A meta-analysis of neural systems underlying delay discounting: implications for transdiagnostic research

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ABSTRACT

Delay discounting is a promising paradigm for transdiagnostic research because both excessive and insufficient tendency to discount future rewards have been reported across diagnoses. Because delay discounting involves multiple neurocognitive functions, researchers have used many strategies to characterize brain activity during delay discounting. However, which of these analytic approaches yield truly robust and replicable findings remains unclear. To this end, we conducted a meta-analysis of 78 fMRI studies of delay discounting, testing which statistical contrasts yield reliable effects across studies. Despite being a widely used analytic approach, comparing impulsive and patient choices did not yield reliable effects across studies. Instead, subjective value reliably engaged the valuation network across studies. We also found that task versus baseline and choice difficulty contrasts reliably engaged regions in the frontoparietal and salience networks. We strongly recommend that future neuroimaging studies of delay discounting use these analytic approaches shown to reliably identify specific networks. In addition, we provide all cluster maps from our meta-analysis for use as *a priori* regions of interest for future experiments.

In 2009, the National Institute of Mental Health launched the Research Domain Criteria (RDoC) initiative to identify common biological mechanisms for understanding mental disorders[1]. After over a decade of research, reliability remains a central challenge for identifying biobehavioral measures that provide novel insights into the core neurocognitive features exhibited across disorders[2]. Delay discounting, or the tendency to devalue rewards that are distant in the future, is a promising candidate paradigm for identifying shared reward-related changes across diagnostic populations[3]. Currently categorized as a subconstruct of reward valuation under positive valence systems, delay discounting has been implicated in a wide range of psychiatric disorders, as both excessive discounting (e.g., substance use disorder, depression, schizophrenia, binge eating disorder) and insufficient discounting (e.g., anorexia) can be maladaptive[4,5]. In addition to this dimensional feature that cuts across diagnoses, delay discounting has been shown to be a strong prognostic indicator of treatment response and relapse[6,7], and can be modified using pharmacological[8–10], neural[11], and behavioral[12,13] interventions, which demonstrates its potential for clinical utility. Coupled with its high test-retest reliability[14] and evidence for genetic basis[15,16], delay discounting indeed has many appealing features as a transdiagnostic construct.

In addition to its reliability as a behavioral construct, delay discounting has been shown in many studies to engage neural networks underlying reward valuation and task engagement, such as the valuation, frontoparietal, and salience networks[17,18]. Furthermore, numerous studies suggest that brain activity during delay discounting varies by psychiatric diagnoses and symptoms[19]. However, researchers have used a wide variety of analytic strategies (i.e., statistical contrasts) to characterize brain activity during delay discounting, and which of these approaches yield truly robust and replicable findings still remains unclear. Identifying the neural effects that

are reliable and reproducible across delay discounting experiments is an important foundation for future transdiagnostic neuroimaging research. Here we used meta-analysis to systematically evaluate the reliability of existing analytic approaches.

One commonly used analytic approach is to characterize neural activity based on choice behavior. This is often accomplished by comparing brain activity when one chooses the smaller sooner reward (SSR) versus the larger later reward (LLR). This approach is motivated by a prominent hypothesis for neural mechanisms underlying maladaptive decision-making called the Competing Neurobehavioral Decision Systems (CNDS) model[20]. The CNDS hypothesis draws upon one of the first neuroimaging studies of delay discounting, which proposed two separate neural systems in the healthy brain: one system, composed of the striatum, vmPFC, and PCC, biases decisions toward the SSR; whereas another competing system, composed of the frontoparietal and salience networks, biases decisions toward the LLR[18]. The CNDS hypothesis posits that impulsive choices are driven by bottom-up reward signals in response to immediate rewards, whereas patient choices are driven by top-down inhibitory control signals that can override this sensitivity. Taken together, both excessive and insufficient discounting can arise when competition between the bottom-up reward signals and top-down inhibitory signals is not balanced. This framework has become instrumental for subsequent clinical neuroscience research, as numerous studies have contrasted SSR and LLR choices to try and identify the neural systems underlying impulsivity and self-regulation features of various psychiatric disorders[21–27].

Another commonly used analytic approach in the delay discounting literature is to characterize brain activity using latent constructs that guide choice behavior, such as subjective value and choice difficulty. In practice, this approach identifies brain activity that is

parametrically correlated with a continuous variable that is either presented (e.g., dollar amount of reward, number of days to wait) or estimated based on choice behavior (e.g., subjective value, choice difficulty). This approach is grounded in another early neuroimaging study of delay discounting, which proposed that the striatum, vmPFC, and PCC, formed a unitary valuation system for both immediate and delayed rewards[17,28]. Later work proposed that the frontoparietal and salience networks engaged in value accumulation or value comparison processes towards making a choice[29,30]. This account is consistent with previous meta-analytic work that found that the ventral striatum and vmPFC encode positive effects of subjective value across multiple reward domains[31]. On this account, disruptions in value signals in either direction can be maladaptive, and reduced value response has been reported across disorders characterized by anhedonia or reduced motivation[32,33], whereas pathological gambling has been linked to exaggerated value signals[34]. However, although contrasts targeting value-related brain activity have been widely used in decision neuroscience, relatively fewer clinical neuroimaging studies of delay discounting have taken this approach[34–36].

It is important to note that both analytic approaches converge on which brain regions are involved during delay discounting: the valuation (e.g., striatum, vmPFC, PCC), frontoparietal and salience networks. However, what differentiates these approaches is how to best identify brain activity in these regions. The former uses binary comparisons between impulsive and patient choices, whereas the latter uses correlations with continuous attributes of choice options, such as subjective value, amount, delay, and choice difficulty.

In this study, we performed a series of meta-analyses of fMRI findings to identify which analytic approaches during delay discounting paradigms yield reliable findings across studies, in the face of variability in study designs and the presence of psychiatric diagnoses. For each of

these analytic approaches, we conducted a multi-level kernel density analysis (MKDA) to quantify the proportion of studies that report consistent effects in a given anatomical location. Our primary aim to assess the reliability of the two most widely used analytic approaches, contrasting impulsive and patient choices and correlating activity with objective (magnitude, delay) or latent model-derived (subjective value) variables. For completeness, though, we also evaluate the reliability of other commonly reported contrasts, including task versus control, hard versus easy choices, and choices involving an immediate reward versus those between only delayed rewards.

