LPFC (DLPFC), the TMS coil was placed over F4 and F3 using the electroencephalogram 10-20 coordination system, as in previous studies[7-10]. Participants wore a tight-fitting lycra cap on which the relevant coordinates of the international 10/20 EEG system were marked. Sham stimulation was accomplished using a Magstim placebo coil, which has an appearance identical to that of the real coil, and also delivers the characteristic "click" sound. Approximately half of the participants in the sham stimulation group received sham rTMS over the right DLPFC, and the other half over the left DLPFC. The rTMS parameters were well within currently recommended guidelines and stimulation based on said parameters results in a suppression of excitability of the targeted cortical region for several minutes following completion of the rTMS train[6]. Participants performed the tasks immediately after the end of the stimulation train in the same laboratory room. As our participants received the task instructions prior to the rTMS train, it was possible to begin the tasks within 20 seconds after the end of the stimulation train and therefore under the influence of the rTMS after-effect.

Choice task. In each of two task administrations, participants made 36 binary choices, each offering a sooner smaller reward (SS) and a later larger (LL) reward (see Figure S1). The 36 trials represented a full factorial design that varied (a) time of delivery of SS ("today" versus "in 2 weeks"), resulting in 18 *now trials* (SS is an immediate reward) and 18 *not-now trials* (SS and LL are both delayed rewards); (b) time interval between SS and LL (2 weeks versus 4 weeks); and (c) relative difference in reward magnitudes of SS and LL (LL was either 0.5, 1, 5, 10, 15, 20, 25, 30, 50, or 75% larger than SS).

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Varying the relative magnitudes of SS and LL rewards across trials allowed us to test the self-control account. For a third of trials, the LL reward was only marginally larger than the SS reward (small relative differences). These trials present low choice conflict. A 0.5 percent increase in reward does not justify waiting two more weeks. Most participants should choose the SS, independent of rTMS treatment. Similarly, for another third of trials, the LL was substantially larger than the SS (large relative differences). These trials also present low choice conflict; virtually everybody will wait two more weeks to nearly double the amount to be received; most participants should (and did) choose the LL, again independent of rTMS treatment. For the remaining third of trials, the LL was moderately larger than the SS (intermediate relative differences). These trials can be expected to result in strong choice conflict, as neither option was clearly more attractive, and participants were hypothesized to require self-control to resist the temptation of the immediate SS and instead choose the LL. We expected rTMS-induced differences in self-control to have the strongest impact on this subset of *now* trials. The choices in trials with small and large relative differences also served to rule out the possibility that LPFC disruption led to random or otherwise nonsensical choice behavior.

Figure S1. Screen shot of the choice task with the SS presented on the left ("Heute" = today) and the LL presented on the right ("4 Wochen" = 4 weeks). Participants indicated their choice by clicking on the radio button below the preferred option. Participants could start the next trial by clicking on the gray button in the middle ("Weiter" = next). The study was run in Switzerland; 1 Swiss Franc (Fr. or CHF) equaled about $0.85 at the time of the study.

Amounts for the SS were pseudo-randomly drawn from a normal distribution with a mean of CHF 45, capped at the lower end at CHF 15 and CHF 85 at the higher end. On each trial, participants were presented simultaneously with the SS and the LL on a computer screen, as shown in Figure S1 (SS was always presented on the left), and expressed their choice by clicking on the radio button below their preferred option. They started the next trial by clicking on a button placed in the middle of the screen. Trials were presented in 6 different pseudo-random orders, counterbalanced across rTMS groups (left rTMS versus right rTMS versus sham rTMS)

and task administration (immediately after rTMS train, *TA1*, versus 30 minutes after rTMS train, *TA2*, i.e., after rTMS can be expected to have worn off[11]). Completion of the choice task took on average 3 min, and there were no significant differences in completion time between rTMS groups.

Valuation task. The valuation task was administered immediately after the choice task. Participants rated 12 single options that each provided a specified monetary amount at a specified time point. These options were taken from the choice task, reflecting the four time points of delivery ("today", "in 2 weeks", "in 4 weeks", "in 6 weeks") crossed with three levels of reward magnitude (low: approximately CHF 30; medium: approximately CHF 45; and high: approximately CHF 60; actual values varied slightly from these approximate numbers as they were taken from the actual choice task; in each case, deviation was less than ± CHF 4.00). Valuation ratings were made on a continuous visual analog scale with endpoints "very unattractive" and "very attractive". The rating scale was anchored in task instructions by low and high anchors that were below the least attractive option and above the most attractive option presented in the ratings (low anchor: "CHF 20 in 6 weeks"; high anchor: "CHF 80 today"). The anchoring and the factorial design allowed us to detect any systematic differences in the subjective values of times of delivery and/or reward magnitudes between rTMS groups, or their integration. Completion of the valuation task took on average 1 minute, and there were no significant differences in completion time between rTMS groups.

Procedure. All tasks were explained and demonstrated to participants before rTMS administration. Two comprehension questions were administered after instructions to ensure full understanding of the tasks and payment procedures. Participants completed the choice task and the valuation task twice, once immediately after the rTMS train and a second time 30 minutes after the rTMS train (see Fig. S2 for an overview of the timing of different parts of the experiment). For the second administration, reward magnitudes were jittered by up to ± CHF 2.00 to reduce potential memory effects.

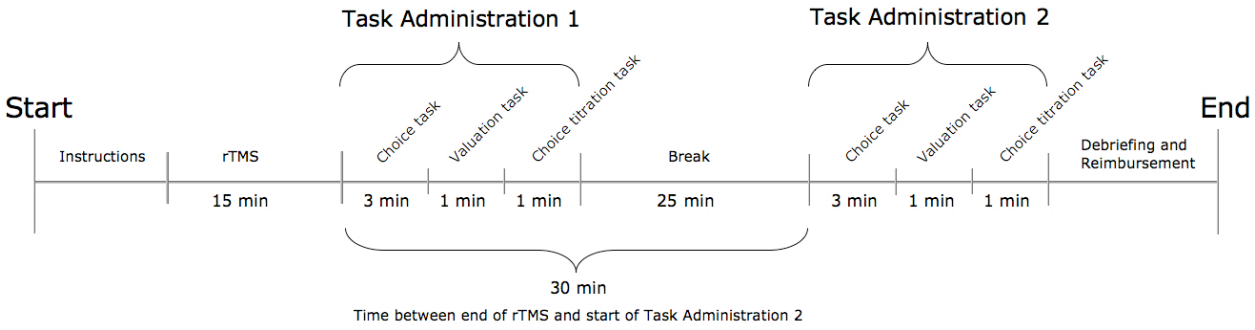

Figure S2. Overview of the different parts and timing of the experiment. (The choice titration task showed the same significant pattern of increased impatience for immediate rewards in the left rTMS group as the choice task, and its results are therefore reported only here in the Supplemental Online Materials.)

