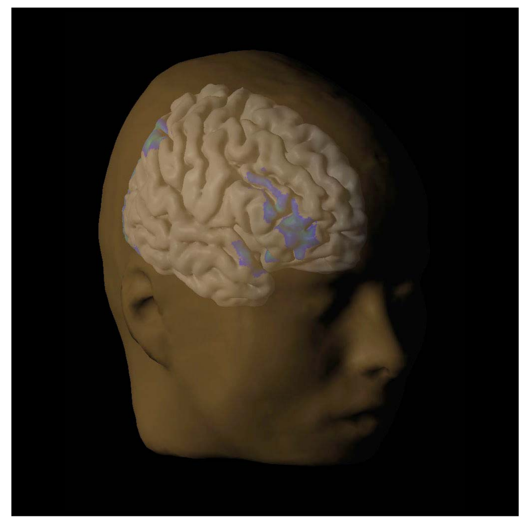
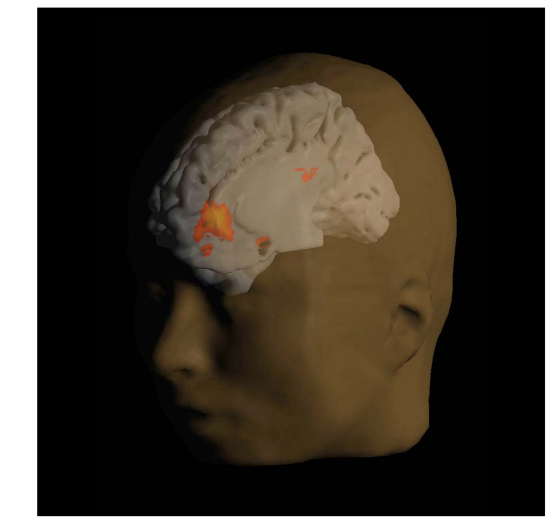


Separate Neural Systems Value Immediate and Delayed Monetary Rewards



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Introduction

We investigate the neural systems that underlie discounting the value of rewards based on the delay until the time of delivery. According to rational choice theory, time discounting ought to employ an exponential discount function in which every moment of delay is associated with a constant percent of discounted value (*1*). This is the only form of discount function for which preferences are time-invariant. However, it has long been recognized that people disproportionately overvalue rewards available in the immediate future (hyperbolic discounting) and hence are susceptible to preference reversals (*2*).

We test the theory that hyperbolic discounting results from the combined function of two separate brain systems (Figure 1; *3*). The β system is hypothesized to place special weight on immediate outcomes, the δ system is hypothesized to exert a more consistent weighting across time. Further, we hypothesize that β is mediated by limbic structures and δ by the lateral prefrontal cortex and associated structures supporting higher cognitive functions.

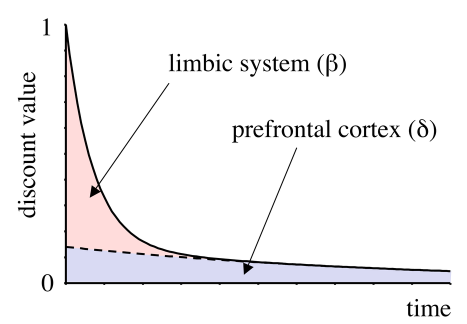

Figure 1. Hyperbolic discounting

Methods

Fourteen Princeton undergraduate and graduate students were recruited to participate in the study (9 females). The mean age was 21.4 years, with standard deviation 1.8; all subjects were right-handed. Informed consent was obtained using a consent form approved by the Institutional Review Panel at Princeton University.

Imaging was performed on a 3 Tesla Siemens Allegra scanner at Princeton University. A high-resolution (0.5mm x 0.5mm x 1.0mm) T1-weighted anatomical image was first acquired to enable localization of functional images. Whole-brain functional images were acquired in 26 axial slices (64 x 64 voxels; in plane resolution 3mm x 3mm; 3mm slices with 1mm slice gap) with a 2 s repetition time. Total scan time varied across subjects; individual scan runs were limited to 7 minutes in duration.

Subjects made a series of preference judgments between two reward options: \$R available at d or \$R' available at d'; \$R < \$R' and d < d'. The absolute dollar amounts were randomly determined (between \$5 and \$40).

Subjects were given one of each choice with the following values for d, d', and difference in reward values. The order of choices was randomly determined.

d	∈ { Today, 2 weeks, 1 month }
d'-d	∈ { 2 weeks, 1 month }
(R'-R)/R	∈ {1%, 3%, 5%, 10%, 15%, 25%, 35%, 50%}

Subjects viewed reward options via a rear-projection computer display (Figure 2). Preferences were registered using a MR-compatible button box. Subjects were allowed as much time as necessary to determine their preferences.