To our knowledge, there is one published meta-analysis on delay discounting fMRI that aimed to systematically compare these contrasts[37]. However, the sample sizes in that paper ranged from 3 to 13 experiments, which does not meet the currently recommended guidelines for meta-analytic sample sizes[38]. Our meta-analyses include significantly more studies, yielding robust samples sizes (9 to 25 experiments per contrast, including >20 for the most critical contrasts), and also permitting the examination of more contrasts (nine versus six). Importantly, with these methodological improvements, we come to a significantly different conclusion. Schuller et al. (2019) found that all analytic contrasts yielded significant clusters, suggesting equal adequacy of both the choice-based and latent construct-based approaches. On the contrary, with more than three times the sample size, we conclude that there are no reliable effects of choice-based contrasts (both LLR and SSR). Given that choice-based contrasts are one of the most commonly used analytic approaches in existing studies, especially in experiments that focus on clinical populations, it is our hope that these more robust findings will help inform analytic decisions for future studies.

Methods

Search strategy. Preregistration of the present meta-analysis is available on PROSPERO under protocol CRD42020150691. We conducted a systematic literature search on PubMed and PsycInfo (final search on March 2, 2023). Based on previous meta-analyses of delay discounting[4,39], we used the following search terms, which yielded 392 unique results:

> ((Delay discounting) OR (Temporal discounting) OR (Delay of gratification) OR (Intertemporal choice) OR (time discounting)) AND (fMRI OR functional magnetic resonance imaging)

We also reviewed the reference lists of previously published review articles and the results of searches for frequently occurring authors (i.e., 10 or more unique articles in the initial search results), which identified 2 additional articles.

Study selection. All articles identified through the above search strategy were evaluated according to the preregistered inclusion/exclusion criteria. For inclusion, the study had to meet the following criteria: (1) English or an English translation is available; (2) human participants with no brain lesions; (3) fMRI data collected while the participants were completing a delay discounting task in the scanner; (4) the task included a delay of at least 1 day and used monetary rewards, regardless of payment contingency; (5) conducted a parametric or categorical contrast analysis across the whole brain; (6) spatial coordinates are available in Talairach or Montreal Neurological Institute (MNI) space, either reported in the manuscript or provided by the corresponding author upon request; and (7) diagnosis of psychiatric disorders can be present. Although existing meta-analyses of self-regulatory decision-making tend to focus on healthy adults or group comparisons[37,40,41], inclusion of individuals with psychiatric disorders achieves two goals. First, it allows greater variability of the clinical or cognitive constructs (e.g., impulsivity, self-regulation, valuation, conflict monitoring, and action planning) that may be

related to delay discounting. Second, given our ultimate aim is to identify specific neural systems engaged during delay discounting that may be related to transdiagnostic neurobehavioral processes, inclusion of psychopathology without regard to specific diagnoses seemed critical. We excluded studies that (1) were not a primary source; (2) used non-monetary rewards; (3) had pharmacological manipulation unless they report effects in the placebo group; (4) resting-state or volumetric analyses; (5) connectivity and multi-voxel pattern analyses; (6) overlapping samples with another included study. In the event of overlapping samples, we included the largest sample. To ensure inclusion criteria were standard and to limit bias, all studies were reviewed using Rayyan (https://rayyan.qcri.org) by at least two independent reviewers (MSK and JWK, MSK and BB, or all three). The inter-rater reliability was high ($\kappa = 0.86$; 93.9% agreement) and all disagreements were discussed and resolved by a consensus decision. A total of 78 studies (1366 foci; 3316 participants) were included in the quantitative meta-analysis (see Figure 1 for the PRISMA flow diagram; Table 1 for the list of studies and contrasts).

Coding contrasts. Following study selection, we coded the studies into the following contrast categories: general task-related activity (*Task*), choices involving an immediate reward (*Immediacy*), choosing the smaller-sooner reward (*SSR*), choosing the larger-later reward (*LLR*), difficult decisions (*Hard*), easy decisions (*Easy*), subjective value (*SV*), objective amount (*Magnitude*), and objective delay (*Delay*). For *Task*, we included positive effects of comparing the delay discounting task to a fixation or implicit baseline or a control task (e.g., choose left/right, choose larger). We also categorized comparing a subset of the task to baseline (e.g., Hard > baseline) as *Task*. In cases where more than one subset was available (e.g., Hard > baseline and Easy > baseline), we included the contrast that would theoretically elicit a larger effect (i.e., Hard > baseline). For *Immediacy*, we included comparing trials involving an

immediate reward to either all trials or trials involving delayed options only. *SSR* included direct comparisons between the two choices (positive effects of SSR > LLR or negative effects of LLR > SSR) and *LLR* included the converse. As described earlier, trials in which the two options are closer in subjective value or near the indifference point are considered to be difficult, and studies categorize trials as hard or easy based on the value distance or distance from the indifference point. Therefore, *Hard* included direct comparisons between hard and easy trials (positive effects of Hard > Easy or negative effects of Easy > Hard) whereas *Easy* included the opposite effects. We also coded negative correlations with unsigned difference in subjective value between the two options as *Hard* and positive correlations as *Easy*. For *SV*, we included brain regions showing positive correlation with the discounted value of the delayed reward. Although SV is frequently calculated using hyperbolic discounting[42], we deferred to the judgment of the original authors and reviewers and included all discounted value regressors regardless of how SV was calculated. For *Magnitude*, we included positive correlations with the objective amount of either the LLR or SSR, although all studies in our meta-analytic sample examined the amount of the delayed option except for one study[43], which examined varying amounts of the immediate option while keeping the amount of delayed reward constant throughout the task. For *Delay*, we included brain regions showing reduced activations as the delay increases (i.e., the negative effects of delay or positive effects of inverse delay). For studies that reported the peaks by comparison groups (e.g., young and older adults, healthy and psychopathology), we included them as separate studies rather than selecting a single group. After coding, there were 29 studies (293 foci) in *Task*, 9 (84 foci) in *Immediacy*, 14 (88 foci) in *SSR*, 23 (177 foci) in *LLR*, 17 (140 foci) in *Hard*, 13 (107 foci) in *Easy*, 23 (269 foci) in *SV*, 10 (92 foci) in *Magnitude* and 9 (116 foci) in *Delay*.

