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An adaptive, individualized fMRI delay discounting procedure to increase flexibility and optimize scanner time

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Abstract

Research on the rate at which people discount the value of future rewards has become increasingly prevalent as discount rate has been shown to be associated with many unhealthy patterns of behavior such as drug abuse, gambling, and overeating. fMRI research points to a fronto-parietal-limbic pathway that is active during decisions between smaller amounts of money now and larger amounts available after a delay. Researchers in this area have used different variants of delay discounting tasks and reported various contrasts between choice trials of different types from these tasks. For instance, researchers have compared 1) choices of delayed monetary amounts to choices of the immediate monetary amounts, 2) 'hard' choices made near one's point of indifference to 'easy' choices that require little thought, and 3) trials where an immediate choice is available versus trials where one is unavailable, regardless of actual eventual choice. These differences in procedure and analysis make comparison of results across studies difficult. In the present experiment, we designed a delay discounting task with the intended capability of being able to construct contrasts of all three comparisons listed above while optimizing scanning time to reduce costs and avoid participant fatigue. This was accomplished with an algorithm that customized the choice trials presented to each participant with the goal of equalizing choice trials of each type. We compared this task, which we refer to here as the individualized discounting task (IDT), to two other delay discounting tasks previously reported in the literature (McClure et al., 2004; Amlung et al., 2014) in 18 participants. Results show that the IDT can examine each of the three contrasts mentioned above, while yielding a similar degree of activation as the reference tasks. This suggests that this new task could be used in delay discounting fMRI studies to allow researchers to more easily compare their results to a majority of previous research while minimizing scanning duration.

Keywords

Delay discounting; fMRI; impulsivity; task development

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1. Introduction

Research on the rate at which people discount the value of future rewards has become increasingly prevalent as this temporal discount rate has been shown to be associated with many unhealthy patterns of behavior such as drug abuse, gambling, and overeating (see Bickel et al., 2012; Bickel et al., 2014 for review, see MacKillop et al., 2011; Amlung et al., 2016 for meta analyses of behavior). The general procedure to characterize an individual's discounting rate is to give them a series of forced choice questions between a smaller amount of money available after a smaller delay versus a larger amount of money available after a larger delay. Behavioral delay discounting data is often quantified with a rate parameter from a hyperbolic function first validated by Mazur (1987). Points of indifference across a series of delays expressed as a proportion of the larger delayed amount are fit to the function $V=1/(1+kD)$ where V is the proportional present value, D is the delay, and k is the discount rate. Indifference curves fit by this function take on a characteristic 'S' shape when plotted on logarithmic axes, where the specific discount rate for an individual participant is determined by the transition of this curve from asymptotic values near 1.0 at lower delays to asymptotic values near 0.0 at higher delays (Figure 1). With a series of delays common in the behavioral discounting literature (ranging from days to years), this transition occurs across a consecutive series of four delays, but importantly, individual differences in discount rates result in a different set of four delays among participants.

Across fMRI delay discounting studies, the tasks examined by researchers seem to fall into two prototypical types, which we have cataloged in Table 1. The first of these types consists of tasks similar to behavioral delay discounting assessments. In these tasks, a series of choices are presented between some amount of money available immediately and a larger amount available after a delayed amount of time (e.g. $10 now versus $50 in 3 weeks), and data are typically analyzed based on the choice made by the participant. For example, some studies have focused on contrasts between choices for the immediate option versus choices of the delayed option, while other studies have focused on 'hard' choices that represent a decision near that participant's indifference curve versus 'easy' choices far from the indifference curve. In Table 1, studies of these *response-focused* tasks are described along with the type of contrast reported.

The second type of task focuses on the difference between choice trials, where trials consisting of two delayed options (e.g. $10 in 1 week versus $50 in 1 month) are interspersed with choices consisting of both a delayed and an immediate option, with roughly half the trials of each type. Data are typically analyzed as a function of the type of trial that was presented, contrasting on whether an immediate option was available (regardless of participant choice). We have therefore labeled these tasks as *stimulus-focused*. These tasks often have the appropriate trial types for the 'hard' versus 'easy' and immediate choice versus delayed choice contrasts, but these are not always reported. Inconsistent reporting of these *response-focused* contrasts may be because they were auxiliary to the goals of these studies or that some studies lacked power to analyze these types of contrasts since the number of choice trials that fall into the *response-focused* trial categories can be small or highly unbalanced.

Across different types of tasks, researchers have compared 1) choices of delayed monetary amounts to choices of the immediate monetary amounts, 2) 'hard' choices made near one's point of indifference to 'easy' choices that require little thought, and 3) trials where an immediate choice is available versus trials where one is unavailable (regardless of the participant's actual choice). Unfortunately, however, capturing all of these contrasts in the existing delay discounting tasks during the same imaging study is difficult, and as a result, researchers are forced to limit their eventual analyses to only a subset of these contrasts. Note that in Table 1, no task has been used to analyze all three of these contrasts. Of course, one option is to simply run both types of tasks to obtain data on both types of contrasts, but the high cost of scanner time and the increased potential for participant fatigue (which often leads to increased head motion) typically precludes this.

Thus, the goal of this project was to develop a task that could incorporate both *response-focused* and *stimulus-focused* trials into a compact fMRI task. A key insight in our approach, similar to approaches used previously (e.g., Kishinevsky et al., 2012; Manning et al., 2014), comes from the observation that existing tasks must be able to capture a wide range of individual discounting rates, and thus current tasks need to include trials that for one individual may be critical because they are near their indifference point, but are inefficient for another individual because they are near either the upper or lower asymptotic regions of their discounting curve. The crux of the task that we developed is that if a participant's discount rate is characterized before the scanning session, the in-scanner portion of the task can be individualized to be optimal for each participant. Thus, we call this the individualized discounting task (IDT). We hypothesized that a task with trials individualized to an individual's pre-estimated discount rate would allow us to examine the common contrasts of both *response-focused* and *stimulus-focused* discounting tasks of Table 1 with a similar scanning duration as either reference task alone. To test this assertion, we directly compared our IDT to prototypical *response-focused* and *stimulus-focused* tasks and evaluated whether our novel IDT met two criteria: 1) it yielded similar activation maps as the two comparison tasks when comparing the same contrast, and 2) it yielded similar activation maps as previous reports in the literature. To examine the tasks on these criteria, we focused on contrasts among the trial types that differentiate existing discounting tasks reported in the literature (see Table 1), but we also examined an 'all-trials' contrast that is not unique to any task to verify that our IDT yields similar results as other tasks with this popular contrast.