Reimbursement. Reimbursement consisted of a flat rate of CHF 60.00 and a variable payment depending on participants' choices. As explained to participants at the beginning of the study, one choice of all the choices made was randomly selected at the end of the study, and the chosen

option on this trial was paid out for real, i.e., the chosen amount was transferred to their bank account on the chosen day of delivery.

NEURAL ACCOUNTS AND THEIR DIFFERENTIAL PREDICTIONS

Neural accounts of intertemporal choice. Research has identified brain regions involved in intertemporal choice, such as the ventral striatum (VS), medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), and lateral prefrontal cortex (LPFC), but their roles and the relationships among them are still debated[3]. Recent fMRI studies have led to neural accounts of intertemporal choice that differ both in the kind and number of components. Two of the models can be classified as "pure" valuation models and are further distinguished by the number of assumed valuation processes; we will refer to these two accounts as the single- and dual-valuation account. In contrast, the third account assumes that choice is determined not by valuation processes alone, but also involves self-control processes; we refer to this account as the self-control account.

The *single-valuation account* (e.g., the neurometric model[12]) assumes that at least one location in the human brain encodes the hyperbolically discounted value of all rewards, both on now and not-now trials, and that the option with the higher discounted value is then chosen. An fMRI study[12] identified brain activation patterns following a hyperbolic discounting function in the VS, MPFC, and PCC; similarly, a single-cell recording study in monkeys found dorsal LPFC neurons encoding the temporally discounted values of choice options[13]. The single-valuation account explains intertemporal choice by assuming a single valuation process, which follows a hyperbolic discount function. For any given choice, the subjective discounted value is computed for the SS and for the LL, and the option with the higher subjective value is chosen.

In contrast, the *dual-valuation account* (e.g., the β-δ model[14], explored in two fMRI studies[15,16]) assumes two different valuation processes during intertemporal choice. An impatient β-process steeply discounts all non-immediate rewards and is active only in now trials, and a more patient δ-process far less steeply discounts all delayed rewards and is active in both now and not-now trials. The impatient β-process effectively puts a premium on immediately available awards, thus explaining the particular attractiveness of immediate rewards (here called the *now effect*, also known as *present bias* and *immediacy effect*) and the (quasi-)hyperbolic shape of the discounting function. The impatient β-process and the more patient δ-process are assumed to operate additively to determine choice. Different brain regions have been associated with the β and δ processes. The β regions include the VS and other reward-related mesolimbic dopamine projection regions, similar to the brain regions implicated in the neurometric model. The δ regions include the LPFC and the posterior parietal cortex (PPC)[15,16].

The single- and dual-valuation accounts differ in the addition of a second valuation process, located in the LPFC (and PPC). Both accounts agree that the choice of an option results directly from the comparison of their valuations, without additional intervening processes such as self-control. In the single-valuation neurometric model, the now effect is modeled by the shape of the single discount function, and in the dual-valuation β-δ model by two additive discount functions.

A self-control account of intertemporal choice has intuitive appeal. Most of us have experienced the temptation of an immediate reward (e.g., staying at home and watching a movie) conflicting with a longer-term goal (e.g., going to the gym for one's future health). The self-control account argues that in such situations, the subjective value of the SS (watching a movie)

might actually be higher than that of the LL (going to the gym), but that we may nevertheless be able to override this difference in subjective valuation and choose the LL.

Beyond this intuition, more compelling reasons suggest that the relationship between valuation and choice is more complex than assumed in the valuation models. An influential behavioral literature on preference reversals[17] (PRs) compared choice-based expressions of preference with those expressed by explicit valuation judgments. The observation of systematic PRs (e.g., option A is valued more highly than option B when evaluated separately, but B is chosen in a direct choice) challenged the standard economic assumption that preferences are independent of how they are expressed. This idea that choice does not follow automatically from valuation has generated significant progress in understanding how judgments and choices are constructed[18]. A second reason stems from recent behavioral and neuroscience evidence for self-control processes that have the ability to override highly valued responses in situations of goal conflict[19-21]. In such situations, one goal may be prepotent, e.g., more fundamental and self-oriented and supported by more automatic processes (e.g., self-interested acceptance of an unfair division of assets in the ultimatum game[1], choosing the tastier but less healthy food item[21], or, in our case, going for the immediate but smaller reward). In contrast, other goals may be more abstract, higher-level, and farsighted (e.g., altruistic punishment of someone making an unfair offer, choosing the healthier but less tasty food, or holding out for the larger delayed reward). Action consistent with the more farsighted goal is assumed to require deliberative processes to override the more immediate and prepotent urges[22]. Such self-control is effortful, and the lateral prefrontal cortex has been implicated as a critical neural substrate[23,24]. Related conceptions of self-control[21,25] assume that, during choice, prefrontal processes modulate the valuation of choice options or choice itself when tempting choice options are present and when the decision maker has the motivation and capacity to override the prepotent response.

In contrast to the single- and dual-valuation accounts, the self-control account explicitly suggests that preference expressed by valuation judgments and choice can be discrepant, because neural valuations reflecting valuation judgments can be overridden in choice. Thus, the self-control account suggests specific PR patterns. For example, a tempting immediate SS might produce a neural signal reflecting higher valuation, but the LL might be chosen, indicating an instance of successful self-control (see, e.g.[26]). A neural self-control component has been discussed for intertemporal choice[3,19,26,27], but to the best of our knowledge it has not been conclusively established that self-control processes need to be included in neural models of intertemporal choice. A recent fMRI study[3] reported activations consistent with a self-control model, showing that LPFC activation was correlated with the duration of the LL's delay. However, this result is not conclusive on whether the LPFC plays a valuation or self-control function. The correlation can either reflect that the LPFC is involved in the evaluation of the time dimension (a valuation function; see[13]) or it can reflect that the requirements of self-control exerted by the LPFC scale with the delay duration (a self-control function: longer delays require more self-control to choose the LL).

In summary, behavioral and neural evidence has provided neural models of intertemporal choice that differ in both the kind and number of assumed processes (single-valuation; dual-valuation; self-control). However, no existing study provides *causal* evidence about the brain processes involved in intertemporal choice. Neuroscience evidence has only been correlational, and causal evidence regarding LPFC involvement in self-control has been in other domains. Our

central goal was to test whether it is necessary to include a self-control element in an account of intertemporal choice and to clarify the role played by the LPFC.

Predictions. Valuation models make three predictions based on the assumption that valuation translates directly into choice. First, they predict that any influence of rTMS to the LPFC on choice should have a comparable influence on explicit valuation judgments (because any observed rTMS effect on choice is mediated by a change in the valuation processes). For example, if disruption of left LPFC makes participants choose more impatiently in *now* trials, left LPFC disruption should also result in higher valuation judgments for immediate rewards[I].

