

Can delay discounting deliver on the promise of RDoC?

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Abstract

The National Institute of Mental Health launched the Research Domain Criteria (RDoC) initiative to better understand dimensions of behavior and identify targets for treatment. Examining dimensions across psychiatric illnesses has proven challenging, as reliable behavioral paradigms that are known to engage specific neural circuits and translate across diagnostic populations are scarce. Delay discounting paradigms seem to be an exception: they are useful for understanding links between neural systems and behavior in healthy individuals, with potential for assessing how these mechanisms go awry in psychiatric illnesses. This article reviews relevant literature on delay discounting (or the rate at which the value of a reward decreases as the delay to receipt increases) in humans, including methods for examining it, its putative neural mechanisms, and its application in psychiatric research. There exist rigorous and reproducible paradigms to evaluate delay discounting, standard methods for calculating discount rate, and known neural systems probed by these paradigms. Abnormalities in discounting have been associated with psychopathology ranging from addiction (with steep discount rates indicating relative preference for immediate rewards) to anorexia nervosa (with shallow discount rates indicating preference for future rewards). The latest research suggests that delay discounting can be manipulated in the laboratory. Extensively studied in cognitive neuroscience, delay discounting assesses a dimension of behavior that is important for decision-making and is linked to neural substrates and to psychopathology. The question now is whether manipulating delay discounting can yield clinically significant changes in behavior that promote health. If so, then delay discounting could deliver on the RDoC promise.

Introduction

The National Institute of Mental Health (NIMH) launched the Research Domain Criteria (RDoC) initiative in 2009 to formalize the Institute's mission to understand dimensions of behavior and their underlying biology. RDoC's premise is that knowledge of the neurobiological basis of psychopathological processes will both elucidate pathophysiology and yield targets for treatment development that are likely to transcend categorical psychiatric diagnoses. Yet there have been challenges with the construction and assessment of behavioral domains (Gordon, 2017) due to the lack of standardization of procedures and paradigms being used across sites, and the relative absence of psychometric data (U.S. Department of Health and Human Services, National Institutes of Health, National Institute of Mental Health, 2016). Within this general critique, delay discounting may be an exception. This construct captures fundamental decision-making processes, making it relevant to a broad group of psychiatric disorders. Moreover, unlike many other paradigms, delay discounting paradigms are standardized and have demonstrated good reliability and validity.

This article reviews the potential usefulness of delay discounting in psychiatric research. The paper describes what delay discounting is and how to measure it, reviews what is known about its neural substrates, and summarizes findings from its application in psychiatric disorders. Potentially fruitful research directions in psychiatry are suggested. Delay discounting has typically been proposed as a stable marker of impulsivity in addictive and other impulsive disorders. This article reviews data indicating that it is more sensitive to within-subject change and more generalizable to non-impulsive disorders than was previously thought. This invites research into laboratory manipulations of delay discounting that can extend the understanding of behavior and its neural underpinnings. In summary, delay discounting offers an opportunity to take a dimensional approach to studying psychopathology and to test whether it can be an effective target for treatment intervention.

What is delay discounting?

Delay discounting refers to the extent to which, for any individual, the value of a reward decreases as the delay to receipt increases. This process is included in the RDoC domain of

Positive Valence Systems, within the construct of reward valuation (U.S. Department of Health and Human Services, National Institutes of Health, National Institute of Mental Health, 2016). Reward valuation is the process by which prospective outcomes or actions are weighed with respect to their costs and benefits. The direct result of valuation is choice.

In delay discounting tasks, people choose between smaller rewards that they could receive sooner and larger rewards that they could receive later. These choices involve trade-offs that commonly occur in everyday life. Such choices can be mundane (e.g. 'Should I enjoy myself tonight or study for the exam tomorrow?') or can have significant consequences for health, relationships, or financial security. While most people discount the value of future rewards, individuals vary widely in the *degree* to which they favor immediate rewards over delayed rewards. These differences can be quantified by their *discount rate* (Peters and Büchel, 2011), the primary outcome variable of delay discounting tasks. Discount rates are steep (high) if delayed rewards have very little value, or shallow (low) if delayed rewards have high value. Discount rates provide a quantifiable metric for examining a complex phenomenon (i.e. choosing *when* to receive and consume rewards) that is frequent and meaningful in human experience.

This experimental approach is valuable for the RDoC framework. In particular, delay discounting tasks have good test-retest reliability, longitudinal stability (Kirby, 2009), and moderate heritability (Anokhin *et al.*, 2011, 2014). They have been used across diverse sites and populations (Jachimowicz *et al.*, 2017), practice effects are negligible, the tasks are short and tolerable, and delay discounting is sensitive to within-person change (Lempert and Phelps, 2016). Moreover, the discounting framework has been used extensively in non-human animal research (Green and Myerson, 2004), providing opportunities to understand and manipulate this process at a molecular and cellular level. Finally, and perhaps most importantly, discounting paradigms have ecological validity, in that discount rates in people have been associated with real-world behaviors, including creditworthiness (Meier and Sprenger, 2012), academic performance (Kirby *et al.*, 2005), overeating (Jarmolowicz *et al.*, 2014), alcohol use (Dom *et al.*, 2006), and risky sexual practices (Chesson *et al.*, 2006).