Multilevel kernel density analysis. Multilevel kernel density analysis (MKDA) is a widely used technique for coordinate-based meta-analysis to quantify the proportion of studies that report activation foci within a given radius, with the null hypothesis that foci are located randomly throughout the brain[31,44]. Unlike traditional meta-analyses that examine the magnitude of effect sizes, here we aimed to identify anatomical locations where an effect is observed consistently across studies that used the same contrast. A previous meta-analysis from our group describes in detail the rationale for refining the MKDA procedure used in the present study[31]. We first converted all peak coordinates from each study into the MNI space using mni2tal to create a binary indicator map (IM)—for interpretability, we assigned 100 for voxels within 10mm of the peaks and 0 for others. We then averaged these maps across studies, resulting in the mean IM ranging from 0-100 that can be interpreted as the percentage of studies reporting a peak within a 10mm radius. For significance testing, we implemented permutation testing in Matlab by simulating a null-hypothesis that foci are randomly distributed, while maintaining the number of studies and number of foci per study. We also applied a cluster-forming threshold for each contrast to improve sensitivity. For each study, we first accounted for the probability of gray matter, where there is a higher probability of observing a positive IM value, by calculating the proportion of voxels with a positive IM value in the top quintile, as indicated by the ICBM tissue probability map (www.loni.ucla.edu/ICBM). These proportions were then treated as independent probabilities to derive the mean IM value that would be exceeded with a probability of less than 0.01 by chance alone. We applied this threshold to the results of each random permutation and recorded the largest cluster mass (sum of all IM values in a given cluster) in the null distribution. We also applied the same threshold to the real data, and the resulting clusters were assigned corrected p-values based on the frequency of equal or larger clusters in the null distribution. All

reported results are based on 200 iterations of permutations (one of which was the observed data) and a threshold of corrected p = 0.05 (one-tailed).

Results

Individual contrasts. We first examined contrasts expected to identify activity in the frontoparietal and salience networks. We found significant clusters for both *Task* and *Hard* contrasts in these regions (Figure 2 and Table 2). For general task-related activations (*Task*), we found significant clusters in bilateral dorsomedial prefrontal cortex (dmPFC), bilateral insula, left middle frontal gyrus, and right frontal pole. We also observed a cluster in bilateral occipital cortex and right occipital pole. For choice difficulty (*Hard*), significant clusters were found in bilateral dmPFC and right insula. For negative effects of difficulty (*Easy*), we found a significant cluster in the left supramarginal gyrus.

We then examined contrasts expected to identify activity in the valuation network (Figure 3), including *SV*, *Magnitude*, *Delay*, and *Immediacy*. The highest meta-analytic statistics (i.e., percentage of studies reporting a peak within 10mm from a given voxel) were found in the striatum for *SV* (66.7%). Additionally, we observed significant clusters for *SV* in the vmPFC, PCC, and middle temporal gyrus. *Magnitude* foci were also clustered in the striatum. For negative effects of *Delay*, significant clustering was found in the right frontal pole and IFG/MFG. We also found significant clusters for *Immediacy* in the left striatum and left vmPFC. Taken together, these results suggest that *SV*, *Magnitude*, and *Immediacy* contrasts all produce reliable activations in overlapping regions, namely the striatum and vmPFC.

Lastly, we examined contrasts between impulsive and future-oriented choices (Figure 4). As previously described, the CNDS framework predicts greater activations in the valuation

network when choosing the smaller-sooner reward (*SSR* > *LLR*) and greater frontoparietal and salience activations when choosing the larger-later reward (*LLR* > *SSR*). Contrary to these predictions, we only observed a small cluster in the left dmPFC for SSR. For LLR, we only found clusters in the left precentral gyrus and left occipital fusiform gyrus. Given the localization of the largest effect in motor cortex, we examined the studies that contributed to this cluster for motor confounds and found that majority of studies that contributed to this cluster instructed participants to choose the LLR using their right middle finger (and SSR with the right index finger)[22,27,45–47]. Based on these findings, we conclude that choice contrasts do not reliably identify the predicted neural networks across experiments.

Discussion

In this paper, we report a series of meta-analyses examining neural effects revealed by commonly used analytic approaches in fMRI studies of delay discounting. Specifically, we investigated the consistency of neural activations in the valuation and frontoparietal and salience networks. Despite its wide use, our results did not reveal reliable effects of choice (*LLR* or *SSR*) in either of these two networks. Instead, the most reliable clusters were found throughout the valuation network as a function of subjective value. Although the objective amount and presence of an immediate option engaged similar regions such as the striatum and vmPFC, we saw more widespread activations for subjective value than the other contrasts. Taken together, these results offer meta-analytic support for examining value-based contrasts rather than comparing choices. In other words, the hypothesis that there are distinct neural networks associated with impulsive or patient choices is not supported by our work.

This conclusion is further bolstered by considering the number of studies that reported null findings. Because MKDA estimates the location of effects rather than the size of effects, null findings are not included and there is no statistical penalty for null findings. Given this, it is worth nothing that 43% of studies (18 out of 42 studies) that used choice contrasts (*LLR*, *SSR*) reported no significant clusters for this contrast[26,28,47–62], whereas only 8% of studies (2 out of 25 studies) reported no significant effects of *SV*[63,64].

Since we began this work, a similar meta-analysis comparing a subset of these contrasts in healthy adults has been published[37]. Schuller et al. (2019) used a different meta-analytic method from ours, activation likelihood estimation (ALE)[65]. The sample sizes for each contrast ranged from 3 to 13 experiments, which is far below the currently recommended sample size of 17 experiments for ALE because this method is susceptible to excessive contribution from a single study[38]. Because we included studies across the lifespan and psychiatric diagnoses, we had a much larger meta-analytic sample (9-25 experiments per contrast). Despite the differences in both study selection and meta-analytic method (MKDA vs. ALE), our results were largely consistent with Schuller et al. (2019) for *SV*, *Magnitude*, *Immediacy*, *Hard*, and *Task* contrasts. However, contradicting Schuller et al. (2019), we did not find that distinct brain regions are engaged when making future-oriented or impulsive choices (*LLR* or *SSR*). Despite including more than three times the sample size for *LLR* (n=7 in Schuller et al. (2019), n=22 in the present study), we found no reliable effects of choice.

