Advanced Review

The neural correlates of temporal reward discounting

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Temporal reward discounting (TD) refers to the decrease in subjective value of a reward when the delay to that reward increases. In recent years, a growing number of studies on the neural correlates of temporal reward discounting have been conducted. This article focuses on functional magnetic resonance imaging (fMRI) studies on TD in humans. First, we describe the different types of tasks (also from behavioral studies) and the dependent variables. Subsequently, we discuss the evidence for three neurobiological models of TD: the dual-systems model, the single-system model and the self-control model. Further, studies in which nontraditional tasks (e.g., with nonmonetary rewards) were used to study TD are reviewed. Finally, we discuss the neural correlates of individual differences in discounting, and its development across the lifespan. We conclude that the evidence for each of the three neurobiological models of TD is mixed, in that all models receive (partial) support, and several studies provide support for multiple models. Because of large differences between studies in task design and analytical approach, it is difficult to draw a firm conclusion regarding which model provides the best explanation of the neural correlates of temporal discounting. We propose that some components of these models can complement each other, and future studies should test the predictions offered by different models against each other. Several future research directions are suggested, including studying the connectivity between brain regions in relation to discounting, and directly comparing the neural mechanisms involved in discounting of monetary and primary rewards.

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INTRODUCTION

Many choices that we face in life require us to trade off anticipated benefits and costs of two options at different points in time. Should I spend all my money now, or should I save for the future? Should I watch this movie, or go to the gym? Should I study for my exam two weeks in advance, or should I wait until I have only one day left? Should I eat a cheeseburger for lunch, or a salad? While eating the cheeseburger might be more rewarding in the short run, healthy food choices have greater long-term benefits. Yet, often people prefer the immediately rewarding option over the option that is more rewarding in the long run. How trade-offs are made in these intertemporal choices has been studied by animal researchers,[1–8] (behavioral) economists,[9–13] psychologists and psychiatrists,[14–17] and, more recently, cognitive neuroscientists.[10,18] We may view these choices from the perspective of temporal discounting (TD), which assumes that the subjective value of a reward decreases as the delay to its receipt increases[19–22] (see also Ref 23; but see Ref 24). Thus, in experimental lab settings, TD tasks are often used to measure these preferences.[16] A typical TD task involves choices between a monetary reward that will be delivered immediately (e.g., $50 today) and a larger monetary reward that will be delivered after a delay (e.g., $100 in 1 month). TD tasks are often viewed as measures of impulsive choice, in that enhanced preferences for immediate rewards may indicate greater impulsivity[17,22,25–30] (see also Ref 31).

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Even though TD varies within participants across contexts and is domain-dependent (e.g., Refs 32, 33), emerging evidence suggests that it has features like a personality trait.[34]

TD tasks have increasingly been used in psychology and neuroscience, possibly because of their high relevance to psychiatric disorders characterized by atypical impulse control, such as substance abuse (see Refs 15, 35–38 for reviews), attention-deficit/hyperactivity disorder (ADHD) (e.g., Refs 39, 40), pathological gambling,[38,41] obesity,[42,43] and anorexia nervosa.[44] In recent years, a growing number of researchers have used functional magnetic resonance imaging (fMRI) to investigate the neural correlates of TD in healthy individuals.[18,45] In this article, we will provide a critical review of these fMRI studies on TD. This review will be limited to studies with human participants, primarily conducted by researchers from the fields of psychology and cognitive neuroscience (see Ref 46 for a review of studies from the field of neuroeconomics). Additionally, this article focuses only on studies in which TD tasks were administered, and in which both the delay preceding the large reward and the magnitude of either the immediate or delayed rewards were systematically varied. Studies in which comparable tasks were used that did not meet these criteria were not included in this review (e.g., Ref 47–49). First, we will review different types of TD tasks (also from behavioral studies) and the dependent variables of these tasks. Subsequently, we will discuss the findings of studies in which the neural mechanisms underlying the discounting of monetary rewards were examined. Three different neurobiological models have been proposed to account for the neural correlates of TD. We will describe these models and report evidence that either supports or argues against each of these models. In addition, we will focus on the neural correlates of discounting as measured with nontraditional tasks, and on neural mechanisms associated with individual differences in TD and its development across the lifespan. Finally, we will suggest future directions for fMRI research on TD.

MEASURING TEMPORAL REWARD DISCOUNTING

In the majority of TD measures, participants are asked to choose between a small reward that is available immediately and a large reward that will be delivered after some delay period. On the basis of participants' preferences in a series of choices between large rewards that are fixed in amount but vary in delay after which they will be delivered and immediate rewards that vary in magnitude but are smaller than the delayed amount, the subjective value of the large reward is determined for each delay duration.[17,20,50] See for an example Table 1. These values are usually plotted in a graph demonstrating that the subjective value of a reward decreases the longer one has to wait for it. The more the value of the large reward is discounted as a function of time, the steeper the discounting function is (see Figure 1). Steep discounting functions are typically interpreted as a sign of impulsivity[17,22,25–30] (see also Ref 31).

Types of Tasks

Hypothetical TD tasks with monetary rewards are most commonly used in studies with humans[51–103] (see Ref 16 for a review). In these tasks, participants make a series of choices between fictional amounts of money, one smaller amount being available immediately and a larger amount available after some specified delay interval. Importantly, participants do

TABLE 1 | Representative Trials and Hypothetical Data of a Temporal Discounting Task with a Fixed Delayed Reward of $10,000

	Delay to Large Reward ($10,000) in Years					
Amount of Immediate Reward in Dollars	0	1	2	5	10	20
100	D	D	D	D	D	D
200	D	D	D	D	D	D
500	D	D	D	D	D	I
1000	D	D	D	D	I	I
2000	D	D	D	I	I	I
5000	D	D	I	I	I	I
10,000	D	I	I	I	I	I
Subjective value of delayed reward	10,000	7500	3500	1500	750	350

Preferences for the delayed reward are indicated with a 'D' and preferences for the immediate reward with an 'I'. For each delay, the subjective value of the delayed reward is located where the choice preference switches from delayed to immediate.

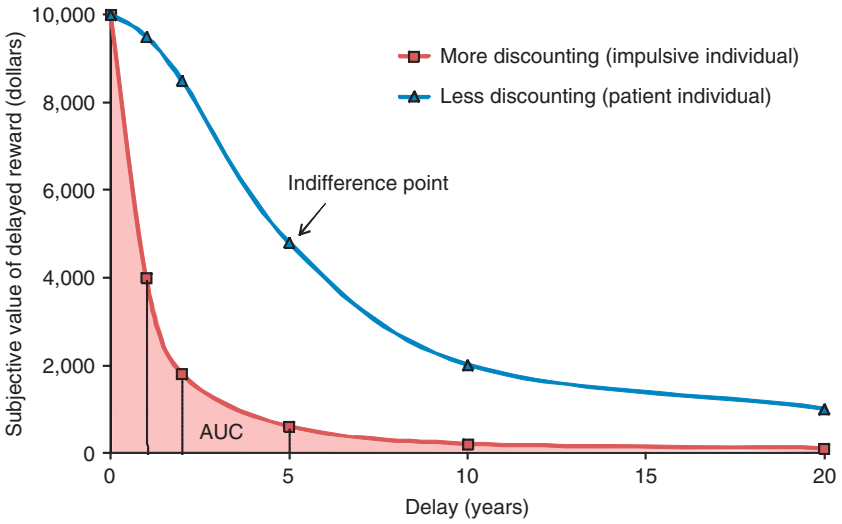


FIGURE 1 | Hypothetical data of a temporal discounting task showing the subjective value of a fixed delayed reward (in this example $10,000) as a function of its delay to receipt, and showing the area under the curve (AUC, shaded area) for the steep discounting curve.

not endure delays and rewards are not paid. In a typical hypothetical TD task,[73] the magnitude of the immediate reward may range between $1 and $1000 in steps of $50, while the delayed reward may be a fixed amount of $1000 available after a delay ranging from 1 week to 25 years. An example of a choice is between $500 today and $1000 after 1 year. Although the money amounts and delay intervals used seem appropriate for human adults, one important limitation of hypothetical tasks is the questionable ecological validity. Presenting a typical hypothetical task as a real task, however, is not feasible, because the money amounts are generally too large to be paid to the participants.

Therefore, some researchers have opted to use *potentially real tasks*, such as Kirby's Monetary Choice Questionnaire.[104] In potentially real tasks, participants are told that one of their choices will be randomly selected and they will be paid according to this one choice.[9,18,29,44,80,86,105–127] The assumption on which this task design relies is that participants will make all of their choices as though they are real, because they do not know which choice will be selected.

Finally, in *real tasks*, also referred to as *experiential tasks*,[128] participants experience the consequences of their choices during the experiment: they endure the waiting times and receive the rewards (money amounts displayed on the screen, or coins delivered to the participant). This is a clear advantage in terms of the ecological validity. In real tasks, reward magnitudes are necessarily smaller (typically up to $1) and delay durations shorter (typically up to 60 seconds) than in hypothetical or potentially real tasks.[40,128–133] Some of these tasks[130,131,133] have proven to be useful in research examining individual differences in children and adolescents.

These hypothetical, potentially real, and real tasks vary greatly in terms of parameter settings. Therefore, one may wonder whether these tasks measure the same construct,[120,134,135] and whether the same neural circuitries are involved. Hypothetical and potentially real TD tasks yielded similar TD functions,[80,113,119,120,136] and recruited similar brain regions.[137] Note, however, that we should be cautious to conclude that any meaningful differences between these two types of discounting are absent based on the lack of statistically significant differences between the hyperbolic discount curves of hypothetical and potentially real tasks (see Ref 138 for an interesting discussion). Hypothetical and real tasks had comparable degrees of discounting,[113,120,133,139] as long as reward magnitudes and delays were equal.[114,133,134] Thus, although temporal discounting of small amounts delivered after short delays does not seem to overlap with temporal discounting of large amounts delivered after long delays (which are typically used in hypothetical tasks), task format per se (hypothetical, potentially real, real) may not lead to great differences in discount curves. However, before drawing definite conclusions, more future research is needed in which the overlap and differences between task format within the same sample are studied, including the computation of correlations between discounting rates obtained in different tasks.

TD tasks vary on other factors as well, including: (1) *Types of rewards*. Some studies have used primary rewards such as food, juice, and drugs (hypothetical or real). Hypothetical food and drug rewards are discounted more steeply than hypothetical money.[58,63,71,84,91,140–152] In terms of real primary

rewards, liquids[153–156] and erotic pictures[157,158] have been used. The use of primary rewards in real tasks has the advantage that the reward can be consumed at the end of every trial, unlike money, which cannot be consumed until the end of the task.[159,160] (2) The *number of different choices*. Some researchers have used tasks in which the magnitude of the immediate reward and the delay to the large reward are kept constant across trials.[142,161–168] Although the proportion preference for immediate/delayed reward can be computed, the trade-off between reward magnitude and delay duration, as expressed in discounting functions, cannot be measured with these tasks. (3) *Discrete versus continuous choices*. In traditional TD tasks, discrete choices are offered in which the magnitude of the immediate reward and the delay to the large reward is fixed *within* trials. However, in a recently developed task,[169] participants were presented with trials in which the reward/delay ratio rapidly diminished. At any moment during this diminishing ratio, participants could decide whether to quit or continue with the trial. Thus, this task is a more continuous measurement of delay tolerance, offering as a main advantage that ceiling/floor effects can be avoided. (4) *Probability of reward delivery*. In real life, rewards that we receive after a waiting time may be relatively uncertain. In line with this, Reynolds and colleagues[128,170] found that adolescents rated delayed reward as less certain than immediate rewards, and ratings of uncertainty correlated with degree of discounting. Thus, the use of delayed rewards that are probabilistic may add to the ecological validity of TD tasks.[48,130,171] This may be implemented optimally in a real task with relatively short waiting times, so that participants can experience the reliability of the delivery of the reward. (5) *The use of delays to the 'immediate' reward*. In hypothetical TD tasks, researchers sometimes add an equal delay to both choice options, in order to measure preference reversals. Specifically, in addition to asking participants whether they prefer $100 today or $1000 after 12 months (NOW TRIALS), participants may also be asked whether they prefer $100 after 1 month or $1000 after 13 months (FUTURE TRIALS). Preference reversals refer to observations that individuals may resist the sooner reward when it is not available immediately, but choose it when it is available right away. This observation has been made in several studies[40,73,114,135,172–174] and suggests that people's choices deviate from what would be predicted by economic theory.[175]

Dependent Variables

A first step in describing intertemporal choice is to determine the *subjective value* (SV) of the delayed reward. This value reflects the indifference point for each delay, that is, the choice at which a person has no clear preference for either the delayed reward or the immediate reward. In order to quickly determine an individual's indifference point, adjusting procedures are often employed. The *adjusting-amount procedure*[4,29,128,171] uses an online algorithm based on previous choices. If an individual chooses the delayed reward, the amount of the immediate reward is increased on the next trial and vice versa, until the smallest immediate amount chosen over the larger delayed amount is determined. Similarly, the *adjusting-delay procedure*[125,176] results in increases and decreases of the delay to reward, until the indifference point is reached. Although both methods yielded similar TD functions, the adjusting amount procedure resulted in the most consistent estimates of degree of discounting.[177]

When researchers administer a fixed set of trials instead of an adjusting procedure, subjective value can be determined by predetermined rules.[20,131] Alternatively, it may be determined by fitting a logistic function to the proportion of preferences for the immediate reward, and subsequently determine the monetary amount at which the probability of choosing the immediate reward is 0.5.[178,179]

When the indifference points (on the y-axis) are plotted for all delays (on the x-axis), the indifference points are connected with one another, resulting in a discounting curve for each individual. This curve (see Figure 1) can be characterized by different equations: the three most commonly used models are exponential,[175] hyperbolic,[8,180] and quasihyperbolic (β–δ)[13] (see Box 1), but also see Ref 138.