Measuring delay discounting

Delay discounting paradigms

All delay discounting tasks present choices between differing amounts of reward at varying time points, where one of the options is a smaller amount of reward available soon or immediately, and the other option is a larger amount of reward available after a longer delay¹. In research with non-human animals, including pigeons, rodents, and primates (Mazur, 1987; Rosati *et al.*, 2007; Mazur and Biondi, 2009), animals are trained to associate food rewards with different delays on the order of seconds (for review, see Vanderveldt *et al.*, 2016). In human research, delays are typically days, weeks, or months, and are explicitly stated.

How the choice is presented differs between tasks. Money is the standard reward, since it can be assumed that human participants want the outcome and there is no risk of satiation. However, other types of rewards (e.g. food, alcohol) have also been used. There are three general classes of delay discounting tasks: titration, adjusting titration, and randomized-choice tasks (see Fig. 1 for summary). There are small differences between them, and they each have advantages and disadvantages.

All discounting paradigms ask participants to make decisions about what they prefer. In 'incentive-compatible' tasks, one trial is selected at random and the participant is compensated according to the choice they made on that trial, either immediately or after a delay (Kable and Glimcher, 2007; Lempert *et al.*, 2015). This approach aims to ensure that participants are motivated to choose according to their actual preferences. In hypothetical paradigms, participants do not receive anything at the end. This method allows for calculation of discount rate across larger values and longer time frames. The few studies comparing these approaches have shown that they are correlated, but not interchangeable (Johnson and Bickel, 2002).

In 'experiential' discounting tasks, if the participant chooses the delayed reward, they sit and wait through a delay of seconds or minutes before receiving the reward (McGuire and Kable, 2012; Jimura *et al.*, 2013). These paradigms are most comparable with the delay discounting paradigms used with non-human animals (Blanchard and Hayden, 2015). Discounting rates from experiential tasks and the more typical tasks described above are not always correlated (Johnson, 2012), however, and likely involve different cognitive processes (Blanchard and Hayden, 2015; Hayden, 2015).

Calculation of individual discount rates

As reviewed elsewhere (Doyle, 2013), there are several ways to calculate an individual's discount rate. The simpler approaches include calculating the discount factor or the area under the indifference curve. These require less computational skill and make no assumptions about the shape of the discounting function. However, the resulting numerical values depend completely on the delay(s) used in the experiment. Thus, findings are less generalizable across studies. More complex methods include fitting a discount rate (k), and this can be used to estimate the subjective value of *any* delayed reward for an individual. This approach does not depend as much on the particular choices made, enabling comparisons across studies and over time. These methods are described below.

Discount factor

In a simple titration task, only one time delay is assessed (e.g. \$60 in 3 weeks), and the discounting measure is the raw indifference point, which can be transformed to the discount factor (Weber *et al.*, 2007; Steinglass *et al.*, 2012; Pinto *et al.*, 2014). The indifference point and discount factor provide a general estimate of how inclined someone is to select immediate or delayed rewards. Unlike discount rate, the discount factor does not indicate how the subjective value of delayed rewards changes as a function of delay.

Area under the (indifference) curve

If more than one delay is probed in the task, an indifference point for each delay can be plotted, yielding an indifference curve. The discount rate is the slope of the indifference curve; it reflects how the subjective value of the delayed reward changes with time. Discount rate can be estimated by calculating the area under this indifference curve (AUC) (Myerson *et al.*, 2001). Larger AUCs indicate less steep discounting of delayed rewards.

Discount rate (k)

Discount rate can also be estimated by fitting the indifference point data to a discounting model. The hyperbolic model has been shown to fit data better than most other models even across species (Mazur, 1987), and is the most commonly used discount