Figure 2. Experiment setup.

Results

Data analysis was performed using SPM, SAS, and self-written software in Matlab. To test our hypotheses we estimated a Generalized Liner Model (GLM) using standard regression techniques. We included two primary regressors in the model, one that modeled decision epochs with an immediacy option in the choice set (the "immediacy" variable), and another that modeled all decision epochs (the "all decisions" variable).

We defined β–areas as voxels that loaded on the "immediacy" variable. Identified regions are shown in Figure 3.

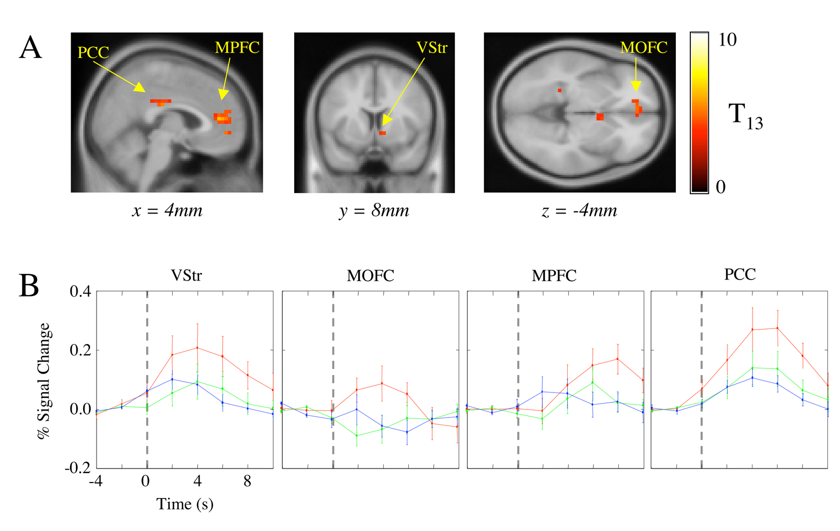

Figure 3. β-regions. **(A)** Brain areas significant at $p < 0.001$ (uncorrected). **(B)** Mean event-related BOLD signal. Dashed line is time of choice.

We considered voxels that loaded on the "all decisions" variable in our GLM to be candidate δ-areas. These were activated by *all* decision epochs and were *not* preferentially activated by experimental choices that included an option for a reward today. This criterion identified several areas (Figure 4), some of which are consistent with our predictions about the δ system (such as lateral prefrontal cortex). However, others (including primary visual and motor cortices) more likely reflect non-specific aspects of task performance, such as visual processing and motor responding.

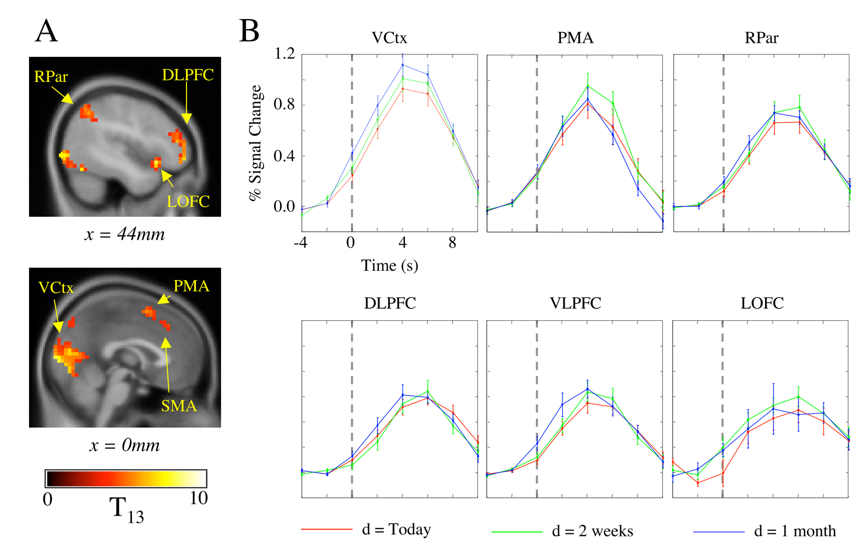

Figure 4. δ-regions. **(A)** Brain areas significant at $p < 0.001$ (uncorrected). **(B)** Mean event-related BOLD signal. Dashed line is time of choice.