Second, we should not observe systematic PRs between valuations and choices. A preference reversal would be observed if in valuation an SS is valued more highly than an LL, but in a direct choice, the LL is preferred. This would be a *self-controlled* preference reversal, where, despite the higher valuation ("temptation") of the immediate SS, the LL is chosen. The opposite case, an *impulsive* preference reversal, occurs when an LL is valued more highly than an immediate SS but, given a choice between the two, the SS is chosen. If choice follows directly from neural valuation, we should not see a large number of PRs of either type. Because both explicit valuation judgments and choice are subject to random error, a small number of PRs can be expected. However, both PR types should occur with about equal frequency.

The third prediction of the valuation accounts is that rTMS should not have a directional effect on the occurrence of either type of preference reversal. LPFC disruption might increase noise during valuation and choice, and therefore the number of PRs, but this would affect both types of reversals equally.

The self-control account makes different predictions for preference reversals. First, it predicts that choice does not follow automatically from neural valuation and that LPFC is involved in choice, but not in explicit valuation judgments. Accordingly, rTMS to the LPFC should only influence choice but not explicit valuation judgments. More specifically, rTMS should affect choice predominantly in *now* trials, since they represent a strong temptation of immediately-available rewards that requires controlling. *Not-now* trials do not offer immediate rewards and therefore self-control requirements are generally lower. Second, the self-control model predicts more self-controlled than impulsive PRs when self-control is intact. The very definition of self-control suggests that one can resist the temptation of the immediately available SS and still choose the LL. Third, to the extent that rTMS to the LPFC leads to diminished self-control capability, we expect both a reduction in self-controlled PRs and an increase in impulsive PRs.

People need to exercise self-control only when there is temptation, such as a conflict between a higher-order goal and prepotent urge. Accordingly, in our choice task, we varied the relative magnitudes of SS and LL rewards across trials, with self-control implications (see *Choice task* above). For a third of trials, the LL reward was only marginally larger than the SS reward and for another third of trials, the LL was substantially larger than the SS. Both of these trial types present low choice conflict. For the remaining third of trials, the LL was moderately larger than the SS. These trials can be expected to result in strong choice conflict, as neither option was clearly more attractive, and participants were hypothesized to require self-control to overcome

[I] While it is not clear how single-cell recording results of monkey's LPFC translate to humans, the single-component account by Kim et al.[13] would most likely predict that LPFC disruption should equally affect valuation and choice.

the prepotent impulse to choose the tempting SS and instead choose the LL. We expected rTMS-induced differences in self-control to have the strongest impact on this subset of *now* trials.

Finally, the two valuation accounts make some differing predictions for the effects of LPFC disruption. The neurometric single-valuation account does not assign an explicit role to the LPFC, and rTMS to the LPFC may have no effect. However, if the LPFC does play a role (yet unspecified in the model), it should affect all valuations (i.e., for immediate and delayed rewards). If rTMS influenced the overall discount factor, for example, this effect should change valuation and choice in *now* and *not-now* trials. In the β-δ dual-valuation model, the LPFC is implicated as a neural substrate for the relatively patient δ-process. LPFC disruption should therefore predominantly disrupt the δ-process and hence may give the impatient β-process more weight in *now* trials, leading to an increased valuation of immediate rewards and increased impatient choice. In *not-now* trials, the decision is solely based on the δ-process. Thus, LPFC disruption may possibly have an even stronger effect on choice, because there is no other process involved, and also have an effect on valuation. Finding an effect of LPFC disruption only in choice but not valuation is a unique prediction of the self-control account.

DATA ANALYSIS

Durations and Response Times

The three rTMS groups did not differ significantly in how long they took to complete the choice task or valuation task (ANOVA, all *P*'s > .3). The choice task at first task administration took on average a little less than 3 minutes to complete, and the valuation task a little more than 1 minute. Together, both tasks took participants on average about 4 minutes and 20 seconds (*M* = 257 sec, *SD* = 57 sec, range = 130-461 sec). This puts these two tasks, even for our slowest participant, within the 7.5 to 9 minute time window of active effects of rTMS on the LPFC, as previously established using identical stimulation parameters to those in the current study[11]. Therefore, decay of the rTMS effects can be ruled out as an explanation for finding no differences between the three rTMS groups in the valuation task. Additional evidence for this claim is presented further below.

Each choice typically took 2 to 3 seconds (with a mean of 3.22 sec, a median of 2.61 sec, and a standard deviation of 0.50 sec)[II]. Evidence for our hypothesis that decision difficulty and choice conflict would follow an inverted-U shape pattern as a function of the relative reward amount difference between the SS and the LL option was confirmed by an analysis of response times. As predicted, when the choice involved either small or large relative differences in reward amounts of an immediate SS and a delayed LL, the better option was obvious, and choices were relatively fast. For intermediate relative differences, when choice conflict should be strongest, response times were longer. Adding a quadratic trend to explain differences in response times as a function of relative difference in SS and LL reward amounts significantly improved how much variance was explained compared to a model including only a linear trend (likelihood ratio test, *P* = .003). Response times for the smallest and largest relative difference were substantially shorter (2.79 and 2.64 sec respectively) than response times for intermediate relative differences, which peaked at 3.48 sec.

[II] For the statistical response time analyses, response times were first log transformed and outliers above and below 3 SDs were excluded (leading to the exclusion of 24 out of a total of 3,744 responses).

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Choice

As shown in the four panels of Figure 1 in the main text, all three rTMS groups in both task administrations and for both *now* and *not-now* trials showed the expected tradeoff pattern between the relative differences in reward magnitudes between the SS and the LL and the differences in time of delivery. At the left in each panel, the clear majority of participants chose the SS, indicating that it was not worth waiting two or four weeks more to receive only very little additional money. At the right in each panel, the clear majority of participants chose the LL, indicating that it was worth waiting to receive up to 75% more money. The data points for the remaining relative differences exhibit a relatively monotonic increase in patience as a function of the relative differences in reward magnitude[III]. For the remainder of the analyses, we will focus on the effect of rTMS on the choices.

Choice data were analyzed with logistic hierarchical models that account for the repeated measures aspect of this data, using the R lmer function of the lme4 library. A base model included, as predictors, characteristics of the choice options describing the reward magnitudes and times of delivery and a random-effects participant term nested in rTMS group. The participant term modeled the repeated-measures nature of our data[28,29] and captures consistent individual differences in discounting. We added contrasts to this base model, representing our hypotheses. This experimental design produces two complementary analysis approaches to investigate possible rTMS effects. A first, *within-groups analysis* compares how the respondents differ in their TA1 and TA2 responses as a function of the type of rTMS received (left, right, sham). This compares choices made immediately after the rTMS train with choices made 30 minutes after the rTMS train, when rTMS effects have dissipated. Any rTMS effects should be present only in TA1 and thus can be detected if the choices in TA1 differ significantly from the choices of the same participants in TA2.