Despite our finding that choice-based contrasts do not produce reliable effects, this approach remains one of the most widely used in the literature. This is especially pronounced in clinical neuroimaging studies of delay discounting. Indeed, a large number of studies included in

our meta-analysis used delay discounting to investigate a wide range of psychiatric disorders and related symptoms – such as substance use[26,27,49,50,66,67], pathological gambling[21,34,35,45], obsessive compulsive disorder[22,68], ADHD[22], schizophrenia[69], major depressive disorder[70], obesity[54,71], prediabetics[72], and insomnia[58]. Among the studies with a psychiatric sample included in our analyses, *Task* and *SSR* were the most frequently used contrasts (n=8 for both), whereas only three studies[34–36] examined the *SV* contrast and only one study[70] examined the effects of *Magnitude* and *Delay*. This suggests that most existing clinical studies (and about half of basic decision neuroscience studies) have used an analytic strategy that has poor reliability. Therefore, we strongly recommend that future neuroimaging studies of delay discounting use value-based contrasts such as subjective value (to identify the valuation network) and choice difficulty (to identify the frontoparietal and salience networks).

There are several limitations to consider when interpreting our findings. First, although the contrasts related to our key findings (*LLR*, *SV*) had large sample sizes, some contrasts had relatively smaller sample sizes. Because MKDA simply calculates the proportion of studies that reported significant results near a given voxel, this is less of a concern than with ALE. Second, because we included studies with samples across the lifespan and clinical conditions, our results may differ from a study that exclusively focused on healthy adults. However, we determined that inclusion of these samples would be more in line with the goals of RDoC and relevant for future studies adopting this framework. Due to the emphasis on including psychiatric conditions, we coded studies that reported the effects of contrasts separated by comparison groups as independent studies, rather than selecting a single set of results to be included. Because these studies are not independent, our results may contain a bias for such studies that may not be present in other meta-analyses. Similarly, it is also important to note that most studies

contributed more than one contrast and that these contrasts tended to go hand in hand (e.g., *SSR* and *LLR*, *Magnitude* and *Delay*, *Hard* and *Easy*). Similarly, because authors tended to use the same contrasts across multiple studies, there were several studies from the same group in a given contrast. Moreover, our study exclusively focused on delay discounting of monetary rewards. Given the evidence supporting a common neural valuation system across commodities[73], we are cautiously optimistic that our results are generalizable to non-monetary rewards (e.g., food, drugs, social reward), but it is possible that there are commodity-specific activations that are not captured in our results.

The present meta-analysis offers several exciting directions for future research. As data archiving becomes more common in the field, future meta-analyses can move beyond the coordinate-based meta-analysis approach and conduct image-based meta-analyses[74]. Unlike coordinate-based methods, which only include peak voxels, image-based methods can include the whole statistical map, allowing researchers to detect consistent but relatively weaker effects and to calculate effect sizes, which is a limitation of coordinate-based methods that only examines effect locations. In order to make the image-based approach possible, it would be crucial for researchers to make whole-brain statistical maps publicly available in established archives, such as NeuroVault (https://neurovault.org/). Future meta-analytic work in delay discounting might also aim to examine the link between these neural effects and individual differences, such as discount rates, cognitive functioning, and psychopathology. Similarly, it would be important for future research to focus on how valuation, frontoparietal and salience networks jointly shape discounting. As more neuroimaging studies of delay discounting in clinical populations become available, it would be worthwhile to conduct a future meta-analysis, both within specific disorders and across psychopathology in line with the RDoC framework.

Similarly, future meta-analyses could also expand on our work and include paradigms that are tailored to clinical relevance (e.g., cigarettes for smokers[75], food for obese individuals[76,77]).

A practical goal of our work was to identify analytic strategies that are reliable and robust and provide recommendations for future research. Given the high reliability and interpretability of effects produced by the subjective value and choice difficulty contrasts, our recommendation for future work is to use these analytic approaches in the absence of specific hypotheses that call for a different approach. Another practical outcome of our work is the generation of cluster maps that can be used as *a priori* regions of interest for future experiments. This would be especially valuable for clinical neuroimaging studies of delay discounting that might be underpowered to detect modest effects using whole-brain approaches. All results will be made publicly available for this purpose.

Conclusion

We found evidence of consistent neural activations in the valuation and frontoparietal and salience networks during delay discounting. The valuation network was most reliability activated by subjective value, and was also reliably engaged by objective magnitude and reward immediacy. The frontoparietal and salience networks were reliably activated by task and choice difficulty contrasts. Despite its wide use, our results did not reveal reliable effects of choosing the larger later or smaller sooner options in either of these two networks. Therefore, we strongly recommend that future neuroimaging studies of delay discounting use analytic approaches shown to reliably identify specific networks (e.g., subjective value for the valuation network, choice difficulty for the frontoparietal and salience networks).

References

1. Insel TR. Translating Scientific Opportunity Into Public Health Impact: A Strategic Plan for Research on Mental Illness. *Arch Gen Psychiatry*. 2009;66(2):128-133. doi:10.1001/archgenpsychiatry.2008.540

2. MacNamara A, Phan KL. Psychobiological operationalization of RDoC constructs: Methodological and conceptual opportunities and challenges. *Psychophysiology*. 2016;53(3):406-409. doi:https://doi.org/10.1111/psyp.12587

3. Lempert KM, Steinglass JE, Pinto A, Kable JW. Can delay discounting deliver on the promise of RDoC? *Psychol Med*. 2019;49(2):190-199. doi:10.1017/S0033291718001770

4. Amlung M, Marsden E, Holshausen K, et al. Delay Discounting as a Transdiagnostic Process in Psychiatric Disorders: A Meta-analysis. *JAMA Psychiatry*. Published online August 28, 2019. doi:10.1001/jamapsychiatry.2019.2102

5. Amlung M, Vedelago L, Acker J, Balodis I, MacKillop J. Steep delay discounting and addictive behavior: a meta-analysis of continuous associations. *Addict Abingdon Engl*. 2017;112(1):51-62. doi:10.1111/add.13535

6. Washio Y, Higgins ST, Heil SH, et al. Delay discounting is associated with treatment response among cocaine-dependent outpatients. *Exp Clin Psychopharmacol*. 2011;19(3):243-248. doi:10.1037/a0023617

7. Sheffer CE, Christensen DR, Landes R, Carter LP, Jackson L, Bickel WK. Delay discounting rates: A strong prognostic indicator of smoking relapse. *Addict Behav*. 2014;39(11):1682-1689. doi:10.1016/j.addbeh.2014.04.019

8. Orsini CA, Mitchell MR, Heshmati SC, et al. Effects of nucleus accumbens amphetamine administration on performance in a delay discounting task. *Behav Brain Res*. 2017;321:130-136. doi:10.1016/j.bbr.2017.01.001

9. de Wit H, Mitchell SH. Drug effects on delay discounting. In: *Impulsivity: The Behavioral and Neurological Science of Discounting*. American Psychological Association; 2010:213-241. doi:10.1037/12069-008