To identify areas among these candidate δ regions that were more specifically associated with the decision process, we examined the relationship of activity to decision difficulty, under the assumption that areas involved in decision-making would be engaged to a greater degree (and therefore exhibit greater activity) by more difficult decisions. As expected, the areas of activity observed in VCtx, PMA and SMA were not influenced by difficulty (Figure 5). In contrast, regions in prefrontal and parietal cortex showed a significant effect of difficulty, with greater activity associated with more difficult decisions.

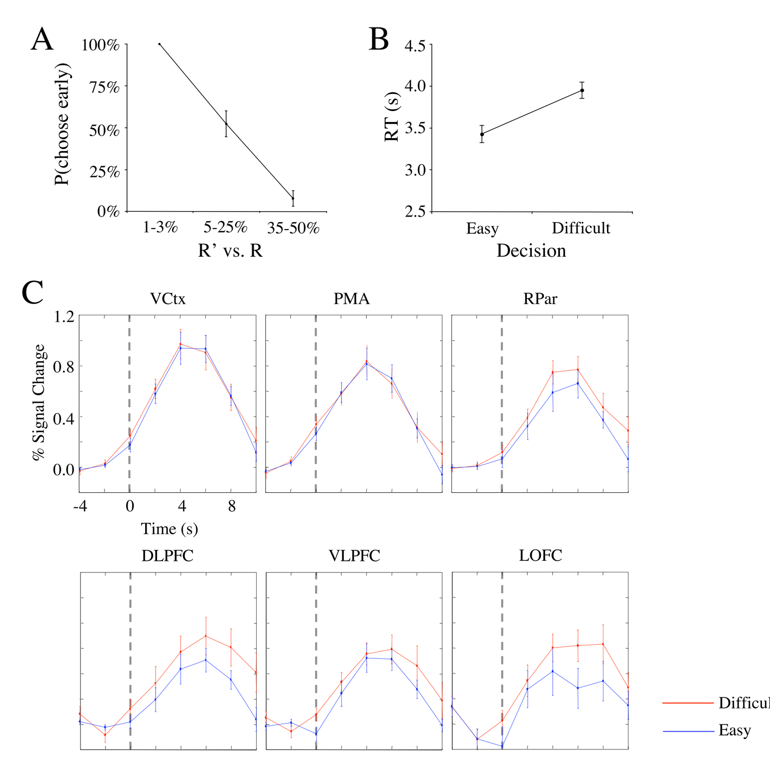

Figure 5. Effect of difficulty. **(A)** Difficult choices were defined as those for which subjects had variable preference. **(B)** This definition corresponded variability in response times (RT). **(C)** Mean event-related BOLD signals averaged over difficult and easy choices.

Our hypothesis also suggests that for choices between immediate and delayed outcomes (*d*=Today), decisions should be determined by the relative activation of the β and δ systems. More specifically, we assume that when the β system is engaged, it almost always favors the earlier option. Therefore, choices for the later option should reflect a greater influence of the δ system. This implies that choices for the later option should be associated with greater activity in the δ system than in the β system. Indeed, δ areas are significantly more active than β areas when participants chose the later option, while activity is comparable when participants chose the earlier option (Figure 5).

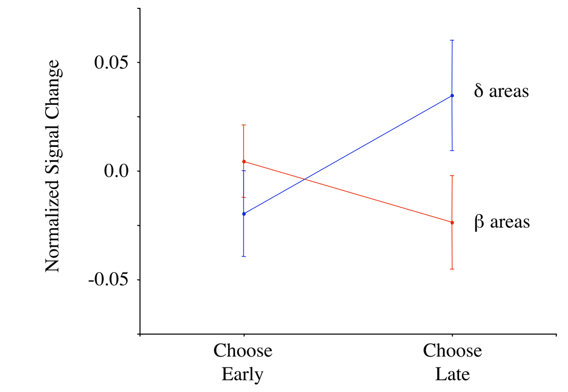

Figure 6. Relative activity in β and δ brain regions for choices involving money available today (d=Today).

Conclusions

- Time discounting results from the combined influence of two neural systems:
  - β: Subcortical limbic structures and associated paralimbic cortex are preferentially recruited for choices involving immediately available rewards.
  - δ: Fronto-parietal systems are recruited for all choices.
- These two systems are separately implicated in 'emotional' and 'cognitive' brain processes.
- When subjects select delayed rewards over immediately available alternatives, δ-areas show enhanced changes in activity.

References

1. T.C. Koopmans, *Econometrica* **32**, 82 (1960).
2. G. Ainslie, *Psych. Bull.* **82**, 463 (1975).
3. D. Laibson, *Quarterly J. Econ.* **112**, 443 (1997).

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