Dependent variables include k, which governs the degree of discounting (decrease in subjective value; see Box 1), and area under the discounting curve (AUC[181]; Figure 1). While higher values of k indicate relatively steep discounting, larger values of AUC indicate relatively shallow discounting. The main advantage of using AUC is that it is model-free: k represents the slope of the discounting curve as estimated with an equation, while AUC is a measure that directly reflects the raw data.[181]

BOX 1

EXPONENTIAL, HYPERBOLIC, AND QUASIHYPERBOLIC EQUATIONS

Exponential Equation[175]

$$SV = Ae^{-kD},$$

where A is the amount of the future reward, D the delay to its delivery, and k a subject-specific constant that governs the degree of decrease in value, that is, the discount rate.[182,183]

The exponential equation assumes that a constant change in the delay is associated with the same proportional change in subjective value. Thus, the subjective value of delayed rewards decreases at a constant rate (exponentially) as a function of time.

Quasihyperbolic Equation[13]

$$SV_t = u(c_t) + \beta \sum_{t=1}^{\infty} \delta^t u(c_{t+\tau}),$$

where u is the utility function, c is a consumption, and discount parameters β and δ are between 0 and 1. The discount factor is δ^t for $t = 0$, and $\beta\delta^t$ for $t > 0$, resulting in a specific weight given to the immediate reward, capturing the present bias.

Hyperbolic Equation[8,180]

$$SV = A/(1 + kD),$$

where A is the amount of the future reward, D the delay to its delivery, and k a subject-specific constant that governs the degree of decrease in value.[182,183]

Hyperbolic and quasihyperbolic discount functions are characterized by relatively steep discounting for short-time periods, and by relatively shallow discounting for long-time periods. Thus, as opposed to the exponential equation, both hyperbolic and quasihyperbolic equations can account for preference reversals. Hyperbolic functions have been reported to best fit empirical data.[182,183]

THE NEURAL BASIS OF TEMPORAL REWARD DISCOUNTING: FMRI RESEARCH

Findings Based on Monetary Tasks

Support for the Dual-System Account

McClure et al.[121] studied the neural basis of preference reversals. In accordance with other dual-systems accounts (e.g., Refs 184–186), they hypothesized that the inconsistency between short-term and long-term preferences is associated with differential activation of separate and distinguishable neural circuitries. Specifically, they hypothesized that limbic areas such as ventral striatum (VS), ventromedial prefrontal cortex (VMPFC), and posterior cingulate cortex (PCC) mediate the special weight placed on immediate outcomes (β), while lateral prefrontal cortex (LPFC) and associated brain structures mediate a more consistent weighting of delays (δ) (see Box 2, Figures 2 and 3). To this end, they used a potentially real TD task with amounts ranging from $5 to $40, and delays ranging from the day of the experiment to 6 weeks later. They included NOW trials and FUTURE trials. The only way in which these trials differed was the presence/absence of an *immediate* reward.

The findings supported their hypotheses (see Box 2) in that (a) deciding during NOW trials as compared to FUTURE trials activated limbic regions (β), i.e., VS, PCC, and medial prefrontal cortex (MPFC). (b) deciding during all choice pairs (NOW and FUTURE) compared with rest activated a δ cluster of regions including intraparietal cortex and dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), and lateral orbitofrontal cortex (LOFC); (c) δ areas were more active than β areas when participants chose the delayed option as compared to the immediate option (see Figure 2). When participants decided not to wait, on the other hand, there was no significant imbalance in activation between δ and β activation (though a trend toward greater β activity was reported). Importantly, these findings remained after controlling for subjective value. The authors interpreted these findings as evidence for competition between two brain systems underlying impulsivity on the one hand and cognitive control on the other.

There is an ongoing discussion as to whether these, and more recent findings, indeed support a dual systems account of TD.[10,18,45,179,188] Here, we will review recent findings that shed more light on this question (see Table 2). First, in support of McClure et al.,[121] several studies have reported activation in limbic areas during NOW trials versus FUTURE trials, including in VS,[156,194,198,199] MPFC,[156,179,194,195,198] and PCC.[156,179,194,195] One study, however, did not find differences in brain activation between NOW and FUTURE trials.[196] Of note is that the overall supporting evidence was observed despite methodological differences in delay durations and reward magnitudes, nature of the reward (money, juice), trial phase used in analysis (viewing vs deciding), age range, and individual levels of impulsivity. Second, support for the initially found activation in δ areas in response to all trials as compared to rest appears to be more mixed. Although one study[195] reported increased DLPFC and superior

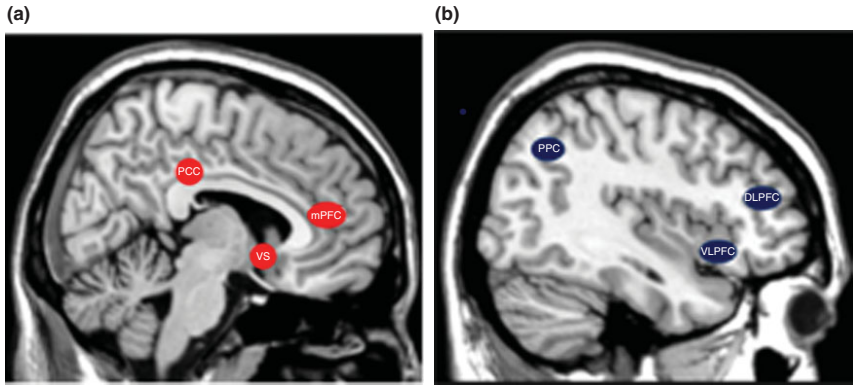
BOX 2

NEURAL ACCOUNTS OF TEMPORAL REWARD DISCOUNTING

In the last decade, there has been a debate about the neural system or systems underlying temporal discounting. In a landmark study, McClure et al.[121,156] proposed that impulsive preference reversals, that is, being more likely to choose the earlier reward when an immediate reward is present than when both rewards are delayed, reflects the differential activation of two distinguishable neural systems: the limbic 'β' system, including VS, MPFC, and PCC, which is primarily sensitive to the value of immediate rewards and less sensitive to the value of future rewards, and the more cognitive 'δ' system, including the LPFC, which is responsive to all types of rewards, whether immediate or delayed, and therefore favors greater rewards even when they are delayed. This led to three specific predictions: (1) NOW trials will preferentially recruit limbic areas as compared to FUTURE trials; (2) NOW and FUTURE trials will trigger activation in δ areas (specifically LPFC) to a similar extent; (3) relatively high levels of LPFC activation are associated with choosing the delayed reward. Recently, this *dual-system account* was challenged by the findings by Kable and Glimcher,[179,188] who proposed that activity in the VS, MPFC, and PCC tracks the *subjective value* of possible rewards during choice, that is, these brain regions are involved in the valuation of all potential rewards, whether immediate or delayed. Further research in which delays were added to both immediate and delayed rewards, led Kable and Glimcher to refine their *single-system account* into an 'as soon as possible' (ASAP) account, which states that subjective value declines hyperbolically relative to the *soonest* possible reward, rather than to the present. Importantly, the ASAP account does not predict preference reversals. A third account was proposed by Figner et al.[212] Unlike the single- and dual-system accounts, their *self-control account* suggests that rather than choice following directly from a valuation process of immediate versus delayed rewards, there is an intervening self-control process, subserved by the LPFC (see also Ref 213). Successful self-control can override a prepotent tendency to choose a smaller immediate reward with higher subjective value. The self-control account, therefore, implicates that there can be a discrepancy between preference expressed by valuation judgments and actual choice. See section *Competing or Complementary Accounts?* of the main text for suggestions as to how model-specific predictions may be tested, and to what extent models may be integrated.

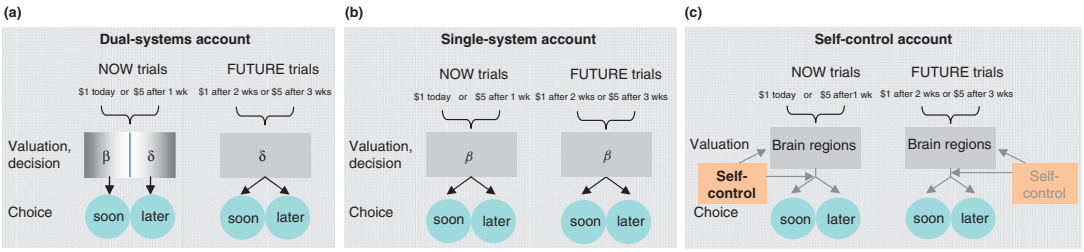
parietal activation during FUTURE trials compared to NOW trials, three other studies reported activation in δ *and* β regions associated with FUTURE trials,[196] or all trials.[137,190] While three studies[121,195,196] used NOW and FUTURE trials, two studies used NOW trials only.[137,190] The absence of FUTURE trials in these studies may (partly) explain the activation in β areas. Third, when examining differences in activation between δ and β regions when participants chose the delayed option as compared to the immediate one, mixed findings have been reported. One study[196] found that DLPFC activation predicted preferences for delayed rewards, but another study[179] did not find any areas in which activity was greater during preferences for delayed versus immediate rewards. Other studies reported activation associated with the preference for delayed rewards, but not necessarily in δ areas, and even in β areas.[195,197] Finally, when participants chose the immediate reward as opposed to the delayed reward, one study reported increased activation in VS.[197] This finding is supported by findings of an fMRI study[200] which showed that VS activation as measured during reward processing correlated positively with k during a TD task administered outside the scanner. Two other studies failed to identify such β activation.[196,192] While McClure et al.[121] looked at the interaction between brain areas (δ, β) and choice (immediate, delayed) and found that the difference in activation between δ and β areas was what predicted choice preferences, later studies have only looked at main effects of choice. This makes it difficult to directly compare the findings across studies.

In sum, the majority of support for the notion that there are two separate brain systems that compete while engaging in TD tasks with short-term and long-term choices comes from the reported activation in limbic (β) areas during the viewing of NOW trials versus FUTURE trials. However, less evidence supporting increased activation in δ areas while viewing all choices, or when choosing the delayed reward, is available. Importantly, differences in task designs and specific statistical analyses/contrasts make it hard to draw firm conclusions.



A. β-areas[116], or areas involved in valuation of immediate rewards. Note that according to Kable & Glimcher[174,181], these areas track the subjective value of all rewards.
B. δ-areas[116], or areas involved in valuation of both immediate and delayed rewards[174,181]. The DLPFC is a brain region involved in self-control, and plays a pivotal role in the self-control model of temporal discounting[204].
Note. DLPFC = dorsolateral prefrontal cortex, MPFC = medial prefrontal cortex, PCC = posterior cingulate cortex, PPC = posterior parietal cortex, VLPFC = ventrolateral prefrontal cortex, VS = ventral striatum

FIGURE 2 | Brain regions involved in temporal discounting of (monetary) rewards. (a) β-areas,[116] or areas involved in valuation of immediate rewards. Note that according to Kable and Glimcher,[174,181] these areas track the subjective value of all rewards. (b) δ-areas,[116] or areas involved in valuation of both immediate and delayed rewards.[174,181] The DLPFC is a brain region involved in self-control, and plays a pivotal role in the self-control model of temporal discounting.[187]



Ad A: Note that is not displayed for FUTURE trials. Although technically, this system is involved during FUTURE trials, its effect is negligible because it discounts very steeply. Ad C: Note that the influence of LPFC-driven self-control is considered to be especially important during NOW trials, since NOW trials tempt people more than FUTURE trials to choose the soon option.