2. Materials and Methods

2.1. Participants

Participants (n = 22) were recruited from the community in and around Roanoke, VA. Participants were excluded if they met DSM-5 use disorder criteria for any drug of abuse other than nicotine (American Psychological Association, 2013) or if they had medical conditions contraindicated for an MRI scan (e.g., ferromagnetic implants, or claustrophobia). This study was conducted as part of a larger trial so inclusion/exclusion criteria and sample size based on power to detect behavioral differences in discounting were inherited from that trial. Four participants moved excessively during the imaging session and

were excluded. Among the excluded participants, one had a mean maximum motion of 6.7 mm (with 10.6 mm as their maximum); the second participant fell asleep and had a mean maximum motion of 6.6 mm (with 17.7 mm as their maximum); the third participant had a mean maximum motion of 10.9 mm (with 15.7 mm as their maximum); and the fourth excluded participant had a mean maximum motion of 4.6 mm (with 8.1 mm as their maximum). The 18 participants who remained in the final analyses had a mean maximum motion of 1.7 mm (+/− 0.6 mm) and were 28% female, were 67% White and 33% African American, had a mean age of 33.7 (SD = 8.4, range 23 to 50), completed a mean of 13.9 years of education (SD = 2.1), and had a mean monthly income of $953 (median = $700, SD = $915).

2.2. Individualized Discounting Task (IDT)

Example screens from the IDT are displayed in Figure 2. As mentioned, our IDT resulted from an examination of the shape of indifference curves and the distribution of choice trials in common discounting tasks in relation to these indifference curves. With a series of delays that is common in the behavioral discounting literature (1 day, 1 week, 1 month, 3 months, 1 year, 5 years, 25 years), the transition of indifference points occurs across a consecutive series of four delays, but the particular four delays involved differs among participants. In the examples drawn in Figure 1, individualized series of four delays capture the transition period well as long as the full delay series from 1 day to 25 years are candidates for selection. Our data suggest that these longer, multiple-year delays are necessary to fully characterize the discounting curve, as some participants do not show appreciable discounting until delays of approximately 1 year (Figure 3).

In the IDT, we focused on this individualized series of four delays to increase the proportion of ‘hard’ choices (defined here as an immediate value for that choice within 0.2 units of the indifference point at that delay where 1 unit is the delayed amount) compared to ‘easy’ choices (all other choices that are not ‘hard’) and to approximately equalize the number of immediate and delayed choices. We chose to divide ‘hard’ and ‘easy’ trials in this way to match the source article for our *response-focused* task (Amlung et al., 2014). We chose this definition as one of the goals of this experiment was to replicate previous results in the literature, but nothing prevents users of this task to use other methods for determining cutoffs between ‘hard’ and ‘easy’ trials (e.g., Pine et al., 2009). The out-of-scanner task (described below) passed the participant’s discounting rate (fitted k value from Mazur’s (1987) hyperbolic equation) and indifference points at each delay to the IDT task. The specific four delays assigned to each participant were determined by the k value with unit days^{-1}, with $k > 0.03542$ assigned delays 1 day to 3 months, $0.03542 \geq k > 0.0098$ assigned delays 1 week to 1 year, $0.0098 \geq k > 0.002813$ assigned delays 1 month to 5 years, and $k \leq 0.002813$ assigned delays 3 months to 25 years. At each of the four assigned delays, the IDT script arranged the following specific trials, with all amounts calculated as proportions of configurable amount of a configurable commodity set at task onset: 10 trials with set immediate proportional amounts of 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95; 1 trial where the immediate amount is at the participant’s predetermined indifference point for that delay; 4 trials with amounts near to the participant’s indifference point at +0.04, +0.08, −0.04, and −0.08 (logic was inserted in the task to prevent these four trials

from creating amounts <0 or >1 – in these cases 0.1 was added to or subtracted from the proportional multiplier as necessary). In addition to these immediate versus delayed trials, the task contained 14 trials spread throughout the task with both options delayed to mimic the similar trials of the McClure et al. (2004) task. A number of tasks employ additional control trials with similar visual and motor response elements as the active trials, but with the choices altered such that only one logical response is available. We incorporated different forms of these trials, including 12 choices between two different amounts of immediately available money, 4 choices between the full larger-later amount available immediately versus the same amount delayed (1 trial at each delay), and 4 choices between nothing now and the full larger-later amount delayed (1 trial at each delay). The total number of trials equaled 98. For the present experiment, we set the amount and commodity to $1000 in US currency because this is the most commonly studied amount of money in the addiction literature (MacKillop et al., 2011) and more effective at distinguishing substance users from controls than smaller amounts (Mellis et al., 2017). Our IDT task script and associated out-of-scanner script can be downloaded from <https://github.com/micned/IDT>.

2.3. Comparison Discounting Tasks

To test whether our IDT was associated with similar neural activity as both *stimulus-focused* and *response-focused* tasks from Table 1, we also administered a comparison task from each type to participants. Example screens from the comparison discounting tasks are displayed in Figure 2. We chose the *stimulus-focused* task used in McClure et al. (2004), and the *response-focused* task used in Amlung et al. (2014). The two tasks were described well by the original authors including images of the visual elements, such that we were able to reprogram them to be highly similar to their original form. When a task element was not specified (e.g., specific font or measurements of screen elements), we chose options to make the three tasks as similar to each other as possible.

2.4. Procedure

After giving informed consent, participants completed a series of behavioral assessments outside of the scanner including a delay discounting task. This out-of-scanner task was used to determine which delays would be included in the IDT for that person (see below). For the out-of-scanner task, we used an adjusting-amount titration task that we have used previously (e.g., Koffarnus & Bickel, 2014), which is based on a task developed by Du et al. (2002). Briefly, this algorithm starts each set of trials based on one delay with a question between the larger-later amount and half that amount available immediately. Based on the participant's choice, the immediate amount then adjusts up or down across a series of six choice trials to increasingly approximate the participant's point of indifference between the immediate amount and the larger-later amount. This task consisted of 42 trials and the mean duration was 4.2 min (*SD* = 1.0 min). Participants then completed the fMRI portion of the study, which consisted of a structural scan and three delay discounting tasks: our IDT and the comparison *response-focused* and *stimulus-focused* tasks (see Figure 2 for task visual elements). The *response-focused* task was split into four parts, each 6.5 min (26 min total), which were always run consecutively in sequential order as was done in the original paper (Amlung et al., 2014). Two of these parts constituted one full run of the task, so two full runs were completed. The mean duration for the *stimulus-focused* task was 13.3 min (*SD* = 1.0

min) and the mean duration of the IDT was 15.1 min (*SD* = 2.7 min). The order that these tasks were presented was randomized across participants. For all discounting tasks in and out of the scanner, participants responded by pressing a button in or under their left and right hands for the option on the left and right side of the screen, respectively. All task choices were hypothetical. Hypothetical choices have been shown to produce similar results as consequated choices in both behavioral and fMRI contexts (Bickel et al., 2009; Johnson & Bickel, 2002; Lagorio & Madden, 2005; Lawyer et al., 2011; Madden et al., 2003; Madden et al., 2004). All procedures were approved by the Virginia Tech Institutional Review Board.