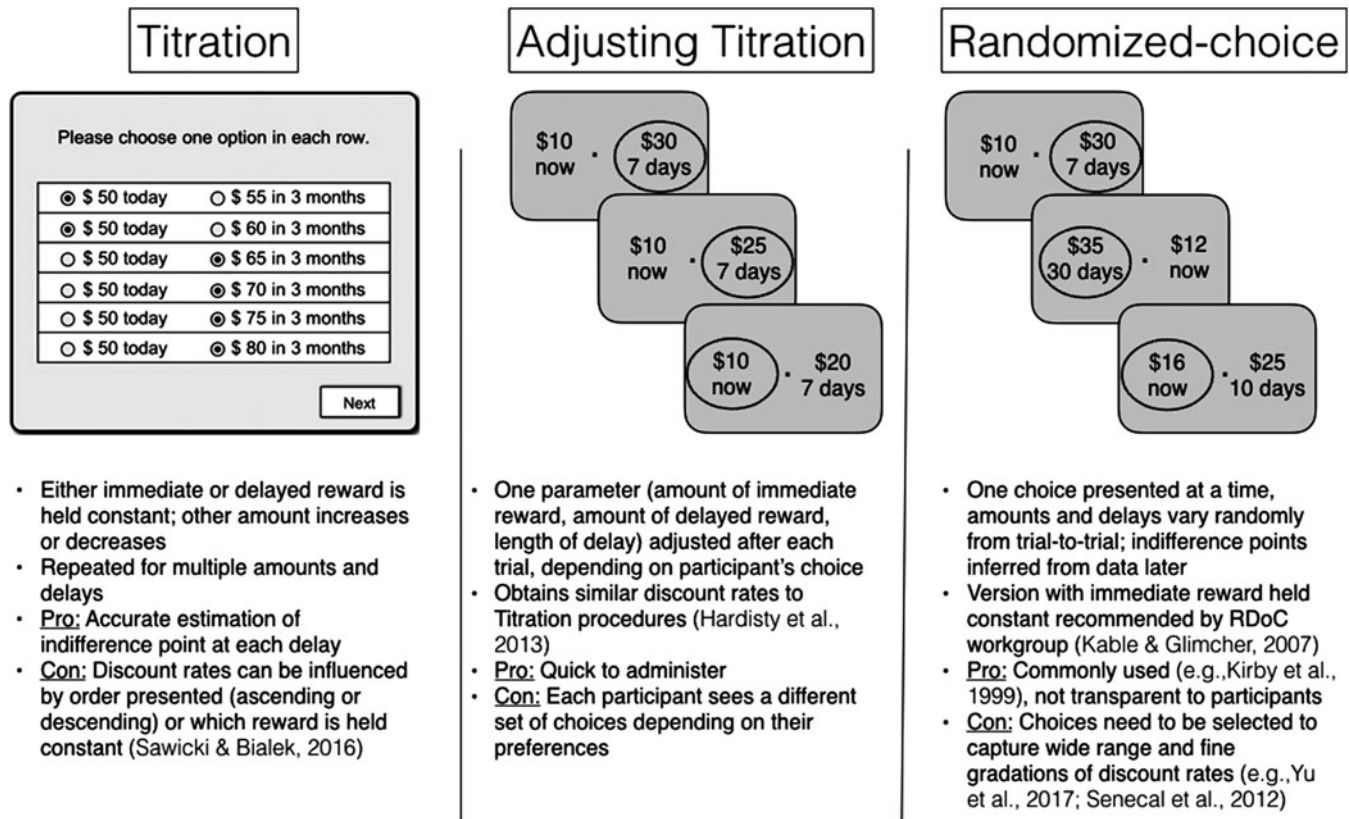


Fig. 1. There are three general classes of delay discounting tasks used in humans: titration, adjusting titration, and randomized-choice tasks. Typical choice screens are illustrated, task structure is summarized, and advantages and disadvantages are listed.

function in psychology and psychiatry:

$$SV = \frac{A}{1 + kD}$$

In this model, SV is the subjective value of the reward, A is the amount of the reward, D is the delay to receiving it (for immediate rewards, $D = 0$ and $SV = A$), and k is a free parameter that represents the discount rate. Larger values of k indicate a stronger preference for smaller/sooner rewards, while smaller values of k indicate less steep (shallower) discounting of delayed rewards. The hyperbolic shape of the model emerges because future rewards are valued in inverse proportion to their expected delays (see Fig. 2 for sample curves). This means that the decline in value, per day, is steepest for goods that will arrive after short delays and becomes gradually less steep as outcomes are delayed farther in the future (Kable and Glimcher, 2010). Discount rates approximated with AUC or fit with the hyperbolic model are highly correlated.

Task considerations

Task design may influence discount rate and needs to be considered when selecting discounting paradigms and comparing findings across studies.

First, the amounts presented in the task serve as 'anchors', which can implicitly influence choice, and thereby affect discount rate (Hardisty *et al.*, 2013). For example, the option that is perceived as the default will be chosen more often (Weber *et al.*, 2007; Lempert *et al.*, 2015; Sawicki and Bialek, 2016).

Second, every task is limited by the range of choices presented, such that only a select range of discount rates is captured. Ceiling and floor effects are possible if people choose either all delayed or all immediate rewards. In these boundary cases, a discount rate cannot be precisely estimated.