10. Demoto Y, Okada G, Okamoto Y, et al. Neural and personality correlates of individual differences related to the effects of acute tryptophan depletion on future reward evaluation. *Neuropsychobiology*. 2012;65(2):55-64. doi:10.1159/000328990

11. Hecht D, Walsh V, Lavidor M. Bi-frontal direct current stimulation affects delay discounting choices. *Cogn Neurosci*. 2013;4(1):7-11. doi:10.1080/17588928.2011.638139

12. Ciaramelli E, Sellitto M, Tosarelli G, di Pellegrino G. Imagining Events Alternative to the Present Can Attenuate Delay Discounting. *Front Behav Neurosci*. 2019;13. doi:10.3389/fnbeh.2019.00269

13. Lempert KM, Speer ME, Delgado MR, Phelps EA. Positive autobiographical memory retrieval reduces temporal discounting. *Soc Cogn Affect Neurosci*. 2017;12(10):1584-1593. doi:10.1093/scan/nsx086

14. Enkavi AZ, Eisenberg IW, Bissett PG, et al. Large-scale analysis of test–retest reliabilities of self-regulation measures. *Proc Natl Acad Sci*. 2019;116(12):5472-5477. doi:10.1073/pnas.1818430116

15. Gray JC, Sanchez-Roige S, de Wit H, MacKillop J, Palmer AA. Genomic basis of delayed reward discounting. *Behav Processes*. 2019;162:157-161. doi:10.1016/j.beproc.2019.03.006

16. Anokhin AP, Grant JD, Mulligan RC, Heath AC. The Genetics of Impulsivity: Evidence for the Heritability of Delay Discounting. *Biol Psychiatry*. 2015;77(10):887-894. doi:10.1016/j.biopsych.2014.10.022

17. Kable JW, Glimcher PW. The neural correlates of subjective value during intertemporal choice. *Nat Neurosci*. 2007;10(12):1625-1633. doi:10.1038/nn2007

18. McClure SM, Laibson DI, Loewenstein G, Cohen JD. Separate Neural Systems Value Immediate and Delayed Monetary Rewards. *Science*. 2004;306(5695):503-507. doi:10.1126/science.1100907

19. Chen Z, Becker B, Qin P, et al. Neural networks during delay discounting as trans-disease marker: A meta-analytical review. *J Psychiatr Res*. 2021;139:62-70. doi:10.1016/j.jpsychires.2021.05.008

20. Bickel WK, Athamneh LN, Basso JC, et al. Excessive discounting of delayed reinforcers as a trans-disease process: Update on the state of the science. *Curr Opin Psychol*. 2019;30:59-64. doi:10.1016/j.copsyc.2019.01.005

21. Wang Y, Hu Y, Xu J, et al. Dysfunctional prefrontal function is associated with impulsivity in people with internet gaming disorder during a delay discounting task. *Front Psychiatry*. 2017;8:10. doi:10.3389/fpsyt.2017.00287

22. Norman LJ, Carlisi CO, Christakou A, et al. Neural dysfunction during temporal discounting in paediatric Attention- Deficit/Hyperactivity Disorder and Obsessive-Compulsive Disorder. *Psychiatry Res Neuroimaging*. 2017;269:97-105. doi:10.1016/j.pscychresns.2017.09.008

23. Murphy CM, Christakou A, Giampietro V, et al. Abnormal functional activation and maturation of ventromedial prefrontal cortex and cerebellum during temporal discounting

in autism spectrum disorder. *Hum Brain Mapp*. 2017;38(11):5343-5355. doi:10.1002/hbm.23718

24. Carlisi CO, Norman L, Murphy CM, et al. Comparison of neural substrates of temporal discounting between youth with autism spectrum disorder and with obsessive-compulsive disorder. *Psychol Med*. 2017;47(14):2513-2527.

25. Carlisi CO, Chantiluke K, Norman L, et al. The effects of acute fluoxetine administration on temporal discounting in youth with ADHD. *Psychol Med*. 2016;46(6):1197-1209.

26. Lim AC, Cservenka A, Ray LA. Effects of Alcohol Dependence Severity on Neural Correlates of Delay Discounting. *Alcohol Alcohol Oxf Oxfs*. 2017;52(4):506-515.

27. Claus ED, Kiehl KA, Hutchison KE. Neural and behavioral mechanisms of impulsive choice in alcohol use disorder. *Alcohol Clin Exp Res*. 2011;35(7):1209-1219.

28. Kable JW, Glimcher PW. An “as soon as possible” effect in human intertemporal decision making: behavioral evidence and neural mechanisms. *J Neurophysiol*. 2010;103(5):2513-2531. doi:10.1152/jn.00177.2009

29. Kable JW, Glimcher PW. The Neurobiology of Decision: Consensus and Controversy. *Neuron*. 2009;63(6):733-745. doi:10.1016/j.neuron.2009.09.003

30. Rodriguez CA, Turner BM, Van Zandt T, McClure SM. The neural basis of value accumulation in intertemporal choice. *Eur J Neurosci*. 2015;42(5):2179-2189.

31. Bartra O, McGuire JT, Kable JW. The valuation system: A coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. *NeuroImage*. 2013;76:412-427. doi:10.1016/j.neuroimage.2013.02.063

32. Kang MS, Wolf D, Kazinka R, et al. Decision value signals in the ventromedial prefrontal cortex and anhedonia across mood and psychotic disorders. *bioRxiv*. Published online December 2, 2020:2020.12.01.407197. doi:10.1101/2020.12.01.407197

33. Brown VM, Wilson J, Hallquist MN, Szanto K, Dombrovski AY. Ventromedial prefrontal value signals and functional connectivity during decision-making in suicidal behavior and impulsivity. *Neuropsychopharmacology*. 2020;45(6):1034-1041. doi:10.1038/s41386-020-0632-0

34. Miedl SF, Peters J, Büchel C. Altered neural reward representations in pathological gamblers revealed by delay and probability discounting. *Arch Gen Psychiatry*. 2012;69(2):177-186.