FIGURE 3 | Visualization of the dual-systems account, the single-system account, and the self-control account. (a) Note that β is not displayed for FUTURE trials. Although technically, this system is involved during FUTURE trials, its effect is negligible because it discounts very steeply.

Support for the Single-System Account

Kable and Glimcher[188] examined whether there are brain regions for which the rate of neural activity is linearly related to the *subjective value* of delayed rewards. For this purpose they designed a potentially real TD task in which participants chose between a fixed immediate reward of $20 and a larger delayed reward that varied from $20.25 to $110, with delays of 6 h up to 180 days. For each trial, they estimated the subjective value of the delayed reward by multiplying the absolute amount of the delayed reward by the discount fraction for that delay, and subsequently used this subjective value as a regressor in their fMRI analysis. They found correlations between *subjective value* and activity in the VS, MPFC, and PCC. Importantly, activity in these regions was better accounted for by subjective value than by either (1) the objective reward amount, (2) the delay to reward, or (3) choice. By showing variation in activity in these 'β' regions when the immediate reward was fixed and only the amount of the delayed reward changed, they argued against the dual-systems account (see Box 2, Figure 3). Specifically, the VS, MPFC, and PCC did not exclusively track the value of *immediate* reward, but rather the combination of immediate versus delayed rewards. In a second study, the authors again found that the VS, MPFC, and PCC encoded subjective value, even when the fixed immediate reward was also delayed.[179] Peters and Büchel[193] also used a fixed immediate reward and replicated the Kable and Glimcher[188] findings.

It should be noted that these studies included individuals who underwent behavioral pretests and were found to have stable discount functions. Individuals with less stable discount functions might show different neural responses.[191] Additionally, these participants' responses appear to be unusual: without preference reversals, and perhaps without exerting

TABLE 2 | Overview of fMRI Studies on Temporal Discounting Providing Evidence for Dual-Systems, Single-System, or Self-Control Account

	Participants		Task					
Study	*N* (female)	Age (years)	Type	Trials (*n*)	Rewards	Delays	Focus of Analysis	Support for Account
Ballard and Knutson[178]	16 (8)	$M = 21.6$	PR	NOW (84)	FIR, VDR	0–6 m	Viewing options	DS/SS/SC
Kable and Glimcher[188]	10 (6)	$M = 21.2$	PR	NOW (144)	FIR, VDR	6 h–6 m	Viewing options	SS
[1]Kable and Glimcher[179]	25 (13)	$M = 22.2$	PR	FUT + NOW (200)	FIR, VDR	1 d–6 m	Viewing options	SS
Kim et al.[189]	33 (15)	$M = 21.6$	HYP	FUT + NOW (?)	VIR, VDR	0–2 m	Decision	DS
Liu and Feng[190]	18 (8)	$M = 22$	PR	NOW (200)	FIR, VDR	1 d–3 m	Viewing + decision	DS
Luo et al.[191]	21 (13)	22–44	PR	NOW (76)	VIR, VDR	4 m	Decision	DS/SS/SC
Marco-Pallares et al.[192]	17 (11)	$M = 28$	PR	NOW (104)	VIR, VDR	5–169 d	Decision	SS
[1]McClure et al.[121]	14 (9)	$M = 21.4$	PR	FUT + NOW (68)[2]	VIR, VDR	0–2 m	Decision	DS
Monterosso et al.[88]	29 (9)	$M = 31.8$	HYP	NOW (72)	VIR, VDR	1 w–3 m	Decision	—
Peters and Büchel[193]	22 (14)	$M = 26.3$	PR	NOW (48)	VIR, VDR	6 h–6 m	Viewing options	SS
Samanez-Larkin et al.[194]	25 (13)	19–26, 63–85	PR	FUT + NOW (84)	VIR, VDR	0–2 m	Decision	DS
Sripada et al.[195]	28 (0)	$M = 28.7$	PR	FUT + NOW (80)	VIR, VDR	0–2 m	Decision	DS/SS
Weber and Huettel[196]	23 (11)	19–36	PR	FUT + NOW (130)	VIR, VDR	0–2 m	Decision	SC
Wittmann et al.[102]	13 (8)	18–39	HYP	NOW (48)	VIR, VDR	5 d–10 y	Decision	—
Wittmann et al.[197]	13 (6)	$M = 30.2$	R	NOW (21–42)	VIR,FDR	2–64 s	Decision	—

PR, potentially real; FIR, amount of immediate reward fixed; FDR, amount of delayed reward fixed; VDR, amount of delayed reward variable; DS, dual-systems account; SS, single-system account; SC, self-control account; FUT + NOW, future trials (all rewards are delayed) and now trials (choices between an immediate and delayed reward); NOW, only now trials; HYP, hypothetical; VIR, amount of immediate reward variable; R, real; h, hours; s, seconds; d, days; w, weeks; m, months; y, years.

[1]Note that only McClure et al.[121] controlled for subjective value in the analyses. Kable and Glimcher[179] tested one prediction from the dual system account, in addition to the predictions from the single system account. Thus, to the best of our knowledge, these studies are the only ones so far which tested predictions of both the single and dual system accounts.

[2]Estimated on the basis of average task duration and intertrial interval. Note that in some studies, support for the models could not be determined from the results.

much self-control (suggested by the relative lack of activation in δ areas). Another factor to consider is these studies' use of a fixed immediate reward, which is relatively uncommon in the TD literature (see Table 2). According to one report,[201] rewards are discounted more when the immediate reward is fixed than when the delayed reward is fixed. It is possible that the neural responses in the abovementioned studies also differ from those using fixed delayed rewards (see also Refs 202–207 for other effects of procedural differences on discounting).

Ballard and Knutson,[178] who separated in time the presentation of the *magnitude* of the delayed reward from the presentation of its *delay*, showed that the VS was primarily responsive to magnitude. The MPFC and the PCC, on the other hand, were responsive to both magnitude and delay, which appears in line with the single-system account. This latter finding, however, only occurred in individuals who most often preferred the immediate reward. This implies that the MPFC and PCC might be more sensitive to preference for immediacy than to the value of delayed rewards, in line with the dual-system account.

Two more recent studies[191,195] found that the VS, MPFC (and PCC) tracked the subjective value of rewards when both the amount of the delayed *and* the immediate reward were variable, lending support to the single-system account. Sripada et al.[195] refined the earlier findings by Kable and Glimcher, by showing that the *difference* in the subjective value of the delayed versus sooner reward showed this correlation, rather than the sum of the subjective values or the larger subjective value of the two rewards. These studies, however, also show some inconsistencies with the single-system/ASAP account. Sripada et al.,[195] for example, found that the MPFC and PCC were also sensitive to the presence of an immediate reward.

In sum, support for the single system account is provided by studies showing that activation in 'β' areas is associated with subjective value, even in trials in which an immediate reward is absent. These findings are inconsistent with the dual-systems notion that β regions respond preferentially to immediacy.

Support for the Self-Control Account

Several researchers have proposed that self-control plays a key role in TD,[14,17,178,186,187,208,209] although support for this notion has been mainly indirect.[107,178,187,191,210,211] Recently, Figner et al.[212] provided direct support for the self-control account. In a repetitive transcranial magnetic stimulation (rTMS) study, transient disruption of the left LPFC led to an increase in preferences for immediate rewards. Critically, disruption of this area did *not* lead to changes in the valuation of the choice options. On the basis

of these findings, Figner et al. suggested that preferences for immediate versus delayed reward do not directly result from valuation. Instead, they suggested that even when an immediate reward is valued more highly than a delayed reward, this valuation may be overridden by DLPFC-driven self-control, resulting in the decision to wait for the large delayed reward. Similarly, Cho et al.[213] demonstrated that stimulation of the DLPFC led to a *decrease* in the degree of discounting. In line with the above findings, Peper et al.[214] showed that enhanced structural integrity of PFC-striatum white matter bundles was associated with less impulsive choices. In line with the self-control account, Luo et al.[191] argued that brain activation associated with *choice* should be distinguished from brain activation associated with *value*. They found that more difficult choices, reflected by longer reaction times, were associated with greater activation in executive control regions including the inferior frontal gyrus (IFG) and LPFC. Additionally, the DLPFC and IFG were more activated during preferences for delayed rewards compared to immediate rewards, which is in line with the self-control and the dual-system account. Finally, results by Ballard and Knutson[178] also appear to fit the self-control account. For instance, they found that the DLPFC was sensitive to delay, but not to the magnitude of rewards. The authors noted that waiting for a larger future reward requires cognitive control, thereby recruiting regions such as the DLPFC (see Box 2, Figure 3).

Competing or Complementary Accounts?

The dual-systems account, the single-system/ASAP account, and the self-control account may be viewed as competing accounts of the neural basis of TD. We suggest here that (1) the specific predictions of these accounts need to be tested against one another in future research; (2) some components of the accounts may complement each other, and a certain level of integration of the accounts may be possible. We will now discuss each of these points in turn.

(1) To the best of our knowledge, only two studies so far were designed in such a way that some of the predictions of both the single and the dual system accounts could be, more or less directly, tested: McClure et al.[121] controlled for subjective value in the analyses used, and Kable and Glimcher[179] tested one prediction of the dual system account in addition to the predictions of the single-system account. As the use of different tasks might produce differences in both behavior and brain activation, future experiments that test the various accounts directly against each other within a single, specified task, will probably be most useful (see also Ref 215). In order to be able to test all three TD accounts, such a task should include both NOW and FUTURE trials in which the magnitude of the immediate/sooner reward is varied. Additionally, participants should be asked to complete ratings (using a Visual Analog Scale or a Likert scale) of how they subjectively value the choice options that are used in the task (see Ref 212). These ratings could be used to directly test the predictions of the self-control account against those of the dual- and single-system accounts. If activity in δ areas (specifically LPFC) is associated with the evaluation of choice options *and* with high valuation of delayed rewards, this would support the dual- and single-system accounts. If, on the other hand, LPFC activation is associated with *discrepancies* between choice and valuation (e.g., choosing delayed rewards despite subjective reports that the immediate alternative is higher in attractiveness), then this would be in favor of the self-control account.

The dual-systems and single-system accounts could be tested against each other by combining in one experiment the approaches that were used by McClure et al.[121] and Kable and Glimcher.[179,188] Specifically, it may be feasible to combine the use of fixed delayed reward trials[121] and fixed immediate reward trials.[188] This would enable one to study whether activity in β areas not only varies as a function of immediacy (NOW vs. FUTURE trials), but also as a function of subjective value and/or delayed reward magnitude. This is relevant, because McClure et al.[121] interpreted the fact that activity in β areas was larger for NOW than for FUTURE trials as evidence supporting the dual systems account. However, these same findings can also be explained by the single system account (activity in β areas reflects the subjective value of rewards at any point in time), because the subjective value of immediate rewards is higher than the subjective value of delayed rewards. Therefore, if future research finds that, within the same group of participants, (1) activity in β areas is larger for NOW than for FUTURE trials, and (2) activity in β areas varies as a function of delayed reward magnitude on fixed immediate reward trials, then that would provide support against the dual system account. If, on the other hand, within the same sample, activity in β areas is stronger for NOW versus FUTURE trials, and there are no regions for which activity is specifically associated with subjective value independent of immediacy/delay, then that would provide support for the dual system account.

(2) Nonetheless, the data of future studies may not provide very clear support in favor of one model and against another. Instead, dual- and single-system accounts might not be mutually exclusive, and integration of both accounts might provide the

best explanation of the data (see also Ref 215). For instance, similar brain regions could be involved in several aspects of TD, such that β-areas correspond to the subjective value of both immediate and delayed rewards (consistent with the single-system account), but that these areas also encode an 'immediacy signal' and are therefore more active during NOW trials compared to FUTURE trials (consistent with the dual-systems account). On a similar note, the fact that β areas have been found to primarily respond to subjective value does not exclude the possibility that there are also unique brain areas responding to unique aspects of the choice options, at the same time. To illustrate this, Ballard and Knutson[178] reported findings within the same sample that provided support for both the single system account and the dual-systems account: Both β and δ areas responded to future rewards, but differentially according to delay (δ) and magnitude (β). Similarly, Sripada et al.[195] found that the VS, MPFC, and PCC tracked subjective value (in accordance with the single system account), while the MPFC and PCC were sensitive to the presence of an immediate reward as well (supporting the dual systems account). Luo et al.[191] reported a positive correlation between subjective value of the chosen reward and activity in the VS and MPFC. More in line with the dual-systems and self-control account, however, the DLPFC and insula/IFG were more activated during preferences for delayed rewards compared to immediate rewards.