A second, *between-groups analysis* focuses on differences in the three different rTMS groups who received either rTMS over the left LPFC (*left* rTMS group), rTMS over the right LPFC (*right* rTMS group), or sham rTMS (*sham* control group). Here we compare differences in the choices made by comparing left versus sham, right versus sham, and left versus right groups in TA1. We also made the analogous comparisons for TA2 as an additional control. Together, the results of both types of analyses allow us to conclusively investigate in which rTMS groups and what kind of choices we observe any rTMS effects.

Within-groups TA1 versus TA2 comparisons. Here we compared participants' choices in TA1 to their choices in TA2. As an example, if rTMS over left LPFC results in increased impatience for immediate rewards, we would expect to find a significant effect when contrasting now trials in

[III] Overall, there was evidence for generally increased impatience in now compared to not-now trials (here called *now effect;* also known as *present bias* or *immediacy effect*), $P = .03$, one-tailed. Comparisons of a hyperbolic (Equation 1) or an exponential model (Equation 2) showed no significant differences. However, comparing various measures of model fit (log likelihood, AIC, deviance) all showed the same trend of the hyperbolic model providing a slightly better fit (similar to the valuation data, see below). This small overall now effect is not important for our analyses and results because neither our choice nor valuation data analyses are based on the assumption of any specific functional form of discounting, since the analyses are computed using the raw (choice and valuation) data. We assume that this overall rather small now effect is likely due to the many repeated and intermixed now and not-now trials which probably lead to a reduced now effect compared to that found in pure between-subjects designs. In contrast, for the preference reversal analysis, we necessarily had to assume a specific functional form of discounting. We report the results for the hyperbolic model, as the majority of studies (including our own data) report better fits for hyperbolic than exponential models. However, to test whether this model assumption biased our results, we also did the same preference reversal analysis using an exponential model. The results were the same.

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TA1 against now trials in TA2. If this rTMS effect were indeed specific for only the left LPFC and immediate rewards, we would further expect no significant effects when contrasting the not-now trials in TA1 against not-now trials in TA2 of the left group; and further, we would expect no significant effects when contrasting either now or not-now trials in TA1 versus TA2 for both the right and sham control groups.

Such TA1 versus TA2 comparisons can be orthogonally computed for each rTMS group and separately for now and not-now trials. Thus, in the within-groups analysis we set up the following two contrasts for each rTMS group, resulting in a total of six contrasts:

- Now trials of TA1 versus now trials in TA2,
- Not-now trials of TA1 versus not-now trials in TA2.

In this type of analysis, the repeated measures nature of our design was modeled by including random effects for participants. In addition, we added random effects for the contrasts, which allows us to model individual differences in the magnitudes of potential rTMS effects, which is possible and reasonable given the "within-subject" nature of the contrasts in this type of analysis[28,29]. The appropriateness of including the random effects for the contrasts was confirmed by the significantly better fit for the model that included random effects for the contrasts compared to the same model without said random effects, as indicated by a significant likelihood ratio test, $P < .001$.

Only the contrast comparing now trials in TA1 versus those in TA2 for the left rTMS group was significant ($P = .025$). All other contrasts were non-significant (P's ranging from .66 to .87). Crucially, the rTMS effect was specific for now trials, as the left rTMS contrast for not-now trials was not significant ($P = .84$). To directly test whether the left LPFC rTMS effect was significantly stronger in now than in not-now trials, we set up a contrast testing exactly this hypothesis. As expected, the contrast was significant ($P = .037$), indicating that rTMS over the left LPFC affected choices involving immediate rewards more strongly than choices involving only future rewards.

Between rTMS groups comparisons. In the between-groups analyses, we compared rTMS groups with each other by setting up separate contrasts between groups for now and not-now trials and separate contrasts within each of the two task administrations (TA1 and TA2). Thus, for each of the four trial types,

- Now trials in TA1
- Now trials in TA2
- Not-now trials in TA1
- Not-now trials in TA2,

we set up three contrasts, comparing (i) left vs. sham, (ii) left vs. right, and (iii) right vs. sham rTMS groups. This results in a total of 12 contrasts.

Consistent with results from the within-groups analysis, only the TA1 contrasts comparing now trials for left versus sham ($P = .006$) and left versus right ($P = .008$) groups were significant, indicating greater impatience for immediate rewards in the left rTMS group. All other contrasts were non-significant (P's ranging from .08 to .99).

As in the within-groups analysis, we directly tested whether the left LPFC rTMS effect was significantly stronger in now than in not-now trials. We set up two contrasts (left vs. sham and left vs. right) testing exactly this hypothesis. As expected, both contrasts were significant ($P =$

.002 and .003, respectively), indicating that rTMS over the left LPFC affected choices involving immediate rewards more strongly than choices involving only future rewards. As control, the analogous contrasts for TA2 were non-significant (P = .15 and .50, respectively), again as expected. The conclusion that there is a stronger left rTMS group effect for now vs. not-now trials in TA1 is consistent with the within-groups analysis, further supporting this characterization of the data.

In summary, we find consistent evidence from all analyses that there was a specific effect of rTMS over the left LPFC such that left LPFC disruption increased impatience, but only when immediate rewards were available. We showed this by finding: (i) increased impatience in now trials, but not in not-now trials comparing TA1 versus TA2 choices in the left rTMS group (with no such significant differences between TA1 and TA2 in the right and the sham group); (ii) increased impatience in now trials, but not in not-now trials of TA1 in the left rTMS group when comparing them to the sham control group (with no such significant difference in TA2); (iii) increased impatience in now trials, but not in not-now trials of TA1 in the left rTMS group when comparing them to the right rTMS group (with no significant difference between the two groups in TA2); (iv) in addition, we directly compared the magnitude of rTMS effects in now versus not-now trials, both for the within-groups and the between-groups analyses. In all cases, we found that the left rTMS group in TA1 showed a significantly stronger rTMS effect of increased impatience in now than in not-now trials.

Finally, inspecting Figure 1a in the main text suggests that the rTMS effect in the left rTMS group was strongest for the intermediate relative differences in reward magnitudes between SS and LL, compared to the small and large relative differences[IV]. This observation is consistent with the predictions of the self-control account, as this account assumes that choice conflict and temptation are strongest for the trials with intermediate relative differences, and thus the need for self-control to choose the LL is high. In turn, disruption of self-control capacities by rTMS should therefore result in stronger behavioral consequences for these trials. We statistically tested this prediction by setting up contrasts comparing trials with intermediate relative differences to trials with small and large relative differences. Consistent with the predictions and impressions from Figure 1a in the main text, we found that the rTMS effect in now trials in the left rTMS group in TA1 was significantly stronger for intermediate than for small and large differences in all three possible comparisons, i.e., the left group TA1 vs. TA2 within-groups comparison (P = .005), the TA1 left vs. sham rTMS comparison (P = .01); and the TA1 left vs. right rTMS comparison (P = .01).