Third, delay discounting can be influenced by how much someone values the amounts of money presented (Andreoni and Sprenger, 2012). Larger amounts tend to be discounted less steeply (a phenomenon known as the 'magnitude effect'; Green *et al.*, 1997). For example, people are more likely to wait for \$100 in 2 weeks than \$20 in 2 weeks, even if the immediate rewards offered are proportional to the delayed rewards offered. In comparisons across countries, currency conversions and purchasing power differences need to be considered when selecting monetary amounts. Even with the same amounts of money, people differ in how much *subjective* value they confer upon a given amount, and this influences discounting (Figner *et al.*, 2010). This can be controlled for partly by matching participants with regard to socioeconomic status or income.

Certain individual difference variables affect delay discounting, suggesting the need for matching groups or controlling outcomes statistically. People with lower incomes tend to discount money more steeply than people with higher incomes (Lawrance, 1991; Green *et al.*, 1996; Tanaka *et al.*, 2010; Jachimowicz *et al.*, 2017), making this an important covariate. There are multiple possible explanations for this effect, including financial need (i.e. if you need money to pay a bill by the end of the week, you are more likely to take the immediate reward), distrust that future rewards will materialize (Jachimowicz *et al.*, 2017), and scarcity leading to a focus on the present (Shah *et al.*, 2012; Bickel *et al.*, 2016). There

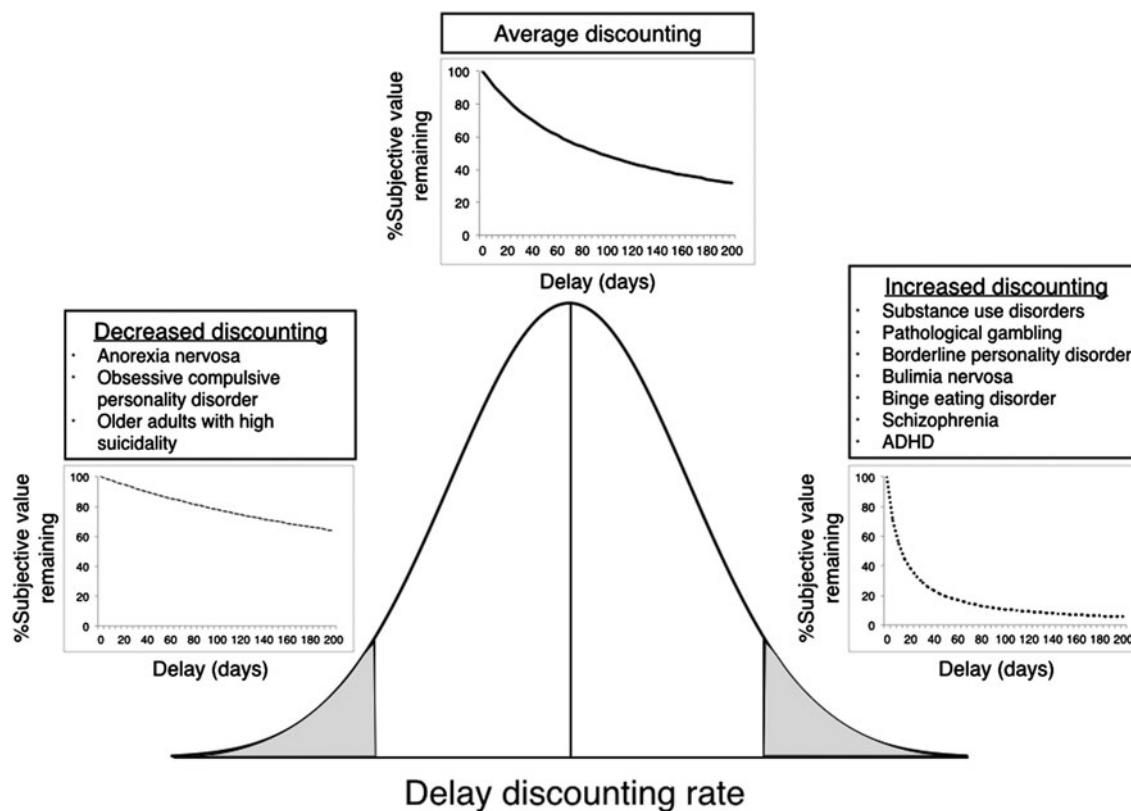


Fig. 2. Hyperbolic delay discounting rates lie on a spectrum. Most individuals discount delayed rewards to some degree, but psychopathology has been associated with discounting delayed rewards too little (left) or too much (right).

is little evidence that gender influences discounting (Silverman, 2003; de Wit *et al.*, 2007). Null or inconsistent results have been found for age among adults (Read and Read, 2004; de Wit *et al.*, 2007; Burrow and Spreng, 2016). Race has been found in some studies (de Wit *et al.*, 2007; Kim *et al.*, 2012) but not in others to affect discounting, but these differences could be due to other factors (e.g. income or education) that are correlated with discounting. In general, cognitive variables such as IQ (de Wit *et al.*, 2007), education (Jaroni *et al.*, 2004) and working memory capacity (Szuhany *et al.*, 2018) are moderately correlated with delay discounting. Personality traits among healthy individuals, however, have not been reliably linked with delay discounting (Burrow and Spreng, 2016; Van Dijk *et al.*, 2017).

