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Lateral prefrontal cortex and self-control in intertemporal choice

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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

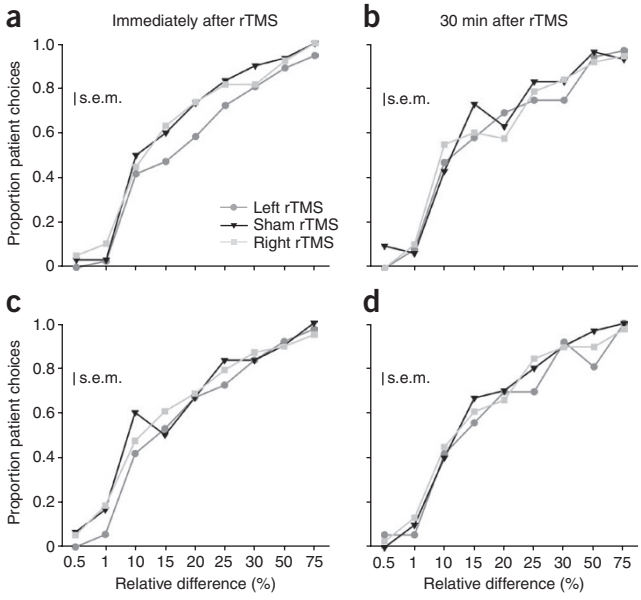

Figure 1 Proportion of patient choices (later-larger) as a function of the relative difference between magnitude of sooner-smaller and later-larger. Lines indicate the proportion of later-larger choices for left, right and sham rTMS groups. (**a**) Now trials in TA1. (**b**) Now trials in TA2. (**c**) 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.

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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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