Thus, the results from the choice data analyses show that disruption of left LPFC function had the specific effect of increasing the choice of immediate rewards in TA1; this effect was not present in not-now trials of TA1, now and not-now trials of TA2, and the right rTMS and the sham control groups. The equally intact general tradeoff patterns between the relative difference

[IV] As an indicator for the strength of the rTMS effect on now trial choices in TA1 in the left rTMS group, we compared their choices to the choices in right and sham groups (pooled): Across the 3 smallest relative differences, the sham (19%) and right (20%) groups chose the LL in about 20% of the cases whereas the left group chose the LL in about 15% of the cases, i.e., there was a 5% difference. For the 3 intermediate relative differences, the sham (72%) and right (73%) groups chose the LL in about 73% of the cases whereas the left group chose the LL in 59% of the cases, i.e., there was a 13% difference. For the 3 largest relative differences, the sham (94%) and right (91%) group chose the LL in about 93% of the cases whereas the left group chose the LL in 88% of the cases, i.e., there was a 5% difference.

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of reward magnitudes and time of delivery in all 3 rTMS groups and both task administrations showed that rTMS did not lead to an increase in either random or otherwise nonsensical responding, further underlining the specific effect rTMS had over left LPFC.

Valuation

The single-valuation and the dual-valuation accounts predict that valuation judgments should reflect the same rTMS effects observed in the choice data, suggesting that the left rTMS group should show higher valuation ratings for immediately available rewards, compared to the other two rTMS groups.

We first analyzed the valuation ratings using a mixed-model analysis of variance (ANOVA) with a 3 (Amount) × 4 (Time of Delivery) × 2 (Task Administration), all within-subjects, × 3 (rTMS Group) between-subjects design. We found significant effects for Amount, Time of Delivery, and Amount × Time (all *P*'s < .001), showing that participants were sensitive to both amount and time when valuing the presented option (see Fig. S3; note that the curves do not form straight lines, due to the fact that the amounts within a category (low, medium, high) differed slightly from each other, as in the choice task. Fig. S4 shows the amounts next to the data points to explain the different kinks in the curves.). The most notable result was that all the other effects and interactions were non-significant, indicating that the three rTMS groups did not differ from each other in their valuation ratings, neither in the first nor the second task administration. Most critically, if the valuation ratings exhibited the same rTMS effect as the choice pattern, we would expect the left rTMS group to show particularly high ratings for immediately available rewards in TA1. If this were the case, we would expect a significant interaction rTMS Group × Task Administration × Time of Delivery. However, this interaction was non-significant (*P* = .33) and visual inspection of the data revealed no tendencies for such an effect (see Fig. S5).

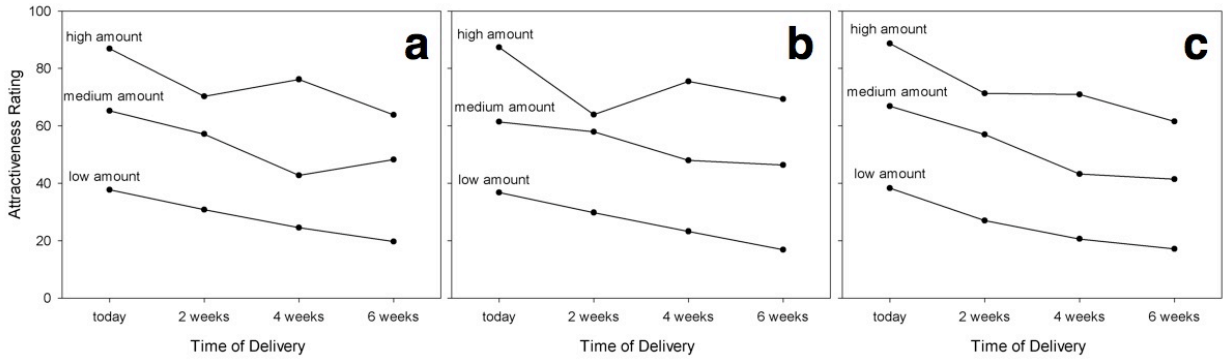

Figure S3. Valuation ratings in TA1. In all three rTMS groups, valuation was influenced by both the time of delivery and the reward magnitude; a = sham group, b = left rTMS group, c = right rTMS group.

The most critical comparison of the self-control and pure valuation accounts is whether the ratings for the three immediate rewards show a similar rTMS effect as the choices did. In order to use statistical methods as comparable as possible to those used in the choice analysis, we used the same hierarchical model approach for the valuation ratings that we used for the choice analysis, but used a linear model instead of the logistic model appropriate for the binary choice data.

Again we used both within-groups and between-groups contrasts. The within-groups approach contrasted the ratings of the three immediate rewards of TA1 versus TA2, within each rTMS group:

- Valuation ratings of the three immediate rewards in TA1 vs. TA2 in left rTMS group
- Valuation ratings of the three immediate rewards in TA1 vs. TA2 in right rTMS group
- Valuation ratings of the three immediate rewards in TA1 vs. TA2 in sham control group

Consistent with the ANOVA-based analysis of the valuation ratings, all three contrasts were non-significant (left rTMS: $P = .38$; right rTMS: $P = .24$; sham control: $P = .90$), indicating that there was no evidence for an rTMS effect in the valuation ratings.

The between-groups analysis contrasts compared the ratings of the three immediate rewards pairwise between the three rTMS groups, separately within TA1 and TA2:

- Left vs. sham, TA1
- Left vs. right, TA1
- Right vs. sham, TA1
- Left vs. sham, TA2
- Left vs. right, TA2
- Right vs. sham, TA2

Again consistent with the previous analyses of the valuation ratings, all six contrasts were non-significant (left vs. sham: TA1 $P = .67$, TA2 $P = .15$; left vs. right: TA1 $P = .26$, TA2 $P = .42$; right vs. sham: TA1 $P = .45$, TA2 $P = .55$).

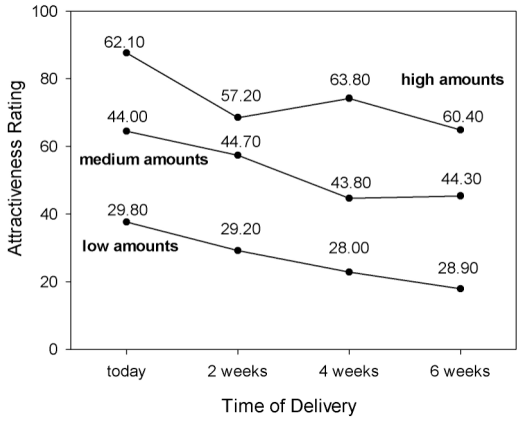

Figure S4. Valuation ratings in TA1, collapsed across all three rTMS groups. Data points are labeled with actual amounts of the valuated options caused by jitter, explaining the kinks in the curves.