Structural and functional brain data were collected on a 3.0 T scanner (Siemens Tim Trio). T1-weighted anatomical volumes were acquired with a 3D magnetization prepared rapid acquisition gradient echo (MPRAGE) pulse sequence with 192 axial slices (resolution = 1 x 1 x 1 mm^3, repetition time (TR) = 2,600 ms, echo time (TE) = 3.02 ms, field of view (FOV) = 256 mm^2, flip angle (FA) = 8°). Functional data consisted of 33 interleaved slices collected every 2 s with an echo time of 30 ms and a 90 degree flip angle using an echo planar sequence (resolution = 3.4 x 3.4 x 4.4 mm^3, FOV = 220 mm^2).

2.5. Data Analyses

All analyses were conducted with 18 participants unless otherwise noted. Behavioral data were analyzed in GraphPad Prism 6. All MRI data processing and analyses were performed using AFNI (Cox, 1996). Preprocessing of functional data were performed using the afni_proc.py python script (Cox, 2012) with default settings unless otherwise specified and included slice timing correction, motion correction, spatial smoothing (6 mm FWHM) and scaling to percent signal change. Anatomical volumes were skull-stripped, aligned to the first functional volume and subsequently co-registered to the MNI 152 template. The resulting functional-to-MNI transformation matrices were applied to the statistical maps generated by the following GLM analyses. For first-level analyses, separate general linear models (GLMs) were obtained for each of the trial categories: Hard Choices, Easy Choices, Immediate Choices, Delayed Choices, Immediate Available, and Immediate Unavailable. Note that because the *response-focused* task always presented an immediate choice, only the *stimulus-focused* and IDT were analyzed with an immediate available versus immediate unavailable contrast. Time points containing motion spikes and time series outliers were censored from the analysis. Apart from baseline and task-related regressors, six additional nuisance regressors were included to account for head motion (roll, pitch, yaw, X, Y, Z). Group analyses were then performed using a mixed effects meta-analysis model with the 3dMEMA command in AFNI (Chen et. al., 2012), which accounts for both within and across participant variability. All statistical maps were thresholded at a False Discovery Rate (FDR) corrected value of 0.05 except the ‘all trials’ contrast which was thresholded at $p < .001$, uncorrected, 5 contiguous voxels as in McClure et al. (2004). Since the stimulus-focused task did not include any control trials, control trials from the other two tasks were also regressed out from the general linear model for this contrast. For only the immediate versus delayed choices, seven participants that did not choose any delayed choices in the *stimulus-focused* task were excluded from analyses with that contrast for that task and task-to-task comparisons. All contrasts were conducted bi-directionally and all statistically

significant results are reported here. Beta maps from analyses reported here can be downloaded in NIfTI format from <https://github.com/micned/IDT>.

3. Results

3.1. Behavioral Data

Fits for the in-scanner discounting curves for the IDT and runs 1 and 2 from the *response-focused* task are shown in Figure 3a and 3b, respectively. The analogous fits for the *stimulus-focused* task are not easily depicted on similar coordinates because the delay of both response options are manipulated, but this task assessed a more narrow range of delays (i.e., immediate to 1 month + 2 weeks. Even though only four indifference points were assessed, the IDT assessed the relevant trials for each participant, excluding the asymptotic portion of each individual's discounting curve. This process resulted in a similar vertical range assessed by these two tasks (Figure 3c), calculated by taking the y-value of the indifference curve at the lowest assessed delay minus the y-value of the indifference curve at the highest assessed delay. Correlations among log-transformed discount rates from the out-of-scanner adjusting amount discounting task and the in-scanner tasks were all statistically significant and generally very high (Table 2).

The primary goal of the IDT was to include sufficient trials of each type reported in the literature as important for understanding the neural correlates of intertemporal choice. The distribution of these trial types for each of the three tasks, expressed as a proportion of all trials, is shown in Figure 4. The distribution of immediate versus delayed choices (first two columns) was approximately equal in the IDT (Figure 4a, $t(17) = 1.53$, $p = .1$, $d_z = 0.36$) and in the *response-focused* task (Figure 4b, $t(17) = 0.54$, $p = .6$, $d_z = 0.13$), but more immediate choices were made in the *stimulus-focused* task with our sample (Figure 4c, $t(17) = 7.82$, $p < .001$, $d_z = 1.84$). The differences in immediate versus delayed trials across tasks was significant with a one-way ANOVA ($F(2, 53) = 4.4$, $p = .03$), with the IDT having a significantly more equitable distribution than the *stimulus-focused* task (Tukey-adjusted $p < .001$) and the *response-focused* task not different from the other two. In all three tasks, significantly more 'easy' choice trials were made than 'hard' choice trials, but this difference was substantially smaller in the IDT (Figure 4a, $t(17) = 2.16$, $p = .046$, $d_z = 0.51$) than in the *response-focused* (Figure 4b, $t(17) = 16.34$, $p < .001$, $d_z = 3.85$) and *stimulus-focused* (Figure 4c, $t(17) = 5.54$, $p < .001$, $d_z = 1.31$) tasks. These differences among tasks were significant ($F(2, 53) = 17.5$, $p < .001$) with the IDT having a significantly more equitable distribution of 'hard' and 'easy' trials than both the *response-focused* ($p < .001$) and *stimulus-focused* ($p = .006$) tasks, which were not significantly different from each other. By design, trials with only delayed options presented were only included in the IDT (18.4% of trials) and *stimulus-focused* task (24.5% of trials), and appreciable numbers of control trials were only included in the IDT (20.5% of trials) and *response-focused* (21.1% of trials). For the purposes of Figure 4, control trials and other trial types are mutually exclusive.

3.2. fMRI Findings for Each Task

The IDT was designed to optimize the availability of contrasts comparing specific trial types within the task to one another, but we also examined an 'all-trials' contrast that is commonly reported in the literature to determine if this novel task reproduces associated effects. Each individual statistical map for all trials versus baseline produces widespread activation in a pattern characteristic to this contrast, and the overlap map obtained by intersecting these individual maps is displayed in Figure 5. Areas of activation include the visual cortex, bilateral dorsolateral prefrontal cortex (DLPFC), premotor area (PMA), supplementary motor area (SMA), bilateral superior and inferior parietal lobules, and bilateral ventrolateral prefrontal cortex. A repeated-measures ANOVA was also performed to compare the activation maps across tasks. The *stimulus-focused* task showed significantly higher activation in the visual cortex compared to the other two tasks for the all trials contrast, reflective of additional visual stimuli and more visual transitions in this task paradigm (see Figure 2). No other significant differences were observed among the tasks.