Finally, the reward itself may impact delay discounting. For example, discount rates for consumable goods, such as food, are higher (steeper) on average (Tsukayama and Duckworth, 2010). This may partially explain why discount rates tend to be steeper in non-human animals, where food rewards are used. There is ongoing debate about whether all types of rewards (e.g. primary *v.* secondary reinforcers) are represented in the same way in the brain.

Neural mechanisms underlying delay discounting

Neuroimaging and lesion studies

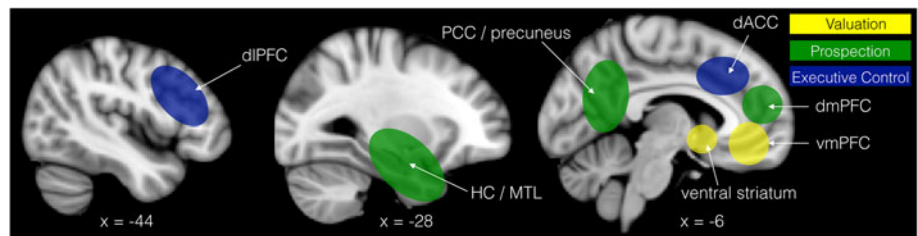
RDoC seeks to link behavioral dimensions with their neural underpinnings. Therefore, one strength of delay discounting is the literature demonstrating the neural substrates engaged during this decision-making process (Peters and Büchel, 2011). These include what have been named the *valuation*, *prospction*, and *executive control* neural systems (Fig. 3). To date, delay

discounting tasks in humans have primarily probed the valuation network. However, individual determination of subjective value involves integration of information, and therefore interaction between these networks.

The *valuation network*, also known as the *reward processing network*, includes the ventromedial prefrontal cortex (vmPFC), ventral striatum (VS), and (to a lesser degree) posterior cingulate cortex. Among its many functions, this network has been shown in numerous functional magnetic resonance imaging (MRI) studies to encode the subjective value of both immediate and delayed rewards (Kable and Glimcher, 2007, 2010; Peters and Büchel, 2010; Lempert *et al.*, 2017). The extent to which an individual values *any* option has been shown to correlate strongly with blood-oxygen-level-dependent (BOLD) signal in VS and vmPFC (Bartra *et al.*, 2013). The vmPFC is particularly relevant for integrating across different attributes when comparing options (Levy and Glimcher, 2012), including how much to delay reward, since both amount and delay have to be considered. Disturbances in vmPFC structure and function impact choice, including delay discounting (Camille *et al.*, 2011; Peters and D'Esposito, 2016), and differences in activity in this network during choice may predict differences in decision-making between groups (Halfmann *et al.*, 2015).

Prospction is the process of imagining possible future episodes (Addis *et al.*, 2009). The *prospction network* includes the medial temporal lobe (MTL), precuneus, and dorsomedial prefrontal cortex. This network is active both when individuals recall episodic memories and imagine future outcomes (Schacter *et al.*, 2007). Since delay discounting decisions involve imagining future outcomes (e.g. receiving rewards after weeks or months), this network plays an important role, and its activation is associated with

Fig. 3. Neural mechanisms of delay discounting. At least three neural systems play a role in choices between smaller/sooner and larger/later rewards. The valuation system, comprising the ventral striatum and ventromedial prefrontal cortex, assigns value to immediate and delayed rewards, based on interactions with the prospection and executive control systems. Regions involved in prospection (posterior cingulate, precuneus, dorsomedial prefrontal cortex, medial temporal lobe) allow the individual to imagine and simulate future outcomes prior to selecting them. Executive control regions (dorsal anterior cingulate cortex, dorsolateral prefrontal cortex) are involved more when choices are difficult, and typically bias choice toward the delayed reward.



reducing discount rate. Cueing participants to engage in prospection prior to making choices reduces delay discounting (Peters and Büchel, 2010; Palombo *et al.*, 2015) and has been associated with increased functional connectivity between prospection regions and valuation regions (Peters and Büchel, 2010; Benoit *et al.*, 2011). Because prospection is involved specifically when making choices about the *future*, individual differences in the integrity of this network are likely to mediate individual differences in discount rate. In structural MRI studies, for example, MTL gray matter volume (Owens *et al.*, 2017), hippocampal and parahippocampal white matter density (Yu, 2012), and white matter density in frontal and temporal white matter tracts (Olson *et al.*, 2009) significantly predicted delay discounting rates across individuals. In sum, the prospection network, through its role in simulating future outcomes, likely contributes to preference for delaying reward.