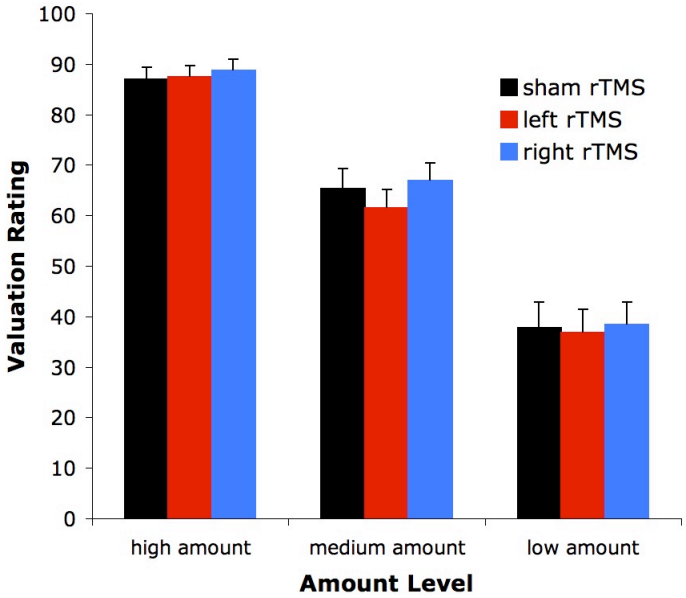

Figure S5. Valuation ratings of the three immediately available rewards in TA1, as a function of rTMS group. The left rTMS group did not differ from the other two groups in the valuation of immediate rewards. If valuations would exhibit the same rTMS effect as choices, valuations of the left rTMS group should be higher compared to the other two rTMS groups.

As noted in the main text, the absence of an rTMS effect on the valuation judgments is a crucial piece of evidence for our argument that a self-control-based neural account is necessary for intertemporal choice. Therefore, it is important to ensure that not finding any significant difference between rTMS groups really means that there is no effect. With this in mind, we conducted several additional analyses to rule out alternative explanations, in particular to (a) rule out that not finding an rTMS effect on valuation was due to decay of the rTMS effects, (b) establish diagnostic sensitivity of the valuation task, and (c) establish formal equivalence[30,31] of the ratings at an α level of $P < .05$.

Could the absence of an rTMS effect on valuation have been caused by decay of the rTMS effects?

In theory, this might be possible because the valuation task was always administered after the choice task. However, we deem this possibility highly unlikely for three reasons: First, the valuation task was completed well within the time window of active rTMS after-effects reported by others using the identical stimulation parameters[6,11]. Second, we correlated the ratings for the immediate rewards with the time since the end of the rTMS train in the left rTMS group. If a decaying rTMS effect were responsible for not finding an effect on valuation, we would expect that the mean rating for the three immediate rewards would correlate with the time since the end of the rTMS train. This correlation was not significant ($r = -.14$, $P = .57$). The strongest evidence is provided by our third task, a choice titrator task, which was always administered after the valuation task. It was affected by rTMS in the same way as the choice task (see below). This strongly suggests that the differences in valuation and choice are not due to rTMS effects decaying during this time window.

Could the absence of an rTMS effect on valuation be caused by a diagnostically-insensitive valuation task?

First, note that the valuation task shows strong effects both for the amounts and the time of delivery in all three rTMS groups and for both task administrations. However, to further investigate task sensitivity, we tested whether the task was sensitive enough to capture the hyperbolic discounting shape that one would expect based on the overwhelming majority of studies in the literature[32]. We focus here on the valuations during TA1 since these are the critical ones regarding the absence of an rTMS effect on the valuations. For each participant, we estimated separately the hyperbolic and exponential discounting parameter that best explained their ratings and then tested whether one type of model significantly outperformed the other.

For the hyperbolic model, we used Mazur's[33] standard one-parameter model of hyperbolic discounting,

$$SubjectiveValue = \frac{ObjectiveAmount}{1 + k \times Delay}, \quad (1)$$

where *Delay* indicates the time of delivery (in years) and k is a constant that is specific to each participant and indicates the steepness of the participant's discounting (with larger values indicating steeper discounting and 0 indicating no discounting at all).

For the exponential model, we used a standard one-parameter model of exponential discounting

$$SubjectiveValue = ObjectiveAmount \times \delta^{Delay}, \quad (2)$$

where *Delay* again indicates the time of delivery (in years) and δ is a constant that is specific to each participant and indicates the steepness of the participant's discounting (ranging between 0 and 1 with smaller values indicating steeper discounting and 1 indicating no discounting at all).

For both the hyperbolic and the exponential model, we assumed that the valuation rating was a linear function of a participant's subjective value of an option and estimated the linear regression

$$Rating = a + b \times SubjectiveValue. \quad (3)$$

For the hyperbolic model, replacing *Subjective Value* with (1), results in

$$Rating = a + b \times \left(\frac{ObjectiveAmount}{1 + k \times Delay} \right). \quad (4)$$

For the exponential model, replacing *Subjective Value* with (2), results in

$$Rating = a + b \times (ObjectiveAmount \times \delta^{Delay}). \quad (5)$$

For the hyperbolic model, we entered the 12 valuation ratings per participant and task administration in a linear regression for values of k ranging from 0 to 20 in increments of 0.1. For the exponential model, we did the same for values of δ ranging from 0 to 1 in increments of

0.005. This ensured that both models had the same fine-grained estimations covering the range of plausible parameter values. For both models, the R^2s of these regressions were plotted and the values for k and δ with the respectively highest R^2 were chosen[V]. Both models explained a substantial amount of the variance in ratings (median R^2s for the hyperbolic and the exponential model were .89 and .88, respectively) and overall performed similarly well. Nevertheless, a sign test indicated that, as expected, the hyperbolic model provided a significantly better fit than the exponential model ($P = .03$, one-tailed). We interpret this to indicate that our valuation task was indeed sensitive in assessing participants' valuations.

Could the absence of an rTMS effect on valuation have been caused by a lack of statistical power?