With respect to the self-control account, Figner et al.[212] primarily view this account as competing with the other two, mainly because in the self-control account, valuation is separated from choice. In the other accounts, on the other hand, choice directly follows from valuation. Additionally, the self-control account is relatively unspecified, both in terms of brain regions involved in the process of valuation, and in terms of the lack of a specific equation which captures the model (see Ref 216 for an *economic* dual-self model of impulse control in which self-control plays a key role). However, we do not want to exclude the possibility that the self-control account may be integrated with the dual- and/or single-system account in the future. But first, more research is needed to further develop the self-control account. Specifically, two important questions include: (1) which brain regions are implicated in valuation? (2) through which specific (neural) mechanisms is LPFC-driven self-control exerted in TD tasks?[212,213] Regarding the first question, tasks in which rewards are passively experienced, in the absence of overt choice may help to further clarify this.[217] Regarding the second question, several possibilities have been proposed.[179,212] One is the possibility that the LPFC acts as a top-down cognitive control system, overriding valuation, which is computed in other brain regions such as MPFC (see Ref 187). As a result, the delayed reward may be chosen even if it is valued lower than the immediate option. Another possibility is that LPFC does not have a direct effect on choice but rather modulates activity in valuation areas such as MPFC (see Ref 187). In that case, changes in value signal in other areas such as MPFC would mediate the effects of LPFC on choice. For an interesting discussion, see Ref 218.

In sum, data from fMRI studies so far do not provide conclusive evidence in favor of one specific account. Rather, data support all accounts to some extent, and we suggest that integration of the accounts may be feasible. Clearly, future research is needed to refine theoretical accounts of the neural basis of TD.

While this discussion has focused on activation in β and δ areas during TD, other areas have been shown to be active as well (see Box 3).

BOX 3

BRAIN REGIONS THAT MAY NEED FURTHER EXAMINATION

Most reports on temporal discounting mainly focus on the VS, MPFC, and PCC (see Figure 2(a)). Other regions that receive considerable attention, either as part of the 'δ' system or in relation to subjective value, are the posterior parietal cortex (PPC), LPFC, VLPFC including the IFG (see Figure 2(b)), VMPFC or medial orbitofrontal cortex (MOFC), LOFC, (rostral) anterior cingulate cortex (ACC), and supplementary motor area (SMA). There are, however, other brain regions that have been implicated in TD, but that have received only little attention. These areas include the insula, temporal–parietal junction (TPJ), amygdala, and hippocampus. Activation of the (posterior) insula has been found to correlate with subjective value.[188] The insula has also been found to be more active during choices for delayed rewards,[102,191] to be activated during both immediate and delayed choices when delays are in the range of seconds,[197] to be part of the 'δ' system,[194] and to be more active when choices are more risky.[196] Together these results suggest that the insula plays a role in preferences for delayed and uncertain rewards. It should be noted that the anterior and posterior part of the insula might play different roles in TD. Activation of the TPJ was found to correlate with subjective value in one study[188] and to

be inversely related to increasing delays of delayed reward in another study.[178] Just like the insula, the TPJ might, therefore, be part of the 'δ' system and/or involved in self-control, as with longer delays, activation in this region decreases, which is likely to correspond to a lower subjective value of the delayed reward. Finally, the amygdala and hippocampus have also been implicated in TD, especially when episodic prospection is involved[219] (see also Findings based on nontraditional tasks). These brain regions have, for example, been found to be more active during choices with a clear preference for either the immediate or delayed reward.[192] Activations in these regions have also been found to correlate with subjective value, and to be more active during choices for later versus earlier rewards.[195] According to McClure et al.,[121] however, the hippocampus is a 'β' region.

Findings Based on Nontraditional Tasks

In addition to the classical TD tasks that have been discussed, nontraditional TD tasks can shed light on the neural mechanisms of TD. These nontraditional tasks include tasks with primary rewards (juice/food/erotic pictures), tasks in which discounting of future rewards are compared to losses, tasks in which participants envisage a future episode, and tasks in which participants make choices for others instead of themselves (see Table 3).

Although no studies have directly compared the neural correlates of intertemporal choices for primary rewards with secondary rewards, in general, these appear to be quite similar. McClure et al.[156] used juice and water, and found involvement of limbic areas including the VS, MOFC, and PCC during preferences for an immediate reward. Interestingly, in contrast to monetary rewards, only fluid rewards that were delivered immediately elicited this limbic response; a limbic response was not evoked when rewards were delayed by at least 5 min. The authors argued that for primary rewards, the limbic system responds to the *absolute* rather than to the *relative* value of delays. This might be an evolutionary adaptation to physiological needs (e.g., rate of body water loss or deterioration of food). In the case of secondary rewards, the limbic system might be more sensitive to relative value.

When erotic pictures were used, temporal discounting was associated with a similar limbic response.[158] As in studies using monetary reward, Prevost et al.[158] found that activity in the VS and the VMPFC correlated positively with the subjective value of the delayed reward.

Discounting behavior can also be influenced by using episodic prospection, that is, imagining future episodes such as spending money in a pub 180 days from now,[220] or during a planned vacation in Paris.[219] Two studies that used episodic prospection found attenuated temporal discounting (i.e., participants were more likely to choose the delayed reward), and this effect was strongest when future episodes were imagined more vividly. At the neural level, Peters and Büchel[219] found that in both the episodic prospection and the control condition, subjective value correlated with activation in the orbitofrontal cortex (OFC), VS, MPFC, and PCC, although this was not examined by Benoit et al.[220] In addition, Peters and Büchel[219] reported a pivotal role for the ACC in signaling increased subjective value associated with episodic prospection. Benoit et al.,[220] however, suggested a pivotal role for the more rostrally located Medial rostral prefrontal cortex (mrPFC) in episodic prospection. These discrepant findings may be accounted for by the many differences in task design, including whether participants envisaged the future episode before choosing, the time period and mental process on which the analyses were focused, task format (real vs hypothetical), and the control conditions. Interestingly, both studies found that attenuated discounting was associated with increased coupling of the key medial prefrontal region, that is, the ACC[219] or the mrPFC,[220] with the hippocampus. According to Peters and Büchel[219] this increased coupling might reflect increased incorporation of episodic prospection or conceptual information into prefrontal decision-making circuits.

Another interesting question that has been addressed is whether discounting of future losses shares a common neural mechanism with discounting of future gains.[137,221] The results of these two studies were inconsistent both at the behavioral and the neural level. Xu et al.[221] showed that, as predicted, participants were more likely to choose smaller/sooner losses than smaller/sooner gains, but Bickel et al.[137] found similar degrees of discounting for losses and gains. In line with their behavioral findings, Xu et al.[221] showed that the neural mechanisms underlying temporal discounting of gains and losses were asymmetric, that is, greater activation was found in the insula, thalamus, VMPFC, and striatum on loss trials than on gain trials. The PCC and DLPFC were activated in both conditions, but more strongly in the loss condition, suggesting a need for increased cognitive control in order to avoid larger future losses. Bickel et al.,[137] on the other hand, did not find robust differences

TABLE 3 | Overview of fMRI Studies on Temporal Reward Discounting Using Nontraditional Tasks

	Participants		Task				
Study	*N* (female)	Age (years)	Type	Reward	Trials	Delays	Main Findings
Albrecht et al.[198]	28 (14)	18–30	PR	Money, playing for self vs. other	80	0–2 m	Steeper discounting and increased activation in VS, anterior MPFC, precuneus, and pregenual ACC when making decisions for self vs other
Benoit et al.[220]	12 (8)	20–36	?	Money, episodic prospection[1]	52	1 m–1 y	Attenuated discounting in imagine trials, associated with increased mrPFC activation and enhanced mrPFC-hippocampus coupling
Bickel et al.[137]	30 (21)	20–67	PR + HYP	Money, gains and losses	168	1 w–6 m	No significant difference in discounting of gains and losses, and no significant neural differences
McClure et al.[156]	*Exp.1*: 20 (12)	?[2]	R	Juice and water	36	0–25 min	β and δ areas similar to those identified in previous study using monetary reward[121]
	Exp.2: 14 (6)				36	10–30 min	β system not responsive to earliest available juice/water reward (in contrast to monetary rewards)
Peters and Büchel[219]	30 (15)	$M = 25.4$	PR	Money, episodic prospection[1]	118	6 h–6 m	Attenuated discounting in imagine trials, associated with increased ACC, PCC and lateral parietal cortex activation and enhanced ACC-hippocampus and ACC-amygdala coupling
Prevost et al.[158]	18 (0)	$M = 23.1$	R	Erotic pictures	240	1.5–9 s	Positive correlation between subjective value and activation in VS, VMPFC and LPFC
Xu et al.[221]	20 (10)	22–29	PR	Money, gains and losses	84	2 w–1 m	Steeper discounting in loss trials than gain trials, associated with more activation in DLPFC, PPC, VMPFC, insula, thalamus, and striatum in loss trials compared to gain trials

s, seconds; min, minutes; h, hours; d, days; m, months; y, years.
[1]Imagining spending an amount of money in the future.
[2]Students, exact age not reported.

between loss and gain trials. More studies are needed to elucidate these discrepant findings. In addition to differences in task design and analysis, differences in mean age might play a role (47^{137} vs 25^{221}).

Finally, Albrecht et al.[198] investigated whether people make the same intertemporal choices for others as they would for themselves. Strong discounters chose the sooner option more often for themselves than they did for others, whereas moderate discounters did not differentiate. When participants made choices only for themselves, more activation was found in the pregenual ACC, VS, anterior MPFC, and precuneus for immediate choices than for delayed choices. These brain regions, therefore, appear primarily involved in choices associated with immediate gratification of one's own needs. The authors conclude that making decisions for others does not involve activation in reward-related brain regions, possibly explaining why strong discounters chose relatively patiently when making decisions for others.

Individual Differences

Temporal discounting of rewards is highly variable across individuals, in that some are willing and able to wait 365 days for a reward of $100, while others do not wait 2 days for the same reward. Neural correlates of individual differences in discounting have been examined by correlating brain activation during decision-making with either self-report measures of impulsivity, or with discounting measures obtained from TD task choices (e.g., k). To ensure large variability in impulsive behavior, some of these studies have included participants who show pathological forms of impulsivity,[88,222,223] but note that clinical case-control comparisons are omitted from this review.

McClure et al.[121] proposed that activation in limbic (β) areas biases people toward preferring immediate rewards. Therefore, it might be hypothesized that impulsive individuals activate these regions to a greater extent compared to less impulsive people. Nonetheless, evidence for increased recruitment of these areas in highly impulsive subjects is lacking. In contrast, several studies have reported *decreased* activity in the VS and MPFC in more impulsive subjects.[178,195]

Further, findings regarding the role of δ regions in individual differences in TD have been inconsistent. While some studies have reported *decreased* activation in the lateral PFC, cingulate and parietal cortex in those subjects who were most impulsive,[88,178] others have found that more impulsive subjects showed *increased* activation in these regions.[191,223] In addition, Boettiger et al.[222] observed both increased and decreased activation in different putative δ regions (DLPFC and LOFC, respectively) in more impulsive subjects. Similarly, Wittmann et al.[102] reported both positive and negative correlations between impulsivity and activation in different parts of the IFG, which has been implicated in inhibitory control.

These inconsistent findings could be attributed mainly to the large differences in task design, focus of fMRI analyses and fMRI contrasts between studies. For instance, some authors have compared brain activation during trials in which an immediate reward was present to activation during trials in which all rewards were delayed.[195] Others have focused on activation during specific choices, such as delayed choices[191] or difficult choices in which the immediate and delayed reward were close in subjective value.[88] Moreover, in some studies the focus of analysis has not been on decision-related activity, but rather on activation associated with the processing of magnitude- and delay-related information.[178] Finally, the TD/impulsivity measures that were correlated with brain activation differ strongly between studies as well. The two studies that used self-report measures of impulsivity[195,223] employed different questionnaires. Most studies have used k as a proxy of TD/impulsivity, but some have used other measures, such as the proportion of immediate choices,[222] or a measure similar to AUC.[102]

In addition to individual differences in impulsivity, two recent studies have focused on other individual differences that might affect TD behavior and brain activation, such as consistency in choices and cultural background. Luo et al.[191] investigated whether the degree of consistency (or stochasticity) in intertemporal choices affects the neural mechanisms associated with these choices. They found that inconsistent participants show increased activation in the IFG and insula during delayed choices, compared to more consistent participants. Kim et al.[189] reported cultural differences in TD, both on a behavioral and neural level. American participants discounted delayed rewards more steeply than Korean participants. This behavioral difference was exclusively driven by differences in VS activation between the two groups. In American participants, the VS activated to a greater extent during NOW trials relative to FUTURE trials. The reverse effect was observed in Korean participants, in that they *deactivated* the VS during NOW trials as compared to FUTURE trials. No group differences were observed in the LPFC or PPC. Kim et al.[189] suggested that these behavioral and neural differences could be attributed to the collectivism that is inherent in Eastern cultures, in which impulsive emotions are discouraged because they might negatively influence the goals of the group.