35. Wiehler A, Petzschner FH, Stephan KE, Peters J. Episodic Tags Enhance Striatal Valuation Signals during Temporal Discounting in pathological Gamblers. *eNeuro*. 2017;4(3). Accessed January 1, 5AD. https://pubmed.ncbi.nlm.nih.gov/28612049/

36. Souther MK, Wolf DH, Kazinka R, et al. Decision value signals in the ventromedial prefrontal cortex and motivational and hedonic symptoms across mood and psychotic disorders. *NeuroImage Clin*. 2022;36:103227. doi:10.1016/j.nicl.2022.103227

37. Schüller CB, Kuhn J, Jessen F, Hu X. Neuronal correlates of delay discounting in healthy subjects and its implication for addiction: an ALE meta-analysis study. *Am J Drug Alcohol Abuse*. 2019;45(1):51-66. doi:10.1080/00952990.2018.1557675

38. Eickhoff SB, Nichols TE, Laird AR, et al. Behavior, Sensitivity, and power of activation likelihood estimation characterized by massive empirical simulation. *NeuroImage*. 2016;137:70-85. doi:10.1016/j.neuroimage.2016.04.072

39. Wesley MJ, Bickel WK. Remember the future II: Meta-analyses and functional overlap of working memory and delay discounting. *Biol Psychiatry*. 2014;75(6):435-448. doi:10.1016/j.biopsych.2013.08.008

40. Han JE, Boachie N, Garcia-Garcia I, Michaud A, Dagher A. Neural correlates of dietary self-control in healthy adults: A meta-analysis of functional brain imaging studies. *Physiol Behav*. 2018;192:98-108. doi:10.1016/j.physbeh.2018.02.037

41. Yuan P, Raz N. Prefrontal cortex and executive functions in healthy adults: A meta-analysis of structural neuroimaging studies. *Neurosci Biobehav Rev*. 2014;42:180-192. doi:10.1016/j.neubiorev.2014.02.005

42. Commons ML, Mazur JE, Nevin JA, Rachlin H. *The Effect of Delay and of Intervening Events on Reinforcement Value: Quantitative Analyses of Behavior*. Psychology Press; 2013.

43. Albert WD. Neurodevelopmental Substrates of Peer Influences on Adolescents' Choice Evaluation and Decision Making. Published online 2011. Accessed May 5, 2021. https://scholarshare.temple.edu/handle/20.500.12613/660

44. Wager TD, Lindquist MA, Nichols TE, Kober H, Van Snellenberg JX. Evaluating the consistency and specificity of neuroimaging data using meta-analysis. *Neuroimage*. 2009;45(1 Suppl):S210-S221. doi:10.1016/j.neuroimage.2008.10.061

45. Miedl SF, Wiswede D, Marco-Pallarés J, et al. The neural basis of impulsive discounting in pathological gamblers. *Brain Imaging Behav*. 2015;9(4):887-898. doi:10.1007/s11682-015-9352-1

46. Christakou A, Brammer M, Rubia K. Maturation of limbic corticostriatal activation and connectivity associated with developmental changes in temporal discounting. *NeuroImage*. 2011;54(2):1344-1354.

47. Waegeman A, Declerck CH, Boone C, Van Hecke W, Parizel PM. Individual differences in self-control in a time discounting task: An fMRI study. *J Neurosci Psychol Econ*. 2014;7(2):65-79. doi:10.1037/npe0000018

48. Schmaal L, Goudriaan AE, Joos L, et al. Neural substrates of impulsive decision making modulated by modafinil in alcohol-dependent patients. *Psychol Med*. 2014;44(13):2787-2798. doi:10.1017/S0033291714000312

49. 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(5):383-393.

50. Stanger C, Elton A, Ryan SR, James GA, Budney AJ, Kilts CD. Neuroeconomics and adolescent substance abuse: individual differences in neural networks and delay discounting. *J Am Acad Child Adolesc Psychiatry*. 2013;52(7):747-755.e6.

51. Marco-Pallarés J, Mohammadi B, Samii A, Münte TF. Brain activations reflect individual discount rates in intertemporal choice. *Brain Res*. 2010;1320:123-129.

52. Kobiella A, Ripke S, Kroemer NB, et al. Acute and chronic nicotine effects on behaviour and brain activation during intertemporal decision making. *Addict Biol*. 2014;19(5):918-930.

53. Mavrogiorgou P, Enzi B, Klimm A, et al. Serotonergic modulation of orbitofrontal activity and its relevance for decision making and impulsivity. *Hum Brain Mapp*. 2017;38(3):1507-1517. doi:10.1002/hbm.23468

54. Morys F, Bode S, Horstmann A. Dorsolateral and medial prefrontal cortex mediate the influence of incidental priming on economic decision making in obesity. *Sci Rep*. 2018;8(1):17595.

55. Hamilton KR, Smith JF, Gonçalves SF, et al. Striatal bases of temporal discounting in early adolescents. *Neuropsychologia*. 2020;144:107492.

56. Weber BJ, Huettel SA. The neural substrates of probabilistic and intertemporal decision making. *Brain Res*. 2008;1234:104-115. doi:10.1016/j.brainres.2008.07.105

57. Pinger M, Thome J, Halli P, Sommer WH, Koppe G, Kirsch P. Comparing Discounting of Potentially Real Rewards and Losses by Means of Functional Magnetic Resonance Imaging. *Front Syst Neurosci*. 2022;16. Accessed April 28, 2023. https://www.frontiersin.org/articles/10.3389/fnsys.2022.867202

58. Martin LE, Pollack L, McCune A, Schulte E, Savage CR, Lundgren JD. Comparison of obese adults with poor versus good sleep quality during a functional neuroimaging delay discounting task: A pilot study. *Psychiatry Res Neuroimaging*. 2015;234(1):90-95. doi:10.1016/j.pscychresns.2015.08.011

59. van den Bos W, Rodriguez CA, Schweitzer JB, McClure SM. Adolescent impatience decreases with increased frontostriatal connectivity. *Proc Natl Acad Sci U S A*. 2015;112(29):E3765-74.

60. 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(4):643-653.

61. van de Groep S, Sweijen SW, de Water E, Crone EA. Temporal discounting for self and friends in adolescence: A fMRI study. *Dev Cogn Neurosci*. 2023;60:101204. doi:10.1016/j.dcn.2023.101204

62. Herman AM, Critchley HD, Duka T. Binge drinking is associated with attenuated frontal and parietal activation during successful response inhibition in fearful context. *Eur J Neurosci*. 2019;50(3):2297-2310.

63. 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 Mapp*. 2011;32(10):1637-1648.