As noted in the main text, the absence of a significant difference between the left rTMS group and the other two groups is not necessarily evidence that their ratings are significantly equal. It has been argued that post-hoc power analysis is inappropriate and that one should instead perform an equivalence test[30,31]. Since we are concerned with the possibility that the "true" mean of the ratings for the immediate options might be higher for the left rTMS group (R_{left}) compared to the mean of these ratings by the other two groups ($R_{right/sham}$), we can establish a one-sided equivalence test. That is, our null hypothesis that we seek to reject with a specified probability P is that $R_{left} > R_{right/sham}$, and the alternative hypothesis is that $R_{left} \leq R_{right/sham}$. According to Wellek[31], a strict criterion for such a test is

$$(R_{left} - R_{right/sham})/\sigma = 0.36, \quad (6)$$

with σ indicating the standard deviation in ratings across the whole sample. This criterion corresponds to an effect size of approximately the same size as the rTMS effect observed in our choice data. Translated into the actual values of the ratings, the critical value that rejects the null hypothesis is 68.04. Because the upper bound of the 95% confidence interval for the left rTMS group (67.15) is below this value, we can reject the null hypothesis at $P < .05$ and thus establish one-sided equivalence for the valuation of immediate rewards by the left rTMS group and the other two groups.

Could the absence of an rTMS effect on valuation have been caused because valuation processes during the valuation task are less vulnerable to rTMS than valuation processes during the choice task?

The valuation and choice tasks differed on a number of characteristics, such as the response format (binary choice versus continuous rating), presentation of two options versus one option, and incentive-compatibility. Could it be that it was not the involvement or non-involvement of self-control processes but the differences in these or other task characteristics that led to the differential effect of rTMS on choices but not valuations? We think this is unlikely. If, for example, the lack of incentive-compatibility of the valuation task had made it invulnerable to rTMS effects, we would expect that the valuation task in general should be less sensitive to characteristics of the stimuli. However, this seems not to be the case. We found that the valuation task was very sensitive to changes in reward magnitude and time of delivery.

[V] This approach was validated by the high R^2 values for the best-fitting regressions and reasonable estimates of k and δ.

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Second, could it be that the difference in response format (binary versus continuous) was responsible for the differential rTMS effect? Again, we think that this is unlikely, given that continuous measures are usually more sensitive than binary response formats, thus making it hard to conceive how a rating scale would be less vulnerable to rTMS effects compared to a binary format, all other things being the same.

Finally, the choice task requires the consideration of two options at a time, whereas the valuation task requires the consideration of only one option at a time, making the choice task probably more taxing for working memory requirements. Since LPFC has been implicated in working memory, could this explain why we found rTMS effects in the choice but not in the valuation task? Again, we think this is unlikely because, if it were "just" working memory effects, it would be surprising to find the specific effects that we found: First, we found rTMS effects only in now trials, but not in not-now trials. Not-now trials might be even more taxing for working memory than now trials. Thus, if the working memory hypothesis were correct, we should find either equal effects in now and not-now trials or even stronger rTMS effects in not-now rather than now trials, which we did not. Second, we found rTMS effects to be strongest for intermediate rather than small and large differences; again, a working memory explanation would not necessarily predict this result. Finally, the patterns of preference reversals that we observed also seem easier to reconcile with a self-control rather than a working memory explanation.

In summary, it seems to us that the self-control explanation is a more parsimonious explanation for the observed pattern of results than assuming that some valuation processes (during choice) are more vulnerable to LPFC disruption than others (during single-option valuations). To reconcile our results with a valuation account, one could argue that neural valuation processes during choice are different from neural valuation processes during expressed valuation, and that only the latter, but not the former, are influenced by our rTMS manipulation. While possible, this would mean that two different neural valuation processes have to be assumed (one type for expressed valuation, the other for choice). Further, additional explanations would be needed for why only choices in now trials, but not choices in not-now trials, are influenced, and why particularly now trials with intermediate relative differences are most sensitive to rTMS effects. In short, we think that, among the three neural accounts (single-valuation, dual-valuation, self-control), the self-control account provides the most parsimonious explanation for the pattern of results that we observed.

Titrator Task

To provide further evidence about rTMS group differences in choice-based preferences, participants completed a choice titrator task immediately after the valuation task. The titrator task consisted of two trials. In the first trial (the *now* titrator), participants made a series of binary choices between a constant SS of CHF 50 today versus a variable LL with a three-month delay. The LL increased in steps of CHF 5, starting with CHF 55 and ending with CHF 105. The dependent measure was the switching point, i.e., the amount of the LL at which participants switched from the SS to the LL. The second titrator task (the *not-now* titrator) presented choices between a constant SS of CHF 30 in 2 months and an LL delivered in 5 months. The amounts of the LL ranged from CHF 35 to CHF 85, in steps of CHF 5. We also presented both titrators in TA2, adding either CHF 2 or subtracting CHF 2 from all amounts to prevent respondents from simply repeating their past answers.

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Because the titrator task results were very similar to the results in the choice task, we will not report them in detail. However, the titrator task provides us with yet more evidence to rule out the possibility that finding no differences between rTMS groups in the valuation task was the result of the effects of rTMS having worn off. Because right and sham groups did not differ significantly from each other on any of the four titrators (now TA1, not-now TA1, now TA2, not-now TA2; *P*'s were .76, .14, .25, and .27, respectively), data from these two groups were pooled (right/sham group). Consistent with the results from the choice task, the left group was significantly more impatient than the right/sham group in the now titrator ($P = .002$), but not in the not-now titrator ($P = .35$) of TA1 and group differences were significantly smaller in TA2 compared to TA1 in the now titrator ($P < .001$), but not in the not-now titrator ($P = .29$), consistent with increased impatience for immediate rewards after rTMS to the left LPFC, which dissipates by the time of TA2.

Thus, the titration task both confirms the results of the choice task and eliminates the possibility that the lack of found differences in the valuation task across rTMS groups is due to a decaying rTMS effect, since the rTMS effect was still in place in the subsequent titrator task.

Preference Reversals

To look for systematic PRs, we compared the preferences directly expressed during the first choice task to the preferences implicit in the valuation ratings that the same choice options would have received. To do this, we first estimated each participant's hyperbolic discount rate *k* that best explained their valuation ratings, as outlined above (see Equations (1), (3), and (4)).

The *k* was then used to derive subjective values for the options presented in the choice pairs[VI]. We then compared each choice to that predicted from the subjective values of the choice options, estimated from the valuation task (*valuation-implied choice*). This yields four possible results for each choice: (1) Both the valuation-implied and actual choice are SS; (2) both the valuation-implied and actual choice are LL; (3) the valuation-implied choice is SS whereas the actual choice is LL, i.e., the participant's actual choice was more patient than we would have predicted based on their valuations (*self-controlled* PR); (4) the valuation-implied choice is LL while the actual choice is SS, i.e., the participant's actual choice was more impulsive than we would have predicted based on the valuations (*impulsive* PR).