In sum, given the great variability in task designs and analytical approaches between studies, it is difficult to draw a coherent conclusion regarding neural underpinnings of individual differences in temporal discounting of rewards. Taken as a whole, studies clearly implicate both δ and β brain regions. Whether impulsive individuals show heightened or attenuated activation in these regions seems largely dependent on the type of task that is being used, and on the contrasts that are chosen for analyses. Comparison between studies might be further complicated by individual differences in cultural background and consistency of choices of participants, as both factors have been shown to affect discounting behavior and brain activation.

Development of Temporal Reward Discounting

Behavioral studies have shown that the ability to wait for a delayed reward improves linearly with age from childhood to adulthood[131,152,224,225] (for lifespan development of TD see Refs 73, 226). However, only a handful of fMRI studies on the development of TD have been conducted. In a sample of 12–31-year-old males, Christakou et al.[227] replicated the previously reported linear increase in AUC with age that was observed in behavioral studies. In addition, they showed that the VMPFC was more active during decision-making in individuals who were older *and* had a greater AUC. In contrast, older age and greater AUC were associated with *decreased* activation in the VS, insula, ACC and parietal cortex during decision-making. Interestingly, increased age and AUC were associated with heightened functional coupling between the VMPFC and VS, and enhanced coupling between the VMPFC and a network of δ regions (e.g., DLPFC, and parietal cortex) during decision-making. Therefore, Christakou et al.[227] concluded that the VMPFC contributes to the development of self-control by regulating reward-related responses in the VS, and by integrating delay-related information from the DLPFC, insula, and parietal cortex. Ripke et al.[124] used the approach of McClure et al.[121,156] to compare β- and δ-activation between adolescents (13–15 years) and adults (19–50 years). While adolescents discounted rewards more steeply than adults, activation in β and δ regions was generally similar in both groups. Adults did show more parietal cortex activation than adolescents during decision-making. Greater parietal cortex activity was also related to more consistent choices, and adults were more consistent than adolescents. Therefore, Ripke et al.[124] speculated that adults compare immediate and delayed rewards more precisely than adolescents because of increased maturation of the parietal cortex.

Two recent studies[111,194] included an even wider age range to study the neurocognitive development of TD. These studies used the approach of McClure et al.[121,156] to compare brain activation between young adults (18–28 years) and older adults (63–85 years). Both studies demonstrated that β and δ activation was largely overlapping in younger and older adults. However, there were also important differences between the studies. Samanez-Larkin et al.[194] did not find a group difference in discounting behavior, whereas Eppinger et al.[111] reported reduced discounting in older adults relative to young adults. Further, Samanez-Larkin et al.[194] observed that the δ-regressor correlated with activation in VS in older adults, but not in younger adults. Thus, a brain area that is usually considered part of the β network actually contributed to a preference for delayed rewards in older adults. Samanez-Larkin et al.[194] proposed that this activation might reflect older adults' increased experience with receiving delayed rewards. This experience could lead them to anticipate positive emotions during the receipt of a delayed reward. In contrast, Eppinger et al.[111] found that the δ-regressor correlated with *less* activation in the dorsal striatum in older adults compared to young adults, and that the β-regressor correlated with *less* activation in the VS in older adults. Eppinger et al.[111] suggested that this attenuated discounting behavior and neural reward sensitivity in older adults could be explained by reduced dopaminergic modulation of the VS with age.

CONCLUSION

In sum, fMRI studies have suggested a variety of brain regions that are involved in the discounting of delayed rewards. These include, but are not limited to, VS, MPFC, PCC, ACC, LPFC, and parietal cortex. According to the dual-systems model, two brain systems (the β-system and δ-system) contribute differentially to the valuation of immediate and delayed rewards. In contrast, the single-system model[188] states that a single network of brain regions tracks the subjective value of both immediate and delayed rewards. A third account posits that self-control processes mediate the valuation of rewards and the eventual choice of a reward, such that even very tempting immediate rewards could be resisted if enough self-control is exerted.

The studies we have reviewed have reported evidence for the dual-systems model,[121,156,189,194,197–199] the single-system model,[179,188,193] the self-control model,[178,191] or multiple models.[19,178,191,195] We

suggest that some components of these models can also be integrated, and that the specific predictions of each model should be tested against each other in future research. At present, it is difficult to draw a firm conclusion regarding the best neurobiological model of TD, because of large differences in task design and analyses between studies. Here we highlight the most pressing issues for the field.

First, some studies, particularly those that have found (partial) support for the single-system model,[178,179,188,193] used fixed immediate rewards. When fixed immediate rewards are used (relative to variable immediate rewards), delayed rewards appear to be discounted more steeply,[201] dissociating the subjective values of the immediate and delayed reward becomes difficult,[195] and a reward prediction error (which activates β-regions) might be induced.[178] Future studies should address these issues. Second, trial types differed between studies, in that many studies followed the approach of McClure et al.[121,156] by including NOW and FUTURE trials, while others only included NOW trials. Third, some studies[178,179,188] selected participants who showed highly consistent behavior across several sessions, which is not considered typical in the discounting literature.[12] As one's consistency affects brain activation during intertemporal choices,[124,191] future research should take the (in)consistency of participants' choices into account. Fourth, some β-regions (i.e., MPFC, PCC, precuneus) show considerable overlap with default mode network regions, which are deactivated during task performance.[228] Thus, some of the β-activity might reflect default mode network activity associated with a decreased need for executive control during NOW trials. This issue could be circumvented by parametrically manipulating the difficulty of NOW trials (see Ref 88). Finally, only McClure et al. examined β- and δ-activity by testing for the *interaction* between choice and brain activation. Additionally, different studies focused on different phases of TD trials in their analyses (viewing the options vs decision-making). Ideally, future studies should measure activation during both phases by using a design in which activity during both phases can be clearly distinguished (e.g., Ref 190).

FUTURE DIRECTIONS

An important future direction is studying functional and structural connectivity between β- and δ-regions in relation to discounting behavior (see Refs 214, 227). Another understudied research question in the current TD literature is the neural mechanisms underlying the development of TD across the lifespan. Future studies should examine within-subject changes in behavioral and neural correlates of TD in children and adolescents using longitudinal designs, or further explore the neurobiological underpinnings of differences in TD between younger and older adults.

It is important to note that individual or age differences in discounting behavior could not only reflect differences in impulsivity, but also differences in other, related processes including subjective time perception[229,230] and working memory.[140] Similarly, an important issue in developmental TD studies is the fact that participants of different ages might value the same amount of money differently. To address this issue, developmental studies should include a measure of subjective valuation of the rewards that are used in the TD tasks (e.g., likert ratings), and control for age differences in this measure in their analyses (cf. Ref 152). In addition, while an increased preference for delayed rewards is often interpreted as self-control, waiting for a delayed reward can also be considered a risky choice, since with longer delays there is a greater chance that the promised reward will not actually be received.[16] Therefore, future research would benefit from including measures to further elucidate the role such processes play in temporal discounting.

Finally, researchers should be emboldened by the growing number of TD studies which have incorporated nonmonetary or primary rewards in their designs. Primary rewards, while not without complications, offer several advantages over monetary rewards (e.g., immediate consumption of the reward is possible). An exciting new avenue for TD research is the direct comparison of brain mechanisms involved in discounting of monetary and primary rewards.

REFERENCES

1. Cardinal RN, Winstanley CA, Robbins TW, Everitt BJ. Limbic corticostriatal systems and delayed reinforcement. *Ann N Y Acad Sci* 2004, 1021:33–50.
2. Kalenscher T, Windmann S, Diekamp B, Rose J, Gunturkun O, Colombo M. Single units in the pigeon brain integrate reward amount and time-to-reward in an impulsive choice task. *Curr Biol* 2005, 15: 594–602.
3. Mazur JE. Species differences between rats and pigeons in choices with probabilistic and delayed reinforcers. *Behav Processes* 2007, 75:220–224.

4. Richards JB, Mitchell SH, de Wit H, Seiden LS. Determination of discount functions in rats with an adjusting-amount procedure. *J Exp Anal Behav* 1997, 67:353–366.
5. Cardinal RN. Neural systems implicated in delayed and probabilistic reinforcement. *Neural Netw* 2006, 19:1277–1301.
6. Kalenscher T, Ohmann T, Gunturkun O. The neuroscience of impulsive and self-controlled decisions. *Int J Psychophysiol* 2006, 62:203–211.
7. Reynolds B, de Wit H, Richards JB. Delay of gratification and delay discounting in rats. *Behav Processes* 2002, 59:157–168.
8. Mazur J. An adjusting procedure for studying delayed reinforcement. In: Commons M, Mazur J, Nevin J, Rachlin H, eds. *Quantitative Analysis of Behavior: Vol 5. The Effects of Delay and Intervening Events on Reinforcement Value*. Hillsdale, NJ: Erlbaum; 1987, 55–73.
9. Baker F, Johnson MW, Bickel WK. Decision-making in state lotteries: half now or all of it later? *Psychon Bull Rev* 2003, 10:965–970.
10. Berns GS, Laibson D, Loewenstein G. Intertemporal choice—toward an integrative framework. *Trends Cogn Sci* 2007, 11:482–488.
11. Frederick S. Valuing future life and future lives: a framework for understanding discounting. *J Econ Psychol* 2006, 27:667–680.
12. Frederick S, Loewenstein G, O'Donoghue T. Time discounting and time preference: a critical review. *J Econ Lit* 2002, 40:351–401.
13. Laibson D. Golden eggs and hyperbolic discounting. *Quart J Econ* 1997, 112:443–477.
14. Ainslie G. Precis of breakdown of will. *Behav Brain Sci* 2005, 28:635–673.
15. de Wit H. Impulsivity as a determinant and consequence of drug use: a review of underlying processes. *Addict Biol* 2009, 14:22–31.
16. Green L, Myerson J. A discounting framework for choice with delayed and probabilistic rewards. *Psychol Bull* 2004, 130:769–792.
17. Monterosso J, Ainslie G. Beyond discounting: possible experimental models of impulse control. *Psychopharmacology (Berl)* 1999, 146:339–347.
18. Peters J, Buchel C. The neural mechanisms of inter-temporal decision-making: understanding variability. *Trends Cogn Sci* 2011, 15:227–239.
19. Ainslie G. *Picoeconomics*. Cambridge: Cambridge University Press; 1992.
20. Critchfield TS, Kollins SH. Temporal discounting: basic research and the analysis of socially important behavior. *J Appl Behav Anal* 2001, 34:101–122.
21. Green L, Myerson J. Alternative frameworks for the analysis of self-control. *Behav Phil* 1993, 21:37–47.
22. Rachlin H. *Judgment, Decision and Choice*. New York: W. H. Freeman; 1989.
23. Pine A, Seymour B, Roiser JP, Bossaerts P, Friston KJ, Curran HV, Dolan RJ. Encoding of marginal utility across time in the human brain. *J Neurosci* 2009, 29:9575–9581.
24. Scholten M, Read D. The psychology of intertemporal tradeoffs. *Psychol Rev* 2010, 117:925–944.
25. Ainslie G. Specious reward: a behavioral theory of impulsiveness and impulse control. *Psychol Bull* 1975, 82:463–496.
26. Barkley RA. Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychol Bull* 1997, 121:65–94.
27. Logue AW. Research on self-control–an integrating framework. *Behav Brain Sci* 1988, 11:665–678.
28. Rachlin H, Green L. Commitment, choice and self-control. *J Exp Anal Behav* 1972, 17:15–22.
29. Richards JB, Zhang L, Mitchell SH, de Wit H. Delay or probability discounting in a model of impulsive behavior: Effect of alcohol. *J Exp Anal Behav* 1999, 71:121–143.
30. Sagvolden T, Johansen EB, Aase H, Russell VA. A dynamic developmental theory of attention-deficit/hyperactivity disorder (ADHD) predominantly hyperactive/impulsive and combined subtypes. *Behav Brain Sci* 2005, 28:397–419.
31. Swann AC, Bjork JM, Moeller FG, Dougherty DM. Two models of impulsivity: relationship to personality traits and psychopathology. *Biol Psychiatry* 2002, 51:988–994.
32. Chapman GB, Elstein AS. Valuing the future—temporal discounting of health and money. *Med Decis Making* 1995, 15:373–386.
33. Chapman GB. Temporal discounting and utility for health and money. *J Exp Psychol Learn Mem Cogn* 1996, 22:771–791.
34. Odum AL. Delay discounting: trait variable? *Behav Processes* 2011, 87:1–9.
35. Bickel WK, Jarmolowicz DP, Mueller ET, Koffarnus MN, Gatchalian KM. Excessive discounting of delayed reinforcers as a trans-disease process contributing to addiction and other disease-related vulnerabilities: emerging evidence. *Pharmacol Ther* 2012, 134:287–297.
36. MacKillop J, Amlung MT, Few LR, Ray LA, Sweet LH, Munafo MR. Delayed reward discounting and addictive behavior: a meta-analysis. *Psychopharmacology (Berl)* 2011, 216:305–321.
37. Perry JL, Carrol ME. The role of impulsive behavior in drug abuse. *Psychopharmacology (Berl)* 2008, 200:1–26.
38. Reynolds B. A review of delay-discounting research with humans: relations to drug use and gambling. *Behav Pharmacol* 2006, 17:651–667.