The *executive control network* includes the dorsolateral prefrontal cortex (dlPFC) and dorsal anterior cingulate cortex (dACC). This network underlies complex reasoning and working memory abilities that are likely necessary to optimally integrate costs and benefits (Wesley and Bickel, 2014) and are therefore relevant for many decision tasks. During delay discounting, choice of the delayed reward is associated with BOLD signal in the dlPFC (McClure *et al.*, 2004; Turner *et al.*, 2018), particularly when choices are difficult (Jimura *et al.*, 2018). Functional connectivity between dlPFC and vmPFC is also increased during choices of delayed reward (Hare *et al.*, 2014). Additionally, differences in structural connectivity to dlPFC across individuals are significantly associated with discount rates (van den Bos *et al.*, 2014). Finally, transcranial magnetic stimulation or transcranial direct current stimulation of dlPFC can alter delay discounting, though studies differ in the directionality and laterality of these effects (Figner *et al.*, 2010; Shen *et al.*, 2016). The role of the dACC in decision-making is debated (Kolling *et al.*, 2016; Shenhav *et al.*, 2016), but it is thought to interact with the dlPFC to instigate behavioral change. In populations marked by cognitive deficits, it may be that a compromised executive control network leads to steeper delay discounting (Avsar *et al.*, 2013).

In summary, several neural systems are involved in delay discounting. Altered delay discounting may emerge if any of these systems is impaired. Studying how valuation, prospection, and executive control networks work together in choice behavior in health and illness may help to elucidate the neural underpinnings of psychopathology and point to new treatment targets. As computational approaches advance, it will be increasingly possible to examine how these networks interact to influence behavior (Maia *et al.*, 2017).

Pharmacological studies

The role of neurotransmitters in delay discounting is less well developed than the neural systems, yet these findings have relevance for psychiatry and the potential development of pharmacologic treatments. The delay discounting literature has focused predominantly on serotonin and dopamine (Cools *et al.*, 2011). Serotonin has been proposed to promote patience (Doya, 2002; Cools *et al.*, 2011): activation of serotonin neurons has been shown to decrease discounting (Miyazaki *et al.*, 2011) and serotonin depletion increases sensitivity to delays in rats (Mobini *et al.*, 2000) and humans (Schweighofer *et al.*, 2008).

The role of dopamine is less straightforward. Dopaminergic medications can increase impulsivity in humans (Pine *et al.*, 2010) and rodents (Logue *et al.*, 1992), but null and opposite (de Wit *et al.*, 2002) results have also been reported. In Parkinson's disease, which selectively damages dopamine neurons, one study found that patients on dopaminergic medication showed *decreased* discounting compared with patients off medication and healthy controls (Foerde *et al.*, 2016). It may be that dopamine's role in delay discounting is secondary to its role in motivation and reward processing more generally. Furthermore, serotonin and dopamine interact (Winstanley *et al.*, 2003), and psychiatric medications can influence both. Neuroscience methods that specifically target dopamine or serotonin neurons (e.g. optogenetics) may shed light on this issue.

Psychopathology and delay discounting

Most psychiatric research on delay discounting has focused on linking increased delay discounting (or preference for immediate reward) to disorders associated with impulsivity. Emerging literature suggests that decreased delay discounting may also be associated with psychopathology.

Increased delay discounting

Discount rate measures an aspect of impulsivity (Reynolds *et al.*, 2006) – specifically, a disregard for future outcomes. Thus, delay discounting has been extensively studied in substance use disorders (reviewed in Amlung *et al.*, 2017) and has been proposed as a candidate behavioral marker for substance use disorders (Bickel *et al.*, 2012). Compared with healthy populations, significantly increased discounting has been found among individuals with alcohol (Petry, 2001), nicotine (Bickel *et al.*, 2008), opioid (Kirby *et al.*, 1999), cocaine (Heil *et al.*, 2006), and methamphetamine (Monterosso *et al.*, 2007) use disorders. Increased discount rates have been related to the severity of substance dependence

(Amlung *et al.*, 2017), and lower discount rates with better prognosis in treatment (Washio *et al.*, 2011). Increased delay discounting may represent a vulnerability for the development of a substance use disorder (Audrain-McGovern *et al.*, 2009). Alternatively, chronic exposure to drugs of abuse may alter the brain in ways that increase delay discounting and maintain substance use (Volkow and Morales, 2015). Data suggest that both occur: increased delay discounting increases the risk for developing substance use disorders, and drug use further exacerbates steep delay discounting (Lamb *et al.*, 2016).