As shown in Table 1 in the main text, a large majority of choices (82, 78, and 80% for left, right, and sham groups respectively) were consistent across elicitation procedures (valuation versus choice), indicating that this comparison is sensible. More interestingly, in the three groups, the frequency of the two types of PRs (self-controlled versus impulsive) differed from each other, with the left rTMS group showing more impulsive than self-controlled PRs (12 vs 6%), and the right and the sham rTMS groups showing more self-controlled than impulsive PRs (16 and 12 versus 6 and 8%).

[VI] As mentioned earlier, to test whether the results of the preference reversal analysis were systematically influenced by the type of discount model used (hyperbolic versus exponential), we also did the same analysis using the exponential model from Equation (2) instead of the hyperbolic model. Perhaps not surprisingly, given the very similar fits of the hyperbolic and exponential models reported above, the preference reversal results were the same for the exponential and the hyperbolic models. Thus, we can rule out that our results critically rest on the assumption of one or the other functional form of discounting.

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We tested for differences in the frequency of the two types of PRs across the three rTMS groups using again the same hierarchical model approach that we used for the choice and valuation analyses (using a Poisson distribution because of the shape of the data). The dependent variable in the first analysis was the number of self-controlled PRs per participant. The dependent variable in the second analysis was the number of impulsive PRs per participant. The independent variable was rTMS group. As expected, we found significant effects of rTMS group in both analyses, indicating a significantly *lower* number of self-controlled PRs ($P < .001$) and a significantly *higher* number of impulsive PRs ($P = .034$) for the left rTMS group. As can be seen in Figures S6 and S7, both types of PRs were most common for choices with intermediate relative differences in reward magnitudes (sham and right rTMS groups are pooled for display purposes, as their patterns were similar). Finally, comparing preference reversals in TA1 and TA2 showed a significant reduction in the differences between left rTMS versus the other two groups, both for self-controlled ($P = .009$) and impulsive preference reversals ($P < .001$), consistent with the wearing off of the rTMS effect in left rTMS group (see Table 1 in the main text and Table S1 here).

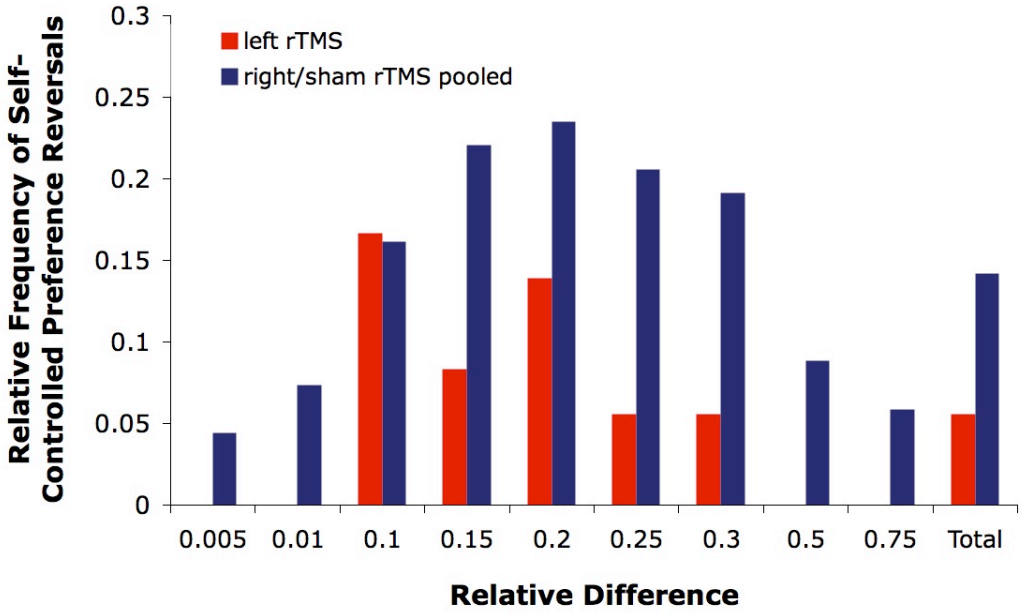

Figure S6. Relative frequencies of self-controlled PRs in now trials of TA1, as a function of rTMS group (right rTMS and sham group combined versus left rTMS group) and relative difference in reward magnitudes.

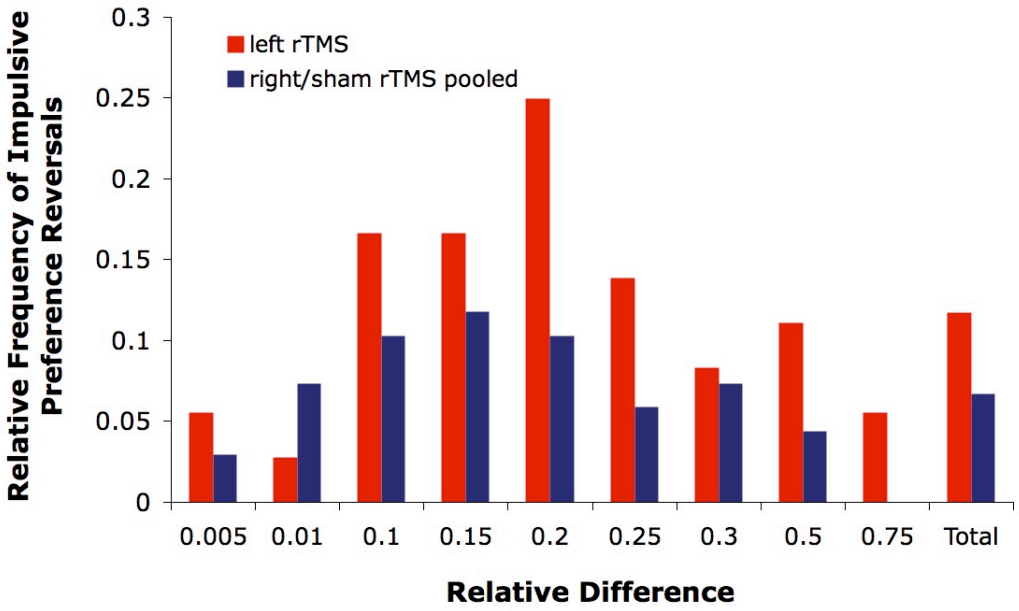

Figure S7. Relative frequencies of impulsive PRs in now trials of TA1, as a function of rTMS group (right rTMS and sham group combined versus left rTMS group) and relative difference in reward magnitudes.

Table S1

Left, right, and sham rTMS group: Frequencies (in %) for combinations of actual versus valuation-implied choices of SS and LL in now trials 30 minutes after rTMS train (TA2).

	Actual Choice					
Valuation-Implied Choice	Left rTMS		Right rTMS		Sham rTMS	
	SS	LL	SS	LL	SS	LL
SS	32	7	31	13	32	14
LL	9	52	10	46	6	47

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