39. Demurie E, Roeyers H, Baeyens D, Sonuga-Barke E. Temporal discounting of monetary rewards in children and adolescents with ADHD and autism spectrum disorders. *Dev Sci* 2012, 15:791–800.
40. Scheres A, Tontsch C, Thoeny AL, Kaczkurkin A. Temporal reward discounting in attention-deficit/hyperactivity disorder: the contribution of symptom domains, reward magnitude, and session length. *Biol Psychiatry* 2010, 67:641–648.
41. Miedl SF, Peters J, Buechel C. Altered neural reward representations in pathological gamblers revealed by delay and probability discounting. *Arch Gen Psychiatry* 2012, 69:177–186.
42. Kishinevsky FI, Cox JE, Murdaugh DL, Stoeckel LE, Cook EW III, Weller RE. fMRI reactivity on a delay discounting task predicts weight gain in obese women. *Appetite* 2012, 58:582–592.
43. Weller RE, Cook EW III, Avsar KB, Cox JE. Obese women show greater delay discounting than healthy-weight women. *Appetite* 2008, 51:563–569.
44. Steinglass JE, Figner B, Berkowitz S, Simpson HB, Weber EU, Walsh BT. Increased capacity to delay reward in anorexia nervosa. *J Int Neuropsychol Soc* 2012, 18:773–780.
45. Monterosso JR, Luo S. An argument against dual valuation system competition: cognitive capacities supporting future orientation mediate rather than compete with visceral motivations. *J Neurosci Psychol Econ* 2010, 3:1–14.
46. Kalenscher T, Pennartz CMA. Is a bird in the hand worth two in the future? The neuroeconomics of intertemporal decision-making. *Prog Neurobiol* 2008, 84:284–315.
47. Gregorios-Pippas L, Tobler PN, Schultz W. Short-term temporal discounting of reward value in human ventral striatum. *J Neurophysiol* 2009, 101:1507–1523.
48. Luhmann CC, Chun MM, Yi D-J, Lee D, Wang X-J. Neural dissociation of delay and uncertainty in intertemporal choice. *J Neurosci* 2008, 28:14459–14466.
49. Tanaka SC, Doya K, Okada G, Ueda K, Okamoto Y, Yamawaki S. Prediction of immediate and future rewards differentially recruits cortico-basal ganglia loops. *Nat Neurosci* 2004, 7:887–893.
50. Rachlin H. Diminishing marginal value as delay discounting. *J Exp Anal Behav* 1992, 57:407–415.
51. Ahn WY, Rass O, Fridberg DJ, Bishara AJ, Forsyth JK, Breier A, Busemeyer JR, Hetrick WP, Bolbecker AR, O'Donnell BF. Temporal discounting of rewards in patients with bipolar disorder and schizophrenia. *J Abnorm Psychol* 2011, 120:911–921.
52. Alessi SM, Petry NM. Pathological gambling severity is associated with impulsivity in a delay discounting procedure. *Behav Processes* 2003, 64:345–354.
53. Appelhans BM, Woolf K, Pagoto SL, Schneider KL, Whited MC, Liebman R. Inhibiting food reward: delay discounting, food reward sensitivity, and palatable food intake in overweight and obese women. *Obesity (Silver Spring)* 2011, 19:2175–2182.
54. Ashare RL, Hawk LW Jr. Effects of smoking abstinence on impulsive behavior among smokers high and low in ADHD-like symptoms. *Psychopharmacology (Berl)* 2012, 219:537–547.
55. Barkley RA, Edwards G, Laneri M, Fletcher K, Metevia L. Executive functioning, temporal discounting, and sense of time in adolescents with attention deficit hyperactivity disorder (ADHD) and oppositional defiant disorder (ODD). *J Abnorm Child Psychol* 2001, 29:541–556.
56. Baumann AA, Odum AL. Impulsivity, risk taking, and timing. *Behav Processes* 2012, 90:408–414.
57. Bickel WK, Jones BA, Landes RD, Christensen DR, Jackson L, Mancino M. Hypothetical intertemporal choice and real economic behavior: delay discounting predicts voucher redemptions during contingency-management procedures. *Exp Clin Psychopharmacol* 2010, 18:546–552.
58. Bickel WK, Odum AL, Madden GJ. Impulsivity and cigarette smoking: delay discounting in current, never, and ex-smokers. *Psychopharmacology (Berl)* 1999, 146:447–454.
59. Bickel WK, Yi R, Kowal BP, Gatchalian KM. Cigarette smokers discount past and future rewards symmetrically and more than controls: is discounting a measure of impulsivity? *Drug Alcohol Depend* 2008, 96:256–262.
60. Bornovalova MA, Daughters SB, Hernandez GD, Richards JB, Lejuez CW. Differences in impulsivity and risk-taking propensity between primary users of crack cocaine and primary users of heroin in a residential substance-use program. *Exp Clin Psychopharmacol* 2005, 13:311–318.
61. Callan MJ, Shead NW, Olson JM. Personal relative deprivation, delay discounting, and gambling. *J Pers Soc Psychol* 2011, 101:955–973.
62. Claus ED, Kiehl KA, Hutchison KE. Neural and behavioral mechanisms of impulsive choice in alcohol use disorder. *Alcohol Clin Exp Res* 2011, 35:1209–1219.
63. Coffey SF, Gudleski GD, Saladin ME, Brady KT. Impulsivity and rapid discounting of delayed hypothetical rewards in cocaine-dependent individuals. *Exp Clin Psychopharmacol* 2003, 11:18–25.
64. Coffey SF, Schumacher JA, Baschnagel JS, Hawk LW, Holloman G. Impulsivity and risk-taking in borderline personality disorder with and without substance use disorders. *Personal Disord* 2011, 2:128–141.
65. Dallery J, Raiff BR. Delay discounting predicts cigarette smoking in a laboratory model of abstinence reinforcement. *Psychopharmacology (Berl)* 2007, 190:485–496.

66. Dierst-Davies R, Reback CJ, Peck JA, Nuno M, Kamien JB, Amass L. Delay-discounting among homeless, out-of-treatment, substance-dependent men who have sex with men. *Am J Drug Alcohol Abuse* 2011, 37:93–97.

67. Dixon MR, Jacobs EA, Sanders S. Contextual control of delay discounting by pathological gamblers. *J Appl Behav Anal* 2006, 39:413–422.

68. Dixon MR, Marley J, Jacobs EA. Delay discounting by pathological gamblers. *J Appl Behav Anal* 2003, 36:449–458.

69. Dom G, D'Haene P, Hulstijn W, Sabbe B. Impulsivity in abstinent early- and late-onset alcoholics: differences in self-report measures and a discounting task. *Addiction* 2006, 101:50–59.

70. Field M, Rush M, Cole J, Goudie A. The smoking Stroop and delay discounting in smokers: effects of environmental smoking cues. *J Psychopharmacol* 2007, 21:603–610.

71. Giordano LA, Bickel WK, Loewenstein G, Jacobs EA, Marsch L, Badger GJ. Mild opioid deprivation increases the degree that opioid-dependent outpatients discount delayed heroin and money. *Psychopharmacology (Berl)* 2002, 163:174–182.

72. Grace RC, McLean AP. Integrated versus segregated accounting and the magnitude effect in temporal discounting. *Psychon Bull Rev* 2005, 12:732–739.

73. Green L, Fry AF, Myerson J. Discounting of delayed rewards—a life-span comparison. *Psychol Sci* 1994, 5:33–36.

74. Green L, Myerson J, Lichtman D, Rosen S, Fry A. Temporal discounting in choice between delayed rewards: the role of age and income. *Psychol Aging* 1996, 11:79–84.

75. Green L, Myerson J, McFadden E. Rate of temporal discounting decreases with amount of reward. *Mem Cognit* 1997, 25:715–723.

76. Green L, Myerson J, Ostaszewski P. Amount of reward has opposite effects on the discounting of delayed and probabilistic outcomes. *J Exp Psychol Learn Mem Cogn* 1999, 25:418–427.

77. Heerey EA, Matveeva TM, Gold JM. Imagining the future: degraded representations of future rewards and events in schizophrenia. *J Abnorm Psychol* 2011, 120:483–489.

78. Heerey EA, Robinson BM, McMahon RP, Gold JM. Delay discounting in schizophrenia. *Cogn Neuropsych* 2007, 12:213–221.

79. Heil SH, Johnson MW, Higgins ST, Bickel WK. Delay discounting in currently using and currently abstinent cocaine-dependent outpatients and non-drug-using matched controls. *Addict Behav* 2006, 31:1290–1294.

80. Heyman GM, Gibb SP. Delay discounting in college cigarette chippers. *Behav Pharmacol* 2006, 17:669–679.

81. Hirsh JB, Guindon A, Morisano D, Peterson JB. Positive mood effects on delay discounting. *Emotion* 2010, 10:717–721.

82. Kirby KN, Petry NM. Heroin and cocaine abusers have higher discount rates for delayed rewards than alcoholics or non-drug-using controls. *Addiction* 2004, 99:461–471.

83. Lawrence KA, Allen JS, Chanen AM. Impulsivity in borderline personality disorder: reward-based decision-making and its relationship to emotional distress. *J Pers Disord* 2010, 24:786–799.

84. Madden GJ, Petry NM, Badger GJ, Bickel WK. Impulsive and self-control choices in opioid-dependent patients and non-drug-using control participants: drug and monetary rewards. *Exp Clin Psychopharmacol* 1997, 5:256–262.

85. Mitchell JM, Fields HL, D'Esposito M, Boettiger CA. Impulsive responding in alcoholics. *Alcohol Clin Exp Res* 2005, 29:2158–2169.

86. Mitchell SH, Wilson VB. Differences in delay discounting between smokers and nonsmokers remain when both rewards are delayed. *Psychopharmacology (Berl)* 2012, 219:549–562.

87. Moallem NR, Ray LA. Dimensions of impulsivity among heavy drinkers, smokers, and heavy drinking smokers: singular and combined effects. *Addict Behav* 2012, 37:871–874.

88. Monterosso JR, Ainslie G, Xu J, Cordova X, Domier CP, London ED. Frontoparietal cortical activity of methamphetamine-dependent and comparison subjects performing a delay discounting task. *Hum Brain Mapp* 2007, 28:383–393.

89. Ohmura Y, Takahashi T, Kitamura N. Discounting delayed and probabilistic monetary gains and losses by smokers of cigarettes. *Psychopharmacology (Berl)* 2005, 182:508–515.

90. Ortner CN, MacDonald TK, Olmstead MC. Alcohol intoxication reduces impulsivity in the delay-discounting paradigm. *Alcohol Alcohol* 2003, 38:151–156.

91. Petry NM. Delay discounting of money and alcohol in actively using alcoholics, currently abstinent alcoholics, and controls. *Psychopharmacology (Berl)* 2001, 154:243–250.

92. Petry NM. Discounting of delayed rewards in substance abusers: relationship to antisocial personality disorder. *Psychopharmacology (Berl)* 2002, 162:425–432.

93. Petry NM, Casarella T. Excessive discounting of delayed rewards in substance abusers with gambling problems. *Drug Alcohol Depend* 1999, 56:25–32.

94. Reed DD, Martens BK. Temporal discounting predicts student responsiveness to exchange delays in a classroom token system. *J Appl Behav Anal* 2011, 44:1–18.