For the contrast between 'hard' and 'easy' choices (those choices near and far to that individual's indifference point for that delay combination, respectively), the analysis for each task used a three-regressor model (hard choices, easy choices, and control trials). The common areas of activation between the IDT and *response-focused* tasks included medial prefrontal cortex and anterior cingulate for hard > easy (Table 3, Figure 6). No significant activations were found for the *stimulus-focused* task, which is likely due to the limited number of trials fitting the 'hard' criteria in many participants (see trial type distributions in Figure 4).

For the contrast of delayed choices versus immediate choices, the analysis used a four-regressor model (delayed choices, immediate choices, control, and immediate unavailable). No areas of activation were statistically significant after FDR error correction ($p < 0.05$) for any of the three tasks examined. Only 11 participants could be included for this contrast in the *stimulus-focused* task due to exclusive or nearly exclusive responding on the immediate option.

Immediate unavailable trials presenting a choice between two delayed options could only be compared to trials with an immediate option available in the *stimulus-focused* task and IDT because these were the only tasks that contained immediate unavailable trials. This comparison used a three-regressor model (immediate available, immediate unavailable, and control). In our sample, we observed no significant activations associated with this contrast with the *stimulus-focused* task, but noted a number of areas with the IDT including Brodmann areas 47, 8, and 6 in the left middle frontal cortex (Table 4, Figure 7).

Regions of interest (ROIs) were also identified from each area reported as significant in one or both of the comparison task papers (Amlung et al., 2014; McClure et al., 2004) for each of these four contrasts. Activation associated with our implementation of the comparison tasks and the IDT were compared for each ROI, the results of which are detailed in Supplementary Material.

3.3. Comparisons between Tasks

When proposing a new behavioral measure, it is important to consider its equivalence to previous measures. Therefore, to determine if areas of activation differed as a function of task, statistical maps for each of the three pairs of trial types were compared across tasks in second-level analyses using a two-way ANOVA with the task as the fixed effect and the participants as the random effect. For the 'all-trials' contrast, the *stimulus-focused* task was associated with greater visual cortex activity than the other two tasks, but this was the only difference noted. This task included colored triangles below the response options and more visual element transitions (Figure 2), which may account for this increased visual cortex activity. For each of the three within-task contrasts examined in this study, no significant main effect of task on activation in any area of the brain was observed, indicating that similar neural activity was associated with the analogous trial types in each of the three tasks. This comparison included all three tasks for immediate choices versus delayed choices ($n = 11$ only due to nearly exclusive responding for the immediate option in many participants on the *stimulus-focused* task) and for 'hard' choices versus 'easy' choices ($n = 18$). For the contrast of immediate available versus immediate unavailable trials ($n = 18$), only the IDT and *stimulus-focused* task could be compared since the *response-focused* task did not have immediate unavailable trials. Furthermore, when the beta coefficients associated with each of the ROIs reported in the comparison task papers (Amlung et al., 2014; McClure et al., 2004) were compared among the tasks, no significant task-associated effect for any area was detected (see Supplementary Material).

4. Discussion

By focusing the choice trials in the in-scanner task on those delays most important for resolving that individual's discount rate and distributing choice trials more evenly among the different trial types, the IDT was able to maximize scanner time while producing activation maps that did not significantly differ from either of the comparison tasks for each of three contrasts commonly performed in the literature and only differed in the visual cortex in a fourth common contrast. Conclusions about some of these contrasts should be interpreted with caution due to the lack of activation with any of the tasks in our sample, but overall, our results suggest that the IDT produces similar activation as two comparison tasks. The IDT differs from existing tasks in two key ways. First, it contains each of the trial types that have been highlighted in other intertemporal choice tasks in sufficient numbers to measure associated neural activation. Second, it maintains a reasonable duration by tailoring the specific questions asked to the individual to equalize the distribution of trial types, effectively optimizing scanner time.

4.1. Similarity of the Individualized Discounting Task Activation Maps to Comparison Tasks

The first basis on which we set out to evaluate the IDT was the degree to which it produced the same activation maps as the comparison tasks for the same contrast. No regions were significantly correlated with immediate choices or delayed choices for any of the tasks, indicating that we may have not had sufficient power with our sample size to detect activations associated with this contrast. Perhaps unsurprisingly, these activation maps were also not significantly different among tasks. For the contrasts with significant neural

correlates, the activation maps from the IDT were also not significantly different from either of the comparison tasks. The 'all-trials' contrast produced maps that look highly similar to those in McClure et al. (2004) and ROI analyses (see Supplementary Material) confirm that the IDT did not differ from either of the other two tasks in these key areas. Visual cortex activation was significantly different among tasks, but this is likely explained by the extra visual content on the screen during the *stimulus-focused* task (see Figure 2). For the immediate available versus unavailable contrast, only the *stimulus-focused* task and IDT could be compared, and activation maps were not significantly different and ROI analyses did not reveal any differences between the tasks (see Supplementary Material). This pattern suggests that individuals completing the IDT recruit similar neural resources when completing the same trial types as each of the two reference tasks. The individual activation maps for these contrasts were not always identical, although significant overlap in the 'hard' versus 'easy' contrast was observed (Figure 6). However, the lack of statistical significance in the second-level comparisons and similar activation in ROIs identified in Amlung et al. (2014) indicate that these apparent differences were perhaps due to power differences among the tasks, not due to significantly different patterns of activity.

4.2. Similarity of the Individualized Discounting Task Activation Maps to the Published Literature

The second basis on which we evaluated the IDT was in comparison to previous literature. Looking at activation associated with all choice trials grouped together, all three tasks were associated with a pattern of activation characteristic of intertemporal choice that includes activation of the visual cortex, bilateral DLPFC, PMA, SMA, bilateral superior and inferior parietal lobules and bilateral ventrolateral prefrontal cortex (Figure 5; also see McClure et al., 2004; 2007; Wesley & Bickel, 2014). Both the *response-focused* task and IDT were associated with activation of the medial prefrontal cortex and anterior cingulate during 'hard' choices (Table 3). Activation in the anterior cingulate is commonly associated with 'hard' trials, including in the original paper for our reference *response-focused* task (Amlung et al., 2014; Monterosso et al., 2007; Pine et al., 2009; McClure et al., 2007). The IDT was associated with a number of areas during immediate unavailable trials (Table 4). Others, including the original paper for our reference *stimulus-focused* task, have reported similar activations, albeit often with responding in general (i.e., not restricted to one trial type, see McClure et al., 2004; McClure et al., 2007; Xu et al., 2009; Eppinger et al., 2012; Sripada et al., 2011; Kim et al., 2012). See Supplementary Material for further discussion of ROI analyses.