64. Miedl SF, Büchel C, Peters J. Cue-induced craving increases impulsivity via changes in striatal value signals in problem gamblers. *J Neurosci*. 2014;34(13):4750-4755. doi:10.1523/JNEUROSCI.5020-13.2014

65. Eickhoff SB, Laird AR, Grefkes C, Wang LE, Zilles K, Fox PT. Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: a random-effects approach based on empirical estimates of spatial uncertainty. *Hum Brain Mapp*. 2009;30(9):2907-2926. doi:10.1002/hbm.20718

66. Hoffman WF, Schwartz DL, Huckans MS, et al. Cortical activation during delay discounting in abstinent methamphetamine dependent individuals. *Psychopharmacology (Berl)*. 2008;201(2):183-193.

67. Meade CS, Lowen SB, MacLean RR, Key MD, Lukas SE. fMRI brain activation during a delay discounting task in HIV-positive adults with and without cocaine dependence. *Psychiatry Res Neuroimaging*. 2011;192(3):167-175. doi:10.1016/j.pscychresns.2010.12.011

68. Mavrogiorgou P, Enzi B, Steinmann S, Mulert C, Juckel G. Relationship Between Neuroanatomical and Serotonergic Hypotheses of Obsessive-Compulsive Disorder: A Combined Functional Magnetic Resonance Imaging-Evoked Potential Study. *J Clin Psychiatry*. 2018;79(6). Accessed January 1, 10AD. https://pubmed.ncbi.nlm.nih.gov/30326190/

69. Avsar KB, Weller RE, Cox JE, Reid MA, White DM, Lahti AC. An fMRI investigation of delay discounting in patients with schizophrenia. *Brain Behav*. 2013;3(4):384-401. doi:10.1002/brb3.135

70. Vanyukov PM, Szanto K, Hallquist MN, et al. Paralimbic and lateral prefrontal encoding of reward value during intertemporal choice in attempted suicide. *Psychol Med*. 2016;46(2):381-391. doi:10.1017/S0033291715001890

71. 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(2):582-592. doi:10.1016/j.appet.2011.11.029

72. Deshpande HU, Mellis AM, Lisinski JM, et al. Reinforcer pathology: Common neural substrates for delay discounting and snack purchasing in prediabetics. *Brain Cogn*. 2019;132:80-88.

73. Levy DJ, Glimcher PW. The root of all value: a neural common currency for choice. *Curr Opin Neurobiol*. 2012;22(6):1027-1038. doi:10.1016/j.conb.2012.06.001

74. Salimi-Khorshidi G, Smith SM, Keltner JR, Wager TD, Nichols TE. Meta-analysis of neuroimaging data: A comparison of image-based and coordinate-based pooling of studies. *NeuroImage*. 2009;45(3):810-823. doi:10.1016/j.neuroimage.2008.12.039

75. MacKillop J, Amlung MT, Wier LM, et al. The neuroeconomics of nicotine dependence: a preliminary functional magnetic resonance imaging study of delay discounting of monetary and cigarette rewards in smokers. *Psychiatry Res*. 2012;202(1):20-29.

76. Weygandt M, Spranger J, Leupelt V, et al. Interactions between neural decision-making circuits predict long-term dietary treatment success in obesity. *NeuroImage*. 2019;184:520-534. doi:10.1016/j.neuroimage.2018.09.058

77. Weygandt M, Mai K, Dommes E, et al. Impulse control in the dorsolateral prefrontal cortex counteracts post-diet weight regain in obesity. *NeuroImage*. 2015;109:318-327. doi:10.1016/j.neuroimage.2014.12.073

78. 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(2):218-225. doi:10.1093/scan/nsq046

79. Albrecht K, Volz KG, Sutter M, von Cramon DY. What do I want and when do I want it: brain correlates of decisions made for self and other. *PloS One*. 2013;8(8):e73531.

80. Ballard K, Knutson B. Dissociable neural representations of future reward magnitude and delay during temporal discounting. *NeuroImage*. 2009;45(1):143-150. doi:10.1016/j.neuroimage.2008.11.004

81. Banich MT, De La Vega A, Andrews-Hanna JR, Mackiewicz Seghete K, Du Y, Claus ED. Developmental trends and individual differences in brain systems involved in intertemporal choice during adolescence. *Psychol Addict Behav*. 2013;27(2):416-430. doi:10.1037/a0031991

82. 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(27):8839-8846. doi:10.1523/JNEUROSCI.5319-08.2009

83. Blain B, Schmit C, Aubry A, Hausswirth C, Le Meur Y, Pessiglione M. Neuro-computational Impact of Physical Training Overload on Economic Decision-Making. *Curr Biol CB*. 2019;29(19):3289-3297.e4.

84. Chantiluke K, Christakou A, Murphy CM, et al. Disorder-specific functional abnormalities during temporal discounting in youth with Attention Deficit hyperactivity Disorder (ADHD), Autism and comorbid ADHD and Autism. *Psychiatry Res Neuroimaging*. 2014;223(2):113-120. doi:10.1016/j.pscychresns.2014.04.006

85. Clithero JA, Carter RM, Huettel SA. Local pattern classification differentiates processes of economic valuation. *NeuroImage*. 2009;45(4):1329-1338.

86. Cox KM, Kable JW. BOLD Subjective Value Signals Exhibit Robust Range Adaptation. *J Neurosci*. 2014;34(49):16533-16543. doi:10.1523/JNEUROSCI.3927-14.2014

87. Eppinger B, Nystrom LE, Cohen JD. Reduced sensitivity to immediate reward during decision-making in older than younger adults. *PloS One*. 2012;7(5):e36953.

88. Eppinger B, Heekeren HR, Li SC. Age Differences in the Neural Mechanisms of Intertemporal Choice Under Subjective Decision Conflict. *Cereb Cortex N Y N 1991*. 2018;28(11):3764-3774.

89. Fröhner JH, Teckentrup V, Smolka MN, Kroemer NB. Addressing the reliability fallacy in fMRI: Similar group effects may arise from unreliable individual effects. *NeuroImage*. 2019;195:174-189. doi:10.1016/j.neuroimage.2019.03.053

90. Fu W, Huang Z, Li J, et al. Reduced sensitivity to delayed time and delayed reward of the post-operative insular glioma patients in delay discounting. *NeuroImage Clin*. 2022;33:102895. doi:10.1016/j.nicl.2021.102895

91. Gardiner CK, Karoly HC, Thayer RE, Gillman AS, Sabbineni A, Bryan AD. Neural activation during delay discounting is associated with 6-month change in risky sexual behavior in adolescents. *Ann Behav Med Publ Soc Behav Med*. 2018;52(5):356-366.