95. Stea JN, Hodgins DC, Lambert MJ. Relations between delay discounting and low to moderate gambling, cannabis, and alcohol problems among university students. *Behav Processes* 2011, 88:202–205.
96. Takahashi T. Cortisol levels and time-discounting of monetary gain in humans. *Neuroreport* 2004, 15:2145–2147.
97. Takahashi T, Furukawa A, Miyakawa T, Maesato H, Higuchi S. Two-month stability of hyperbolic discount rates for delayed monetary gains in abstinent inpatient alcoholics. *Neuro Endocrinol Lett* 2007, 28:131–136.
98. Takahashi T, Shinada M, Inukai K, Tanida S, Takahashi C, Mifune N, Takagishi H, Horita Y, Hashimoto H, Yokota K, et al. Stress hormones predict hyperbolic time-discount rates six months later in adults. *Neuro Endocrinol Lett* 2010, 31:616–621.
99. Wilson VB, Mitchell SH, Musser ED, Schmitt CF, Nigg JT. Delay discounting of reward in ADHD: application in young children. *J Child Psychol Psychiatry* 2011, 52:256–264.
100. Wing VC, Moss TG, Rabin RA, George TP. Effects of cigarette smoking status on delay discounting in schizophrenia and healthy controls. *Addict Behav* 2012, 37:67–72.
101. Acheson A, Vincent AS, Sorocco KH, Lovallo WR. Greater discounting of delayed rewards in young adults with family histories of alcohol and drug use disorders: studies from the Oklahoma family health patterns project. *Alcohol Clin Exp Res* 2011, 35:1607–1613.
102. Wittmann M, Leland DS, Paulus MP. Time and decision making: differential contribution of the posterior insular cortex and the striatum during a delay discounting task. *Exp Brain Res* 2007, 179:643–653.
103. Yu R. Regional white matter volumes correlate with delay discounting. *PLoS One* 2012, 7:e32595.
104. Kirby KN, Petry NM, Bickel WK. Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *J Exp Psychol Gen* 1999, 128:78–87.
105. Augustine AA, Larsen RJ. Affect regulation and temporal discounting: interactions between primed, state, and trait affect. *Emotion* 2011, 11:403–412.
106. Bjork JM, Hommer DW, Grant SJ, Danube C. Impulsivity in abstinent alcohol-dependent patients: relation to control subjects and type 1-/type 2-like traits. *Alcohol* 2004, 34(2–3):133–150.
107. Bjork JM, Momenan R, Hommer DW. Delay discounting correlates with proportional lateral frontal cortex volumes. *Biol Psychiatry* 2009, 65:710–713.
108. de Wit H, Enggasser JL, Richards JB. Acute administration of D-amphetamine decreases impulsivity in healthy volunteers. *Neuropsychopharmacology* 2002, 27:813–825.
109. Dennhardt AA, Murphy JG. Associations between depression, distress tolerance, delay discounting, and alcohol-related problems in European American and African American college students. *Psychol Addict Behav* 2011, 25:595–604.
110. Dombrovski AY, Szanto K, Siegle GJ, Wallace ML, Forman SD, Sahakian B, Reynolds CF 3rd, Clark L. Lethal forethought: delayed reward discounting differentiates high- and low-lethality suicide attempts in old age. *Biol Psychiatry* 2011, 70:138–144.
111. Eppinger B, Nystrom LE, Cohen JD. Reduced sensitivity to immediate reward during decision-making in older than younger adults. *PLoS One* 2012, 7:e36953.
112. Ersner-Hershfield H, Wimmer GE, Knutson B. Saving for the future self: neural measures of future self-continuity predict temporal discounting. *Soc Cogn Affect Neurosci* 2009, 4:85–92.
113. Johnson MW, Bickel WK. Within-subject comparison of real and hypothetical money rewards in delay discounting. *J Exp Anal Behav* 2002, 77:129–146.
114. Kirby KN. Bidding on the future: evidence against normative discounting of delayed rewards. *J Exp Psychol Gen* 1997, 126:54–70.
115. Kirby KN, Marakovic NN. Delay-discounting probabilistic rewards: rates decrease as amounts increase. *Psychon Bull Rev* 1996, 3:100–104.
116. Kirby KN, Marakovic NN. Modeling myopic decision—evidence for hyperbolic delay-discounting within-subjects and amounts. *Organ Behav Hum Decis Process* 1995, 64:22–30.
117. Lempert KM, Porcelli AJ, Delgado MR, Tricomi E. Individual differences in delay discounting under acute stress: the role of trait perceived stress. *Front Psychol* 2012, 3:251.
118. MacKillop J, Tidey JW. Cigarette demand and delayed reward discounting in nicotine-dependent individuals with schizophrenia and controls: an initial study. *Psychopharmacology (Berl)* 2011, 216:91–99.
119. Madden GJ, Begotka AM, Raiff BR, Kastern LL. Delay discounting of real and hypothetical rewards. *Exp Clin Psychopharmacol* 2003, 11:139–145.
120. Madden GJ, Raiff BR, Lagorio CH, Begotka AM, Mueller AM, Hehli DJ, Wegener AA. Delay discounting of potentially real and hypothetical rewards: II. Between- and within-subject comparisons. *Exp Clin Psychopharmacol* 2004, 12:251–261.
121. McClure SM, Laibson DI, Loewenstein G, Cohen JD. Separate neural systems value immediate and delayed monetary rewards. *Science* 2004, 306:503–507.
122. Milenkova M, Mohammadi B, Kollewe K, Schrader C, Fellbrich A, Wittfoth M, Dengler R, Munte TF. Intertemporal choice in Parkinson's disease. *Mov Disord* 2011, 26:2004–2010.
123. Olson EA, Collins PF, Hooper CJ, Muetzel R, Lim KO, Luciana M. White matter integrity predicts delay discounting behavior in 9- to 23-year-olds: a

diffusion tensor imaging study. *J Cogn Neurosci* 2009, 21:1406–1421.

124. Ripke S, Hubner T, Mennigen E, Muller KU, Rodehacke S, Schmidt D, Jacob MJ, Smolka MN. Reward processing and intertemporal decision making in adults and adolescents: the role of impulsivity and decision consistency. *Brain Res* 2012, 1478:36–47.
125. Rodriguez ML, Logue AW. Adjusting delay to reinforcement: comparing choice in pigeons and humans. *J Exp Psychol Anim Behav Process* 1988, 14:105–117.
126. Stoeckel LE, Murdaugh DL, Cox JE, Cook EW. *Weller RE*. Brain Imaging Behav: Greater impulsivity is associated with decreased brain activation in obese women during a delay discounting task; 2012, 7:116–128.
127. Wilson M, Daly M. Are juvenile offenders extreme future discounters? *Psychol Sci* 2006, 17:989–994.
128. Reynolds B. The experiential discounting task is sensitive to cigarette-smoking status and correlates with a measure of delay discounting. *Behav Pharmacol* 2006, 17:133–142.
129. Johnson MW. An efficient operant choice procedure for assessing delay discounting in humans: initial validation in cocaine-dependent and control individuals. *Exp Clin Psychopharmacol* 2012, 20:191–204.
130. Reynolds B, Schiffbauer R. Measuring state changes in human delay discounting: an experiential discounting task. *Behav Processes* 2004, 67:343–356.
131. Scheres A, Dijkstra M, Ainslie E, Balkan J, Reynolds B, Sonuga-Barke E, Castellanos FX. Temporal and probabilistic discounting of rewards in children and adolescents: effects of age and ADHD symptoms. *Neuropsychologia* 2006, 44:2092–2103.
132. Scheres A, Lee A, Sumiya M. Temporal reward discounting and ADHD: task and symptom specific effects. *J Neural Transm* 2008, 115:221–226.
133. Scheres A, Sumiya M, Thoeny AL. Studying the relation between temporal reward discounting tasks used in populations with ADHD: a factor analysis. *Int J Methods Psychiatr Res* 2010, 19:167–176.
134. Lane SD, Cherek DR, Pietras CJ, Tcheremissine OV. Measurement of delay discounting using trial-by-trial consequences. *Behav Processes* 2003, 64:287–303.
135. Navarick DJ. Discounting of delayed reinforcers: Measurement by questionnaires versus operant choice procedures. *Psychol Rec* 2004, 54:85–94.
136. Lawyer SR, Schoepflin F, Green R, Jenks C. Discounting of hypothetical and potentially real outcomes in nicotine-dependent and nondependent samples. *Exp Clin Psychopharmacol* 2011, 19:263–274.
137. Bickel WK, Pitcock JA, Yi R, Angtuaco EJC. Congruence of BOLD response across intertemporal choice conditions: fictive and real money gains and losses. *J Neurosci* 2009, 29:8839–8846.
138. Killeen PR. An additive-utility model of delay discounting. *Psychol Rev* 2009, 116:602–619.
139. Lagorio CH, Madden GJ. Delay discounting of real and hypothetical rewards III: steady-state assessments, forced-choice trials, and all real rewards. *Behav Processes* 2005, 69:173–187.
140. Bickel WK, Yi R, Landes RD, Hill PF, Baxter C. Remember the future: working memory training decreases delay discounting among stimulant addicts. *Biol Psychiatry* 2011, 69:260–265.
141. Estle SJ, Green L, Myerson J, Holt DD. Discounting of monetary and directly consumable rewards. *Psychol Sci* 2007, 18:58–63.
142. Forzano LB, Logue AW. Predictors of adult humans self-control and impulsiveness for food reinforcers. *Appetite* 1992, 19:33–47.
143. Johnson MW, Bickel WK, Baker F. Moderate drug use and delay discounting: a comparison of heavy, light, and never smokers. *Exp Clin Psychopharmacol* 2007, 15:187–194.
144. Kirby KN, Guastello B. Making choices in anticipation of similar future choices can increase self-control. *J Exp Psychol Appl* 2001, 7:154–164.
145. Logue AW, King GR, Chavarro A, Volpe JS. Matching and maximizing in a self-control paradigm using human-subjects. *Learn Motiv* 1990, 21:340–368.
146. Logue AW, Penacorreal TE, Rodriguez ML, Kabela E. Self-control in adult humans—variation in positive reinforcer amount and delay. *J Exp Anal Behav* 1986, 46:159–173.
147. Odum AL, Baumann AA. Cigarette smokers show steeper discounting of both food and cigarettes than money. *Drug Alcohol Depend* 2007, 91:293–296.
148. Odum AL, Baumann AA, Rimington DD. Discounting of delayed hypothetical money and food: effects of amount. *Behav Processes* 2006, 73:278–284.
149. Odum AL, Rainaud CP. Discounting of delayed hypothetical money, alcohol, and food. *Behav Processes* 2003, 64:305–313.
150. Sellitto M, Ciaramelli E, di Pellegrino G. Myopic discounting of future rewards after medial orbitofrontal damage in humans. *J Neurosci* 2010, 30:16429–16436.
151. Yankelevitz RL, Mitchell SH, Zhang Y. Gender differences in factors associated with alcohol drinking: delay discounting and perception of others' drinking. *Drug Alcohol Depend* 2012, 123(1–3):273–276.
152. Demurie E, Roeyers H, Baeyens D, Sonuga-Barke E. Age-related changes in temporal reward discounting as a function of primary and secondary reinforcing properties. Submitted for publication.
153. Jimura K, Myerson J, Hilgard J, Braver TS, Green L. Are people really more patient than other animals? Evidence from human discounting of real liquid rewards. *Psychon Bull Rev* 2009, 16:1071–1075.

154. Jimura K, Myerson J, Hilgard J, Keighley J, Braver TS, Green L. Domain independence and stability in young and older adults' discounting of delayed rewards. *Behav Processes* 2011, 87:253–259.

155. Kirk JM, Logue AW. Effects of deprivation level on humans' self-control for food reinforcers. *Appetite* 1997, 28:215–226.

156. McClure SM, Ericson KM, Laibson DI, Loewenstein G, Cohen JD. Time discounting for primary rewards. *J Neurosci* 2007, 27:5796–5804.

157. Lawyer SR. Probability and delay discounting of erotic stimuli. *Behav Processes* 2008, 79:36–42.

158. Prevost C, Pessiglione M, Metereau E, Clery-Melin ML, Dreher JC. Separate valuation subsystems for delay and effort decision costs. *J Neurosci* 2010, 30:14080–14090.

159. Hyten C, Madden GJ, Field DP. Exchange delays and impulsive choice in adult humans. *J Exp Anal Behav* 1994, 62:225–233.

160. Jackson K, Hackenberg TD. Token reinforcement, choice, and self-control in pigeons. *J Exp Anal Behav* 1996, 66:29–49.

161. Antrop I, Stock P, Verte S, Wiersema JR, Baeyens D, Roeyers H. ADHD and delay aversion: the influence of non-temporal stimulation on choice for delayed rewards. *J Child Psychol Psychiatry* 2006, 47:1152–1158.

162. Kuntsi J, Oosterlaan J, Stevenson J. Psychological mechanisms in hyperactivity: I. Response inhibition deficit, working memory impairment, delay aversion, or something else? *J Child Psychol Psychiatry* 2001, 42:199–210.