4.3. Conclusions

The IDT was the only one of the three tested that was able to simultaneously 1) produce activation maps that did not differ from the other two tasks, 2) examine all three commonly discussed contrasts in all participants, and 3) resolve each participant's discounting rate in-scanner. For these reasons, we consider this task an improved method for studying the neural correlates of intertemporal choice behavior.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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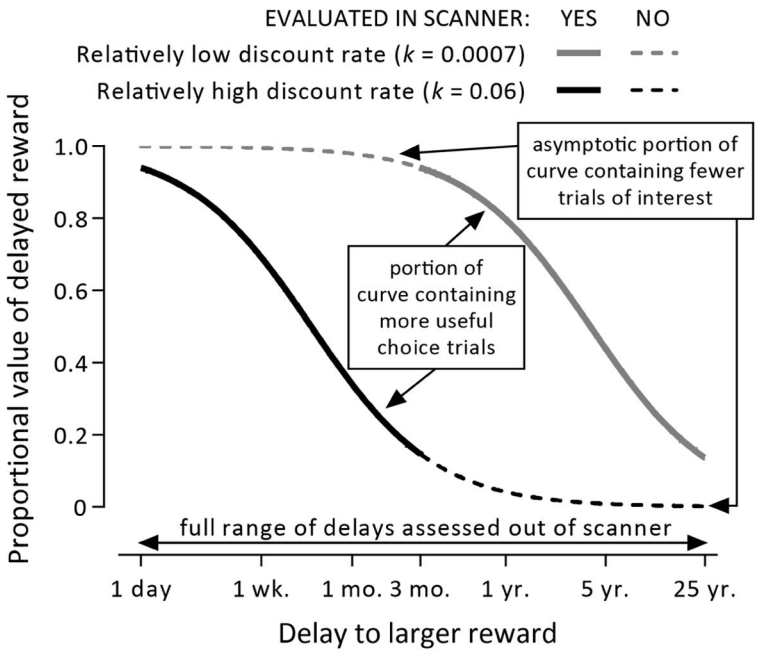

Figure 1.

Examples of two indifference curves representing discount rates that are within the range of typical values. The shape of the curve is similar across discount rates, but is shifted left or right depending on the specific rate. After an individual's discount rate is determined by evaluating the full range of delays in an out-of-scanner task, the Individualized Discounting Task only assesses the portion of the curve for each participant (solid lines) that is most relevant to resolving the discount rate without assessing the asymptotic portions of the curve that are less useful (dashed lines).

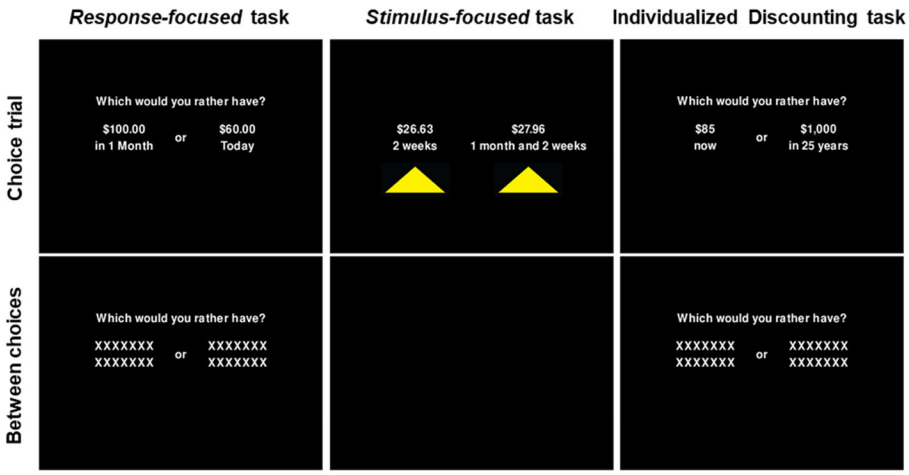

Figure 2.

Example images from each of the in-scanner tasks. Visual elements described by the source papers (Amlung et al., 2014; McClure et al., 2004) were included as to match as closely as possible, while other elements not described by the source papers (e.g., font) were kept similar across tasks. The *response-focused* task and IDT were very similar in appearance, while the *stimulus-focused* task had fewer on-screen instructions and yellow triangles under the response options. When a response was made, the yellow triangle under the selected option turned red briefly and the other disappeared. Between choice trials, the *stimulus-focused* task went to a blank screen, while the text elements in the *response-focused* task and IDT remained on the screen, but with amount and delay information temporarily replaced by a series of X's.

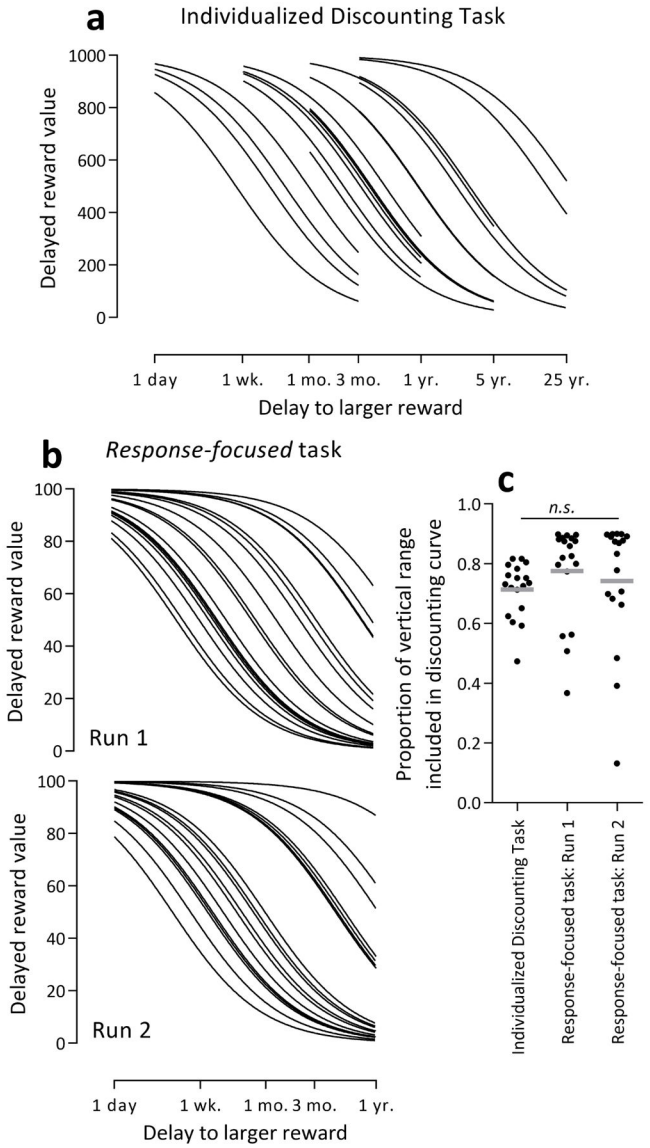

Figure 3.

