Supporting Information

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SI Methods

Basic Procedures. All procedures were approved by the University of Rochester Institutional Animal Care and Use Committee and were designed and conducted in compliance with the Public Health Service's Guide for the Care and Use of Animals. Three male rhesus monkeys (*Macaca mulatta*) served as subjects.

Initially, each animal was outfitted with a small prosthesis using standard technique (1). Four weeks later, animals were habituated to laboratory conditions and trained to perform oculomotor tasks for liquid reward. Standard reinforcement training was used with only positive rewards; punishment was never used, nor was aversive conditioning. Animals received analgesics and antibiotics after all surgeries.

In each session, the animal was transported from the colony at the University of Rochester to the testing room, about 100 feet away in the same building. The testing room was built specifically for primate studies and houses a computer screen and floor plate for firm mounting of the ergonomically designed primate chair (Crist). Animals made all task-relevant decisions using gaze shifts to selected targets. Horizontal and vertical eye positions were sampled at 1,000 Hz by an infrared eye-monitoring camera system (SR Research). Stimuli were controlled by a computer running Matlab (MathWorks) with Psychtoolbox (2) and Eyelink Toolbox (3).

A standard solenoid valve controlled the duration of water delivery (Parker). We estimated the precision of fluid volume delivered by the solenoid across the range of open time commands used in this study. We confirmed that water delivery volume was constant regardless of the volume of water in the reservoir over the ranges used in this experiment. All reward volumes were measured and confirmed. Fluid access was controlled outside of experimental sessions.

Behavioral Task. Our computer monitor had a 1,024 × 768 pixel resolution and was placed 144.8 cm (57 inches) in front of the subjects. Visual stimuli were small colored rectangles on a computer monitor placed directly in front of the animal and centered on his eyes (or in some cases photographic images; see below). On each trial of the task, a fixation spot first appeared in the center of the monitor. Once the subject acquired fixation and maintained it for 100 ms, two targets appeared, 275 pixels to the left and right of the central spot. Both stimuli were vertically oriented rectangles (80 pixels wide, 1–300 pixels tall). Stimuli were one of five colors (orange, yellow, gray, blue, and green). These colors indicated the size of the reward that would be obtained for the choice of this target (orange, 75; yellow, 97; gray, 135; blue, 175; and green, 212 μL, respectively). The height indicated the delay associated with choice of that target (0–6 s, respectively). The subject then selected a target by shifting the gaze toward it. Following the choice, the cued delay occurred, during which the bar shrunk at a constant rate (50 pixels per second). This shrinking thus provided a reminder of the linkage between cue length and delay. Once a choice was made, subjects could move their eyes freely without penalty. Once the cue shrunk entirely, the reward was given and the postreward buffer began. The screen was blank throughout the postreward buffer and the intertrial interval. Once this postreward buffer ended, an intertrial interval (1 s in all cases) began. No cue signaled the change from buffer period to intertrial interval time.

In the standard intertemporal choice task, postreward delays were buffered so that total trial length was equal regardless of choice. Because prereward delays varied randomly from 0 to 6 s, postreward delays varied, in a wholly conjugate manner, from 0 to 6 s as well. We collected at least 10,000 trials of the standard intertemporal choice task before moving on to any variants. All variants were tested in the same order for all monkeys.

In the constant buffer task, postreward delays were the same, regardless of the monkey's choice. Postreward buffers were either 0, 1, 2, 3, 4, 5, or 10 s and were run in blocks of the same type so as to give the monkey the opportunity to learn the postreward delay. In all other aspects the task was the same as the standard intertemporal choice task. At least 1,000 trials were collected per condition over multiple sessions. Trials were not interleaved with other tasks. Order of collection for specific postreward buffers was randomized separately for each monkey to reduce any possible order effects. Constant buffer data were compared with standard intertemporal choice data collected immediately beforehand to reduce possible long-term learning effects.

In the random buffer task, postreward delays were chosen randomly from 0 to 6 s, without regard to the monkey's choice. In all other aspects the task was the same as the standard intertemporal choice task. The random buffer was run in conjunction with the standard intertemporal choice task in interleaved blocks of 300–500 trials, on multiple days. At least 3,000 trials total were collected in each of the two (random and standard) conditions. For analysis purposes, random buffer data were compared with standard intertemporal choice data collected in the same behavioral sessions to mitigate any possible variations in preferences.

Blocks were signaled to the subject in the following way. Following the completion of a block, the monitor went blank and returned to the default task screen. Then the next session started. This entire process took about 30 s and validly predicted a change in task rules.

In the two-reward task, a second small reward (75 μL) was given at the end of the buffer period, before the 1-s intertrial interval. In all other aspects the task was the same as the standard intertemporal choice task. Only two monkeys were tested in this task due to the third monkey's unavailability for testing.

Statistics. Discount factors were computed using a standard method developed by Kirby and Marakovic and modified for use in immediate feedback studies (4, 5). For each decision, we computed the discount factor (k value) that would produce indifference between the two options. We then sorted all decisions in ascending order and computed the best fit sigmoidal curve (using matlab's fit.m algorithm) for the observed data. We defined the crossover point of this sigmoid as the monkey's discount factor for the dataset. To compute error bars, we used a jackknife procedure (6). We repeated the calculation of discount factor on a subset of 95% of the data, randomly selected. Then we repeated this procedure 20 times, using different random sets (without replacement), and used these 20 estimates to compute the SE. The jackknife SD was defined as the SE multiplied by the square root of 20.

Because discount factors are model-fitted parameters with highly skewed distributions that may not conform to standard statistical tests, we performed a bootstrap analysis of the null hypothesis that choices in the two conditions were drawn from the same process. To do this, we generated 20,000 bootstrap datasets by ignoring condition labels in our dataset and drawing samples (with replacement) of size equal to the number of trials in each condition. We then calculated a k value for each condition in each bootstrap dataset and generated a distribution of k value differences. Under the null hypothesis, the difference in k values should be 0, and our observed difference should lie inside the range of variation of the bootstrap distribution generated by ignoring condition labels. We rejected the null hypothesis when the observed difference in k values lay either below the 2.5% or above the 97.5% quantiles of the bootstrap distribution.

Values were confirmed by a complementary method we have previously developed to quantify discounting parameters in rhesus monkeys in a similar task (7). In brief, we fit animals' choices across all days for each task variant using a maximum log likelihood procedure. Numerical fits were performed via custom scripts using the Matlab Optimization Toolbox. For the two models, we paired a value function (used to assign a number to each option) with a logistic choice function that determined the probability of choosing each option based on the difference in subjective values estimated according to each model. Importantly, because each model used a separate, fitted rescaling parameter to accommodate subjects' variability in choices, subjective values could only be determined up to an overall constant. That is

$$P(LL) = logistic\left(\frac{V_{LL} - V_{SS} - b}{\sigma}\right), \quad \textbf{[S1]}$$

where v1 and v2 are the subjective values of the options, b is a bias, and sigma captures the variance of choice behavior. However, if we rescale v→alpha*v, b→alpha*b, sigma→alpha*sigma, this produces exactly the same probabilities. Thus, v is only defined up to overall rescaling. Accordingly:

$$V = \frac{1}{1 + k * D} = \frac{1}{k} * \frac{1}{k^{-1} + D}, \quad \textbf{[S2]}$$

which is the same as our boundedly rational model (Eq. **1**), up to an overall rescaling and the identification omega = 1/k. Thus, our model produces exactly the same predictions as hyperbolic discounting, albeit with a different underlying interpretation.

Data from all trials were analyzed.

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