163. Marco R, Miranda A, Schlotz W, Melia A, Mulligan A, Muller U, Andreou P, Butler L, Christiansen H, Gabriels I, et al. Delay and reward choice in ADHD: an experimental test of the role of delay aversion. *Neuropsychology* 2009, 23:367–380.

164. Solanto MV, Abikoff H, Sonuga-Barke E, Schachar R, Logan GD, Wigal T, Hechtman L, Hinshaw S, Turkel E. The ecological validity of delay aversion and response inhibition as measures of impulsivity in AD/HD: a supplement to the NIMH multimodal treatment study of AD/HD. *J Abnorm Child Psychol* 2001, 29:215–228.

165. Sonuga-Barke EJ, Taylor E, Sembi S, Smith J. Hyperactivity and delay aversion--I.The effect of delay on choice. *J Child Psychol Psychiatry* 1992, 33:387–398.

166. Schweitzer JB, Sulzer-Azaroff B. Self-control in boys with attention deficit hyperactivity disorder: effects of added stimulation and time. *J Child Psychol Psychiatry* 1995, 36:671–686.

167. Dougherty DM, Mathias CW, Marsh DM, Jagar AA. Laboratory behavioral measures of impulsivity. *Behav Res Methods* 2005, 37:82–90.

168. Forzano LB, Szuba M, Figurilli JM. Self-control and impulsiveness in children: effects of visual food cues. *Psychol Rec* 2003, 53:161–175.

169. Muller UC, Sonuga-Barke EJ, Brandeis D, Steinhausen HC. Online measurement of motivational processes: introducing the Continuous Delay Aversion Test (ConDAT). *J Neurosci Methods* 2006, 151:45–51.

170. Patak M, Reynolds B. Question-based assessments of delay discounting: do respondents spontaneously incorporate uncertainty into their valuations for delayed rewards? *Addict Behav* 2007, 32:351–357.

171. Rachlin H, Raineri A, Cross D. Subjective probability and delay. *J Exp Anal Behav* 1991, 55:233–244.

172. Ainslie G, Haendel V. The motives of the will. In: Gottheil E, Druley K, Skodola T, Waxman H, Charles C, eds. *Etiology Aspects of Alcohol and Drug Abuse*. Springfield: Thomas; 1983.

173. Green L, Myerson J, Macaux EW. Temporal discounting when the choice is between two delayed rewards. *J Exp Psychol Learn Mem Cogn* 2005, 31:1121–1133.

174. Kirby KN, Herrnstein RJ. Preference reversals due to myopic discounting of delayed reward. *Psychol Sci* 1995, 6:83–89.

175. Samuelson PA. A note on measurement of utility. *Rev Econ Stud* 1937, 4:155–161.

176. Mazur JE, Stellar JR, Waraczynski M. Self-control choice with electrical stimulation of the brain as a reinforcer. *Behav Processes* 1987, 15(2–3):143–153.

177. Holt DD, Green L, Myerson J. Estimating the subjective value of future rewards: comparison of adjusting-amount and adjusting-delay procedures. *Behav Processes* 2012, 90:302–310.

178. Ballard K, Knutson B. Dissociable neural representations of future reward magnitude and delay during temporal discounting. *Neuroimage* 2009, 45:143–150.

179. Kable JW, Glimcher PW. An 'as soon as possible' effect in human intertemporal decision making: behavioral evidence and neural mechanisms. *J Neurophysiol* 2010, 103:2513–2531.

180. Ainslie G. Derivation of rational economic-behavior from hyperbolic discount curves. *Am Econ Rev* 1991, 81:334–340.

181. Myerson J, Green L, Warusawitharana M. Area under the curve as a measure of discounting. *J Exp Anal Behav* 2001, 76:235–243.

182. Myerson L, Green L. Discounting delayed rewards: models of individual choice. *J Exp Anal Behav* 1995, 64:263–276.

183. Calvert AL, Green L, Myerson L. Discounting in pigeons when the choice is between two delayed rewards: implications for species comparisons. *Front Neurosci* 2011, 5:96.

184. Hofmann W, Friese M, Strack F. Impulse and self-control from a dual-systems perspective. *Perspect Psychol Sci* 2009, 4:162–176.

185. Loewenstein G. Out of control: visceral influences on behavior. *Organ Behav Hum Decis Process* 1996, 65:272–292.

186. Metcalfe J, Mischel W. A hot/cool-system analysis of delay of gratification: dynamics of willpower. *Psychol Rev* 1999, 106:3–19.

187. Hare TA, Camerer CF, Rangel A. Self-control in decision-making involves modulation of the VMPFC valuation system. *Science* 2009, 324:646–648.

188. Kable JW, Glimcher PW. The neural correlates of subjective value during intertemporal choice. *Nat Neurosci* 2007, 10:1625–1633.

189. Kim B, Sung YS, McClure SM. The neural basis of cultural differences in delay discounting. *Philos Trans R Soc Lond B Biol Sci* 2012, 367:650–656.

190. Liu L, Feng T. The neural predictors of choice preference in intertemporal choice. *Brain Res* 2012, 1436:92–100.

191. Luo S, Ainslie G, Pollini D, Giragosian L, Monterosso JR. Moderators of the association between brain activation and farsighted choice. *Neuroimage* 2012, 59:1469–1477.

192. Marco-Pallares J, Mohammadi B, Samii A, Muente TF. Brain activations reflect individual discount rates in intertemporal choice. *Brain Res* 2010, 1320:123–129.

193. Peters J, Buechel C. Overlapping and distinct neural systems code for subjective value during intertemporal and risky decision making. *J Neurosci* 2009, 29:15727–15734.

194. Samanez-Larkin GR, Mata R, Radu PT, Ballard IC, Carstensen LL, McClure SM. Age differences in striatal delay sensitivity during intertemporal choice in healthy adults. *Front Neurosci* 2011, 5:126–126.

195. Sripada CS, Gonzalez R, Phan KL, Liberzon I. The neural correlates of intertemporal decision-making: contributions of subjective value, stimulus type, and trait impulsivity. *Hum Brain Map* 2011, 32:1637–1648.

196. Weber BJ, Huettel SA. The neural substrates of probabilistic and intertemporal decision making. *Brain Res* 2008, 1234:104–115.

197. Wittmann M, Lovero KL, Lane SD, Paulus MP. Now or later? Striatum and insula activation to immediate versus delayed rewards. *J Neurosci Psychol Econ* 2010, 3:15–26.

198. Albrecht K, Volz KG, Sutter M, Laibson DI, von Cramon DY. What is for me is not for you: brain correlates of intertemporal choice for self and other. *Soc Cogn Affect Neurosci* 2011, 6:218–225.

199. Plichta MM, Vasic N, Wolf RC, Lesch K-P, Brummer D, Jacob C, Fallgatter AJ, Groen G. Neural hyporesponsiveness and hyperresponsiveness during immediate and delayed reward processing in adult attention-deficit/hyperactivity disorder. *Biol Psychiatry* 2009, 65:7–14.

200. Hariri AR, Brown SM, Williamson DE, Flory JD, de Wit H, Manuck SB. Preference for immediate over delayed rewards is associated with magnitude of ventral striatal activity. *J Neurosci* 2006, 26:13213–13217.

201. Tesch AD, Sanfey AG. Models and methods in delay discounting. *Ann NY Acad Sci* 2008, 1128:90–94.

202. Dai Z, Grace RC, Kemp S. Reward contrast in delay and probability discounting. *Learn Behav* 2009, 37:281–288.

203. Robles E, Vargas PA. Functional parameters of delay discounting assessment tasks: order of presentation. *Behav Processes* 2007, 75:237–241.

204. Robles E, Vargas PA. Parameters of delay discounting assessment: number of trials, effort, and sequential effects. *Behav Processes* 2008, 78:285–290.

205. Robles E, Vargas PA, Bejarano R. Within-subject differences in degree of delay discounting as a function of order of presentation of hypothetical cash rewards. *Behav Processes* 2009, 81:260–263.

206. Rodzon K, Berry MS, Odum AL. Within-subject comparison of degree of delay discounting using titrating and fixed sequence procedures. *Behav Processes* 2011, 86:164–167.

207. Stillwell DJ, Tunney RJ. Effects of measurement methods on the relationship between smoking and delay reward discounting. *Addiction* 2012, 107:1003–1012.

208. Mischel W, Ayduk O, Berman MG, Casey BJ, Gotlib IH, Jonides J, Kross E, Teslovich T, Wilson NL, Zayas V, et al. 'Willpower' over the life span: decomposing self-regulation. *Soc Cogn Affect Neurosci* 2011, 6:252–256.

209. Mischel W, Shoda Y, Rodriguez ML. Delay of gratification in children. *Science* 1989, 244:933–938.

210. Casey BJ, Somerville LH, Gotlib IH, Ayduk O, Franklin NT, Askren MK, Jonides J, Berman MG, Wilson NL, Teslovich T, et al. Behavioral and neural correlates of delay of gratification 40 years later. *Proc Natl Acad Sci U S A* 2011, 108:14998–15003.

211. Knoch D, Fehr E. Resisting the power of temptations—the right prefrontal cortex and self-control. *Ann NY Acad Sci* 2007, 1104:123–134.

212. Figner B, Knoch D, Johnson EJ, Krosch AR, Lisanby SH, Fehr E, Weber EU. Lateral prefrontal cortex and self-control in intertemporal choice. *Nat Neurosci* 2010, 13:538–539.

213. Cho SS, Ko JH, Pellecchia G, Van Eimeren T, Cilia R, Strafella AP. Continuous theta burst stimulation of right dorsolateral prefrontal cortex induces changes in impulsivity level. *Brain Stimul* 2010, 3:170–176.

214. Peper JS, Mandl RC, Braams BR, de Water E, Heijboer AC, Koolschijn PC, Crone EA. Delay discounting and

frontostriatal fiber tracts: a combined dti and mtr study on impulsive choices in healthy young adults. *Cereb Cortex* 2013, 23:1695–1702.

215. Rustichini A. Dual or unitary system? Two alternative models of decision making. *Cogn Affect Behav Neurosci* 2008, 8:355–362.
216. Fudenberg D, Levine DK. A dual-self model of impulse control. *Am Econ Rev* 2006, 96:1449–1476.
217. Smith DV, Hayden BY, Truon T, Son AW, Platt ML, Huettel SA. Distinct value signals in anterior and posterior ventromedial prefrontal cortex. *J Neurosci* 2010, 30:2490–2495.
218. Kable JW. Just a little (lateral prefrontal) patience. *Nat Neurosci* 2010, 13:523–524.
219. Peters J, Buchel C. Episodic future thinking reduces reward delay discounting through an enhancement of prefrontal-mediotemporal interactions. *Neuron* 2010, 66:138–148.
220. Benoit RG, Gilbert SJ, Burgess PW. A neural mechanism mediating the impact of episodic prospection on farsighted decisions. *J Neurosci* 2011, 31:6771–6779.
221. Xu L, Liang Z-Y, Wang K, Li S, Jiang T. Neural mechanism of intertemporal choice: from discounting future gains to future losses. *Brain Res* 2009, 1261:65–74.
222. Boettiger CA, Mitchell JM, Tavares VC, Robertson M, Joslyn G, D'Esposito M, Fields HL. Immediate reward bias in humans: fronto-parietal networks and a role for the catechol-O-methyltransferase 158(Val/Val) genotype. *J Neurosci* 2007, 27:14383–14391.
223. Hinvest NS, Elliott R, McKie S, Anderson IM. Neural correlates of choice behavior related to impulsivity and venturesomeness. *Neuropsychologia* 2011, 49:2311–2320.
224. Olson EA, Hooper CJ, Collins P, Luciana M. Adolescents' performance on delay and probability discounting tasks: contributions of age, intelligence, executive functioning, and self-reported externalizing behavior. *Person Indiv Diff* 2007, 43:1886–1897.
225. Steinberg L, Graham S, O'Brien L, Woolard J, Cauffman E, Banich M. Age differences in future orientation and delay discounting. *Child Dev* 2009, 80:28–44.
226. Read D, Read NL. Time discounting over the lifespan. *Organ Behav Hum Decis Process* 2004, 94:22–32.
227. Christakou A, Brammer M, Rubia K. Maturation of limbic corticostriatal activation and connectivity associated with developmental changes in temporal discounting. *Neuroimage* 2011, 54:1344–1354.
228. Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, Shulman GL. A default mode of brain function. *Proc Natl Acad Sci U S A* 2001, 98:676–682.
229. Ray D, Bossaerts P. Positive temporal dependence of the biological clock implies hyperbolic discounting. *Front Neurosci* 2011, 5:2–2.
230. Zauberman G, Kyu Kim B, Malkoc SA, Bettman JR. Discounting time and time discounting: subjective time perception and intertemporal preferences. *J Market Res* 2008, 46:543–556.