The individualized delay series of the IDT captured the informative delays for each participant well (a) in fewer trials than the *response-focused* task (b). The vertical range of the discounting curves captured by these two tasks did not differ significantly (c).

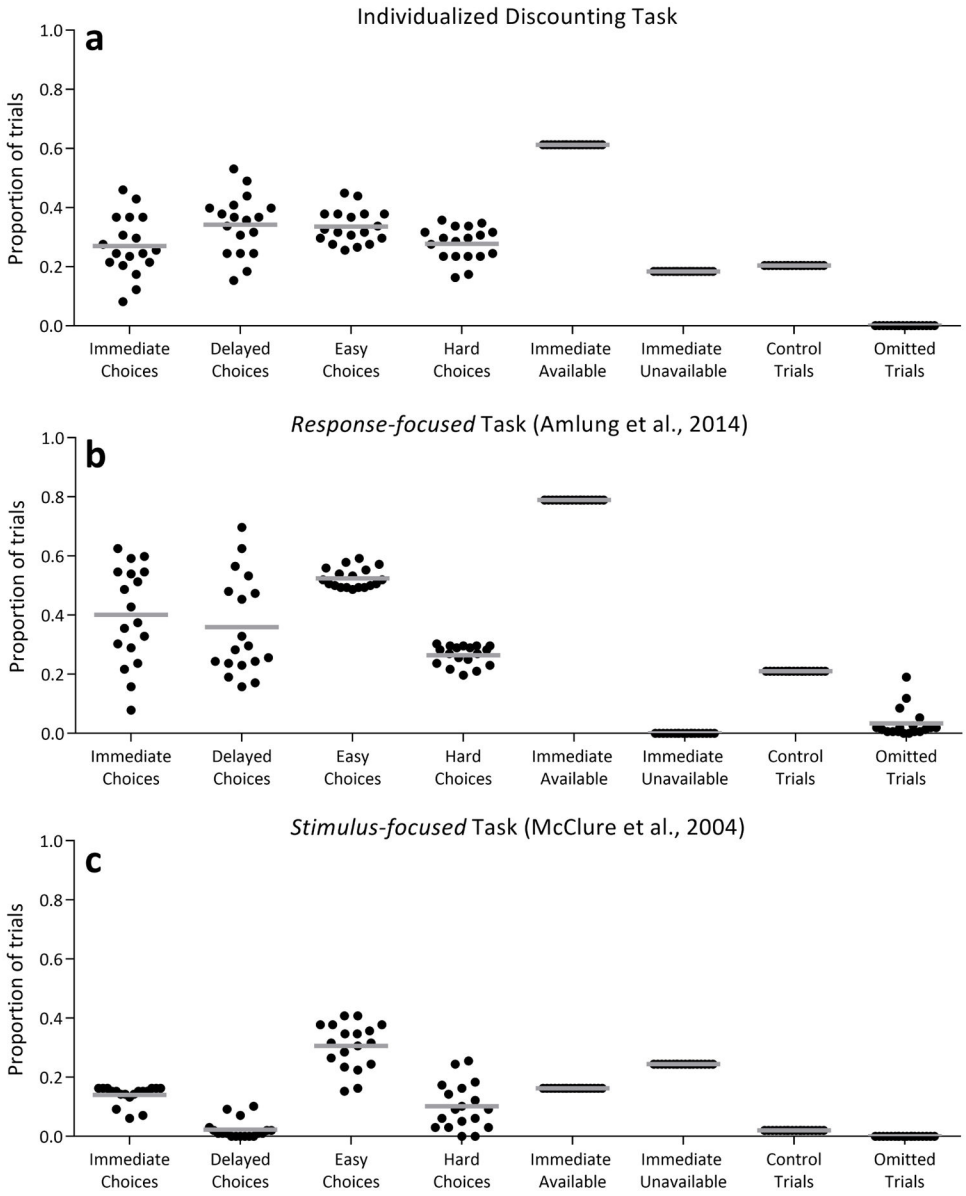

Figure 4.

The obtained distribution of trial types for the IDT task (a), *response-focused* task (b), and *stimulus-focused* task (c). The IDT was designed to equalize the number of immediate and delayed choices and the number of 'easy' and 'hard' choices while including immediate unavailable trials and control trials.

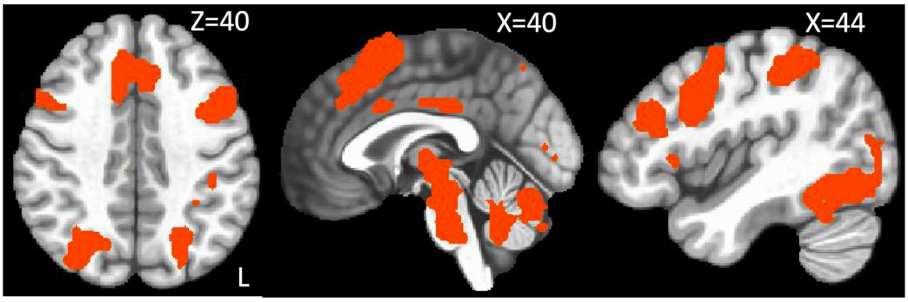

Figure 5.

Overlap of significant statistical maps for all trials independent of delay for all three in-scanner tasks. Regions in the overlap are preferentially activated compared to baseline during any choice trial (control trials regressed out). These areas include the visual cortex, bilateral dorsolateral prefrontal cortex (DLPFC), premotor area (PMA), supplementary motor area (SMA), bilateral superior and inferior parietal lobules and bilateral ventrolateral prefrontal cortex.

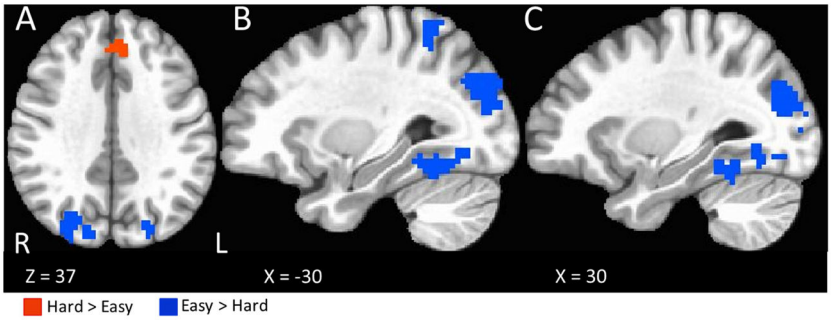

Figure 6.

Areas of activation overlap for the contrast of 'hard' choices minus 'easy' choices between the *response-focused* task and the IDT.