Steep discount rates have also been found in other disorders associated with impulsivity, including pathological gambling (Miedl *et al.*, 2015), attention-deficit/hyperactivity disorder (Jackson and MacKillop, 2016), mania (Mason *et al.*, 2012), borderline personality disorder (Barker *et al.*, 2015), bulimia nervosa (McClelland *et al.*, 2016), and binge eating disorder (McClelland *et al.*, 2016). Increased delay discounting has also been consistently found in individuals with schizophrenia (Heerey *et al.*, 2011; Yu *et al.*, 2017), which may be linked to executive function deficits (Heerey *et al.*, 2011) or to motivational aspects of the disorder (Yu *et al.*, 2017).

Decreased delay discounting

Delaying reward was presumed to represent healthy behavior. However, emerging data suggest that some types of psychopathology are linked to discounting rates that are lower than those of healthy individuals.

Individuals with anorexia nervosa (AN) consume inadequate amounts of food, seemingly foregoing the immediate reward of food consumption in favor of a potential future reward (further weight loss). Four studies have shown that, when acutely ill, adults with AN show decreased discounting of monetary rewards compared with healthy controls; that is, they choose delayed rewards in a higher proportion than healthy individuals (Steinglass *et al.*, 2012, 2017; Decker *et al.*, 2015; Steward *et al.*, 2017). Some evidence suggests that low discount rates in AN may be a characteristic of acute illness, rather than of vulnerability: the only longitudinal study of AN found that discount rates normalized with weight restoration (Decker *et al.*, 2015) and one cross-sectional study found no difference between healthy controls and individuals remitted from AN (Wierenga *et al.*, 2015).

On the other hand, three studies of acutely ill individuals with AN found no significant differences in delay discounting between AN and healthy controls (Ritschel *et al.*, 2015; King *et al.*, 2016; Bartholdy *et al.*, 2017). Differences in findings between studies may reflect differences in the paradigms or outcome measures used. At the same time, differences between AN and healthy controls across most studies are in the same direction, suggesting that decreased discounting may be a small effect that can only be captured in larger sample sizes.

Individuals with obsessive-compulsive personality disorder (OCPD) show personality traits of perfectionism and rigidity, as well as ritualized behaviors (Pinto *et al.*, 2014), without the intrusive obsessions seen in obsessive-compulsive disorder (OCD). Four studies have found that individuals with OCD do not differ from healthy individuals in delay discounting (Vloet *et al.*, 2010; Pinto *et al.*, 2014; Carlisi *et al.*, 2017; Steinglass *et al.*, 2017), while the only study that also included individuals with OCPD found significantly decreased delay discounting in that group (Pinto *et al.*, 2014).

Next steps

Taking a dimensional approach

Most studies assessing delay discounting in psychiatric disorders have compared diagnostic groups. An alternative approach would be to examine traits correlated with delay discounting transdiagnostically. For example, whereas AN is defined by abnormalities in eating behavior, it shares clinical features (e.g. avoidance, preoccupations) with anxiety disorders such as OCD and social anxiety disorder (SAD). One study that examined discounting in these three disorders (AN, OCD, SAD) and in healthy individuals found that those with higher trait anxiety tended to choose more delayed rewards (Steinglass *et al.*, 2017). These findings suggest that some traits (such as impulsivity) may be correlated with higher delay discounting and other traits (such as anxiety) may be correlated with lower discounting.

Taking a dimensional approach might also clarify why delay discounting findings are mixed in some disorders (e.g. autism spectrum disorders and major depressive disorder; Dombrovski *et al.*, 2011; Carlisi *et al.*, 2017). Discounting in depression, in particular, merits further study, as subtypes of depression or associated features (such as suicidality) may be associated with different decision tendencies. For example, one study (Dombrovski *et al.*, 2011) showed that only those depressed older (aged 60+) adults with high-lethality suicide attempts showed *decreased* delay discounting compared with healthy controls. If replicated, this suggests that delay discounting could be used as a biomarker for serious clinical outcomes and may better match to biology than the categorical diagnosis of major depression.

Elucidating dimensions of impulsivity

Impulsivity is a multidimensional construct (Duckworth and Kern, 2011). Delay discounting is one dimension that captures how people trade off reward amounts and delays. However, the extent to which delay discounting captures control or regulatory processes is debated, since not all discounting decisions involve self-control. Just as a person who is not addicted to cigarettes does not need to exert control to avoid smoking, a person with a low discounting rate may not need to exert self-control to choose a delayed reward. Thus, discounting tasks could be complemented by other measures (e.g. neuropsychological tasks measuring behavioral inhibition) in order to gain a more sophisticated understanding of impulsive behavior.