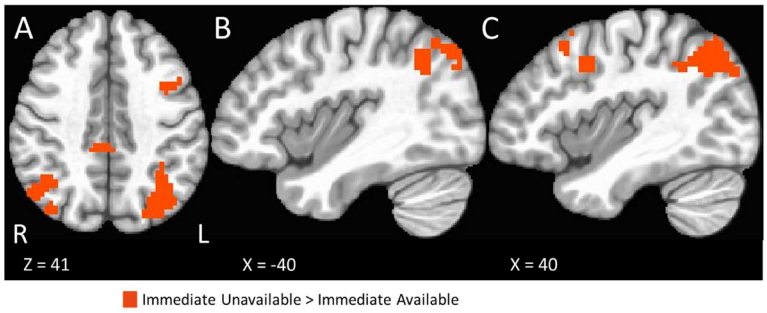

Figure 7.

Map of immediate unavailable versus immediate available trials for the IDT (FDR corrected at $p < .05$). Note, no significant regions were observed for the stimulus-focused task.

Table 1

Previous papers examining a monetary delay discounting task with an fMRI framework. Summarized here are two categories of tasks that either consist entirely of choices between an immediate option and a delayed option or tasks that are defined by trials in which an immediate option is available versus trials between two delayed options. For each analysis category, we have indicated whether the task allowed the authors to determine participants' discount rates in-scanner, whether the task included control trials, and whether authors reported on a significant result for each trial comparison category. For each column, we have identified if the task feature was possible and reported on (Yes), was not possible due to task limitations (No), may have been possible but was not reported on (?). Note that for many of the reports below, the goals and hypotheses of the paper did not align with the three categories of contrasts we have focused on here, and a failure to report a contrast does not necessarily mean that a particular contrast could not have been performed.

						Contrast type		
Citation	**Study *n***	**Mean age (range)**	**Total choice trials**	**Resolve discount rate**	**Control choices**	**Immediate vs. delayed choices**	**'Hard' vs. 'easy' choices**	**Immediate available vs. unavailable**
Response-focused tasks								
Amlung et al., 2014 †	25	22.5 (nr)	120	**Yes**	**Yes**	**Yes**	**Yes**	No
Ballard & Knutson, 2009	16	21.6 (nr)	84	**Yes**	**Yes**	**Yes**	?	No
Bickel et al., 2009	30	47.1 (20–67)	56	**Yes**	**Yes**	?	?	No
Boettiger et al., 2007	19	28.3 (nr)	37	**Yes**	No	**Yes**	?	No
Boettiger et al., 2009	19	28.3 (nr)	37	**Yes**	No	**Yes**	?	No
Carlisi et al., 2016	32	15.1 (11–17)	60	**Yes**	No	**Yes**	?	No
Chantiluke et al., 2014	64	14.6 (11–17)	60	**Yes**	No	?	?	No
Christakou et al., 2011	40	20.2 (12–32)	60	**Yes**	No	**Yes**	?	No
Clewett et al., 2014	72	33.2 (nr)	72	?	**Yes**	?	**Yes**	No
Elton et al., 2017	95	25.9 (18–40)	252	**Yes**	No	?	?	No
Ersner-Hershfield et al., 2009	18	nr (18–23)	137	**Yes**	**Yes**	**Yes**	?	No
Fassbender et al., 2014	14	26.1 (20–36)	62	**Yes**	No	?	?	No
Hare et al., 2014	27	24.1 (19–40)	216	**Yes**	No	**Yes**	?	No
Hinvest et al., 2011	34	23.8 (18–49)	56	**Yes**	**Yes**	No	**Yes**	No
Hoffman et al., 2008	36	35.7 (nr)	160	**Yes**	**Yes**	?	**Yes**	No
Hu et al., 2017	22	24 (19–28)	96	**Yes**	No	?	?	No
Kable & Glimcher, 2007	10	21.2 (nr)	144	**Yes**	No	**Yes**	?	No
King et al., 2016	62	15.9 (12–22)	90	**Yes**	No	?	**Yes**	No

Citation	Study *n*	Mean age (range)	Total choice trials	Resolve discount rate	Control choices	Contrast type		
						Immediate vs. delayed choices	'Hard' vs. 'easy' choices	Immediate available vs. unavailable
Kishinevsky et al., 2012	19	33.4 (19–50)	160	**Yes**	**Yes**	**Yes**	**Yes**	No
Li et al., 2013	23	22.8 (20–25)	168	**Yes**	**Yes**	?	**Yes**	No
Liu et al., 2012	19	21.7 (19–25)	200	**Yes**	**Yes**	?	?	No
Luhmann et al., 2009	20	23.4 (19–30)	58	?	No	**Yes**	?	No
Luo et al., 2011	21	29.8 (22–44)	38	**Yes**	**Yes**	**Yes**	?	No
MacKillop et al., 2012	13	40.2 (nr)	54	**Yes**	**Yes**	**Yes**	?	No
Manning et al., 2014	37	24.9 (20–32)	108	**Yes**	No	?	?	No
Marco-Pallares et al., 2010	17	28 (nr)	27	**Yes**	No	**Yes**	**Yes**	No
Martin et al., 2015	21	43 (18–65)	120	?	No	**Yes**	?	No
Mavrogiorgou et al., 2016	20	31.3 (nr)	140	**Yes**	**Yes**	**Yes**	?	No
Meade et al., 2011	39	48.1 (18–59)	36	**Yes**	**Yes**	?	**Yes**	No
Meade et al., 2016	35	41 (18–55)	120	**Yes**	**Yes**	?	**Yes**	?
Miedl et al., 2012	32	nr (21–50)	48	**Yes**	No	?	?	No
Miedl et al., 2015	30	36.5 (27–47)	108	**Yes**	No	**Yes**	**Yes**	No
Monterosso et al., 2007	29	32 (nr)	27	**Yes**	No	?	**Yes**	No
Onoda et al., 2011	30	21.7 (nr)	100	No	No	No	No	No
Ortiz et al., 2015	21	nr (19–45)	49	**Yes**	No	?	?	No
Peters & Buchel, 2009	22	26.3 (nr)	48	**Yes**	No	?	?	No
Peters & Buchel, 2010	30	25.4 (nr)	48	**Yes**	No	?	?	No
Pine et al., 2009	24	nr (19–28)	200	**Yes**	**Yes**	No	**Yes**	No
Pine et al., 2010	14	21 (18–30)	200	**Yes**	**Yes**	No	**Yes**	No
Ripke et al., 2012	263	15.7 (13–50)	90	**Yes**	No	?	?	No
Ripke et al., 2014	206	nr (13–15)	90	**Yes**	No	?	?	No
Ripke et al., 2015	206	nr (13–15)	90	**Yes**	No	?	?	No
Rodriguez et al., 2015	23	24.5 (19–46)	240	**Yes**	No	?	?	No
Sasse et al., 2015	23	25.0 (21–30)	72	**Yes**	No	?	?	No
Schmaal et al., 2014	32	42.3 (nr)	48	**Yes**	No	**Yes**	?	No

Citation	Study *n*	Mean age (range)	Total choice trials	Resolve discount rate	Control choices	Contrast type		
						Immediate vs. delayed choices	'Hard' vs. 'easy' choices	Immediate available vs. unavailable
Schneider et al., 2014	48	14.3 (13–15)	84	**Yes**	No	?	?	No
Sohn et al., 2015	20	24.0 (20–29)	60	**Yes**	No	?	?	No
Stanger et al., 2013	30	15.7 (12–18)	100	**Yes**	**Yes**	**Yes**	?	No
Steinbeis et al., 2014	20	9.7 (6–12)	48	**Yes**	No	?	?	No
Stoeckel et al., 2012	24	nr (19–50)	160	**Yes**	**Yes**	?	**Yes**	No
Taylor et al., 2016	129	nr (31–53)	27	**Yes**	No	?	?	No
Vanyukov et al., 2016	48	nr (46–90)	48	**Yes**	No	**Yes**	?	No
Wang et al., 2014	28	22.1 (nr)	256	No	No	**Yes**	No	No
Wang et al., 2016a	63	21.5 (nr)	72	**Yes**	No	?	?	No
Wang et al., 2016b	39	22.6 (nr)	72	**Yes**	No	?	?	No
Weber & Huettel, 2008	23	23 (19–36)	30	?	No	?	?	No
Wittmann et al., 2007	13	26 (nr)	48	**Yes**	No	**Yes**	?	No
Wittmann et al., 2010	13	30.2 (nr)	25	**Yes**	**Yes**	**Yes**	?	No
Yu et al., 2015	80	26 (nr)	120	No	**Yes**	?	?	No
Stimulus-focused tasks								
Albrecht et al., 2010	28	nr (nr)	42	**Yes**	No	?	?	**Yes**
Aranovich et al., 2016	19	33.6 (nr)	128	**Yes**	No	?	?	?
Bos et al., 2014	22	20.4 (nr)	70	**Yes**	No	?	?	?
Decker et al., 2015	93	24.8 (nr)	144	**Yes**	No	**Yes**	?	**Yes**
Eppinger et al., 2012	30	45.3 (18–80)	42	?	No	?	?	**Yes**
Kable & Glimcher, 2010	25	22.2 (nr)	200	**Yes**	No	?	?	**Yes**
Kim et al., 2012	33	21.5 (nr)	42	?	No	?	?	**Yes**
Kobiella et al., 2013	66	41.3 (30–60)	40	**Yes**	No	a	?	**Yes**
Luo et al., 2012	15	nr (nr)	51	?	No	?	?	?
McClure et al., 2004 †	14	21.4 (nr)	42	?	No	?	**Yes**	**Yes**
McClure et al., 2007	34	nr (nr)	42	?	No	?	**Yes**	**Yes**
Samamez-Larkin et a., 2011	25	48.7 (19–85)	42	**Yes**	No	?	?	**Yes**

Citation	Study *n*	Mean age (range)	Total choice trials	Resolve discount rate	Control choices	Contrast type		
						Immediate vs. delayed choices	'Hard' vs. 'easy' choices	Immediate available vs. unavailable
Sellitto et al., 2016	89	nr (nr)	70	**Yes**	**Yes**	?	?	**Yes**
Sripada et al., 2011	20	28.7 (nr)	42	?	No	?	**Yes**	**Yes**
Xu et al., 2009	18	25 (22–29)	42	?	No	?	**Yes**	**Yes**
Our *Individualized Discounting Task*	18	33.7 (23–50)	98	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

[†]Chosen as a comparison task to the IDT.

[a]A contrast was reported between smaller sooner trails and larger later trials, with smaller sooner included both immediate options and less delayed options. Study sample sizes represent those reported after any exclusion criteria were applied.

nr = not reported.

Table 2

Correlation matrix of discounting rates as measured by the out-of-scanner adjusting amount task, the IDT, the two runs of the *response-focused* task, and the *stimulus-focused* task. Correlations are Pearson *r* values among the log(*k*) values determined by least-squares fits of Mazur's (1987) hyperbola to indifference points at each delay combination. All correlations significant at $p < .003$.

Task	2.	3.	4.	5.
1. Out of scanner	.88	.87	.85	.66
2. IDT		.88	.90	.75
3. *Response-focused* run 1			.95	.75
4. *Response-focused* run 2				.76
5. *Stimulus-focused*				

Table 3

Areas of activation overlap for the contrast of hard choices versus easy choices between the *response-focused* task and the IDT. Foci are in MNI coordinates and reflect the peak *t*-value for voxels with $p < 0.05$ after FDR correction. Only clusters with at least 20 voxels were considered.

	IDT task results						
Region	**voxels**	**BA**	**x**	**y**	**z**	***t* value**	***t* value of same *response-focused* task area**
Hard > Easy							
Bilateral Medial Prefrontal, L Anterior Cingulate	46	9	−4	36	32	3.36	3.01
Easy > Hard							
R Lingual, Fusiform, & Parahippocampal	654	18	28	−46	−16	−5.09	−4.75
L Middle Occipital	305	19	−32	−84	18	−5.90	−5.46
L Lingual, Parahippocampal	274	19	−30	−64	−8	−3.97	−4.89
R Superior and Inferior Parietal Lobes	58	7/40	28	−52	60	−4.63	−6.40
L Inferior Occipital	21	18	−34	−78	−10	−5.87	−3.65

Table 4

Areas of greater activation during immediate unavailable trials than immediate available trials for the IDT. No significant areas of activation were observed in the *stimulus-focused* task. Foci are in MNI coordinates and reflect the peak *t*-value for voxels with $p < 0.05$ after FDR correction. Only clusters with at least 20 voxels were considered.

	IDT task results					
Region	**voxels**	**BA**	**x**	**y**	**z**	***t* value**
L Superior Parietal Lobule	310	7	−34	−78	50	4.36
R Superior Parietal Lobule	187	7	36	−76	50	4.87
L Middle Frontal	88	47	−52	42	−6	5.01
L Middle Frontal	41	6	−48	12	50	4.02
L Lingual	37	17	−10	−98	−10	4.46
L Middle Frontal	30	8	−40	20	50	4.02
L Cerebellum (Declive)	29	45	−10	−84	−28	5.78
Bilateral Paracentral Lobule/Cingulate	24	31	2	−34	38	4.27
R Lentiform Nucleus	20	47	14	8	2	4.13