Risk-seeking behavior has also been conflated with delay discounting (i.e. short-sighted decisions are often termed 'risky' decisions). Whereas someone's attitude toward risk can influence their discount rate (Lopez-Guzman *et al.*, 2018)², the two are distinct. Thus, assessing risk attitudes (e.g. with a gambling task) can clarify whether differences in decision-making among individuals are best accounted for by differences in discount rate or by differences in risk preference. Teasing apart these two influences on decision-making may be particularly important in psychiatric populations and lead not only to better models of maladaptive behavior but also to more precise interventions.

Manipulating delay discounting

Delay discounting is a useful construct for studying reward valuation partly because it is relatively stable over time. As a result, some consider it an endophenotype for substance use disorders (Bickel, 2015). However, discount rates are also sensitive to

within-subject change. Indeed, certain laboratory manipulations in both healthy individuals and psychiatric populations can shift discount rates in predictable ways (MacKillop *et al.*, 2011; Lempert and Phelps, 2016). That these choices are malleable holds promise for the development of interventions in psychopathology.

Increasing either awareness of or subjective valuation of future outcomes can decrease discount rate (Bartels and Urminsky, 2015). For example, when choices are reframed so that they include 'explicit zeros' (e.g. \$10 today and \$0 in 2 weeks *v.* \$0 today and \$20 in 2 weeks), people tend to choose more delayed rewards (Radu *et al.*, 2011). This simple manipulation draws attention to the negative future consequences of taking the immediate reward. Including an instruction that participants should consider such opportunity costs also decreases discounting (Senecal *et al.*, 2012).

In addition, several studies have shown that thinking about positive future events before or during choice increases the likelihood of choosing delayed rewards (Peters and Büchel, 2010; Benoit *et al.*, 2011; Palombo *et al.*, 2015). Future thinking can also be encouraged through more subtle means, by framing the delayed reward as the 'default' option. That is, when individuals are asked if they would prefer to receive an immediate reward now, or to receive a larger reward later, they tend to choose the immediate reward; if they are first given the option of the future reward and then told that they could 'accelerate' its delivery at a cost, they are more likely to stick with the later reward (Loewenstein, 1988; Weber *et al.*, 2007). This re-framing encourages people to think of reasons to keep the delayed reward first (Weber *et al.*, 2007), and reasons that are thought of first tend to have greater weight.

Because delay discounting can be manipulated in the laboratory in healthy humans (Lempert and Phelps, 2016), some researchers are starting to use delay discounting as a target for treatment development in clinical populations. For example, cueing individuals to engage in episodic future thinking has been shown to decrease discount rate and cigarette self-administration in smokers (Stein *et al.*, 2016), as well as alcohol demand in alcohol-dependent individuals (Snider *et al.*, 2016). This suggests that delay discounting may be a promising target for treatment development. Since most laboratory manipulations identified so far have focused on reducing discounting, more research is needed into how to *increase* delay discounting as well for those who delay reward to a pathological extent (e.g. AN or OCPD).

Conclusions

NIMH is invested in the RDoC approach, recognizing that its utility will depend on appropriate identification and assessment of behavioral domains. As reviewed above, delay discounting tasks have been extensively used in healthy individuals. As a result, there are now several standard tasks that produce reproducible behavioral results and have a known underlying neurobiology. These tasks are useful for studying the constructs of reward valuation, as well as executive function and prospection. In psychiatric populations, extremes in discounting at both ends of the continuum – inability to wait and waiting too long – are associated with poor mental health. Emerging data indicate that discount rates measured in the laboratory can be manipulated, suggesting opportunities for treatments with a defined target to engage.

Despite its virtues, this paradigm is not without its limitations. First, the extent to which neural circuits involved in discounting

are specific to this process, or general to all value-based decision tasks is not established. Therefore, when studying delay discounting, it is important to assess the behavior on other tasks that are different in their future-directedness yet similar in other respects (e.g. reward motivation, difficulty). It may be that valuation and executive control networks are more general to value-based decisions, whereas the prospection network is more specific to decisions about the future. Second, when comparing human and animal studies, it is important to consider the ecological relevance of these paradigms to the species being studied (Hayden, 2015). Finally, task design and certain demographic variables may influence choices in these tasks, so task parameters and covariates should be selected carefully.

Despite these caveats, delay discounting is a paradigm that can assess behavioral dimensions of psychopathology to determine underlying neurobiology. The question now is whether changing this target can yield changes in clinical outcomes. If so, then delay discounting may deliver on the promise of RDoC.

Notes

¹ Note that the smaller, sooner reward does not have to be immediate, but since it usually is, 'immediate' rather than 'smaller, sooner' will be used throughout this review.

² According to expected utility theory in economics, risk attitudes reflect the relationship between an objective amount of money and its subjective value, which then affects discount rate (see *Task considerations* section). If risk attitudes are not accounted for, discount rates might be substantially underestimated or overestimated (Lopez-Guzman *et al.* 2018).

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