92. Halcomb M, Dzemidzic M, Shen YI, et al. Delay discounting and alcohol consumption correlate with dorsal anterior insula activation during choice in nontreatment-seeking heavy drinkers. *Alcohol Clin Exp Res*. 2022;46(8):1397-1407. doi:10.1111/acer.14888

93. Hare TA, Hakimi S, Rangel A. Activity in dlPFC and its effective connectivity to vmPFC are associated with temporal discounting. *Front Neurosci*. 2014;8:50.

94. Ikink I, Engelmann JB, van den Bos W, Roelofs K, Figner B. Time ambiguity during intertemporal decision-making is aversive, impacting choice and neural value coding. *NeuroImage*. 2019;185:236-244. doi:10.1016/j.neuroimage.2018.10.008

95. Koffarnus MN, Deshpande HU, Lisinski JM, Eklund A, Bickel WK, LaConte SM. An adaptive, individualized fMRI delay discounting procedure to increase flexibility and optimize scanner time. *NeuroImage*. 2017;161:56-66. doi:10.1016/j.neuroimage.2017.08.024

96. Laube C, Lorenz R, van den Bos W. Pubertal testosterone correlates with adolescent impatience and dorsal striatal activity. *Dev Cogn Neurosci*. 2020;42:100749.

97. Liu L, Feng T, Wang J, Li H. The neural dissociation of subjective valuation from choice processes in intertemporal choice. *Behav Brain Res*. 2012;231(1):40-47. doi:10.1016/j.bbr.2012.02.045

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

99. Luo S, Ainslie G, Pollini D, Giragosian L, Monterosso JR. Moderators of the association between brain activation and farsighted choice. *NeuroImage*. 2012;59(2):1469-1477. doi:10.1016/j.neuroimage.2011.08.004

100. Massar SAA, Libedinsky C, Weiyan C, Huettel SA, Chee MWL. Separate and overlapping brain areas encode subjective value during delay and effort discounting. *NeuroImage*. 2015;120:104-113. doi:10.1016/j.neuroimage.2015.06.080

101. Meade CS, Cordero DM, Hobkirk AL, Metra BM, Chen NK, Huettel SA. Compensatory activation in fronto-parietal cortices among HIV-infected persons during a monetary decision-making task. *Hum Brain Mapp*. 2016;37(7):2455-2467.

102. Murawski C, Harris PG, Bode S, Domínguez D JF, Egan GF. Led into temptation? Rewarding brand logos bias the neural encoding of incidental economic decisions. *PloS One*. 2012;7(3):e34155.

103. Neukam PT, Deza-Araujo YI, Marxen M, et al. No evidence for the involvement of serotonin or the 5-HTTLPR genotype in intertemporal choice in a larger community sample. *J Psychopharmacol Oxf Engl*. 2019;33(11):1377-1387.

104. O'Connell G, Hsu CT, Christakou A, Chakrabarti B. Thinking about others and the future: Neural correlates of perspective taking relate to preferences for delayed rewards. *Cogn Affect Behav Neurosci*. 2018;18(1):35-42.

105. Peters J, Büchel C. Overlapping and distinct neural systems code for subjective value during intertemporal and risky decision making. *J Neurosci Off J Soc Neurosci*. 2009;29(50):15727-15734.

106. Peters J, Büchel C. Episodic future thinking reduces reward delay discounting through an enhancement of prefrontal-mediotemporal interactions. *Neuron*. 2010;66(1):138-148. doi:10.1016/j.neuron.2010.03.026

107. Pine A, Seymour B, Roiser JP, et al. Encoding of marginal utility across time in the human brain. *J Neurosci Off J Soc Neurosci*. 2009;29(30):9575-9581.

108. Pine A, Shiner T, Seymour B, Dolan RJ. Dopamine, time, and impulsivity in humans. *J Neurosci*. 2010;30(26):8888-8896. doi:10.1523/JNEUROSCI.6028-09.2010

109. Piva M, Velnoskey K, Jia R, Nair A, Levy I, Chang SW. The dorsomedial prefrontal cortex computes task-invariant relative subjective value for self and other. *eLife*. 2019;8. Accessed January 1, 6AD. https://pubmed.ncbi.nlm.nih.gov/31192786/

110. Rodriguez-Moreno DV, Cycowicz YM, Figner B, et al. Delay discounting and neurocognitive correlates among inner city adolescents with and without family history of substance use disorder. *Dev Cogn Neurosci*. 2021;48:100942. doi:10.1016/j.dcn.2021.100942

111. Ripke S, Hübner T, Mennigen E, et al. Reward processing and intertemporal decision making in adults and adolescents: The role of impulsivity and decision consistency. *Brain Res*. 2012;1478:36-47. doi:10.1016/j.brainres.2012.08.034

112. Samanez-Larkin G, Mata R, Radu P, Ballard I, Carstensen L, McClure S. Age Differences in Striatal Delay Sensitivity during Intertemporal Choice in Healthy Adults. *Front Neurosci*. 2011;5:126. doi:10.3389/fnins.2011.00126

113. Sasse LK, Peters J, Büchel C, Brassen S. Effects of prospective thinking on intertemporal choice: The role of familiarity. *Hum Brain Mapp*. 2015;36(10):4210-4221.

114. Sasse LK, Peters J, Brassen S. Cognitive control modulates effects of episodic simulation on delay discounting in aging. *Front Aging Neurosci*. 2017;9:11.

115. Schneider S, Peters J, Peth JM, Büchel C. Parental inconsistency, impulsive choice and neural value representations in healthy adolescents. *Transl Psychiatry*. 2014;4(4):e382.

116. Steinbeis N, Haushofer J, Fehr E, Singer T. Development of behavioral control and associated vmPFC–DLPFC connectivity explains children's increased resistance to temptation in intertemporal choice. *Cereb Cortex*. 2016;26(1):32-42. doi:10.1093/cercor/bhu167

117. van den Bos W, Rodriguez CA, Schweitzer JB, McClure SM. Connectivity strength of dissociable striatal tracts predict individual differences in temporal discounting. *J Neurosci Off J Soc Neurosci*. 2014;34(31):10298-10310.

118. Vetter NC, Steding J, Jurk S, Ripke S, Mennigen E, Smolka MN. Reliability in adolescent fMRI within two years - a comparison of three tasks. *Sci Rep*. 2017;7(1):2287. doi:10.1038/s41598-017-02334-7

119. Wang Q, Luo S, Monterosso J, et al. Distributed value representation in the medial prefrontal cortex during intertemporal choices. *J Neurosci*. 2014;34(22):7522-7530. doi:10.1523/JNEUROSCI.0351-14.2014

120. Wang Q, Wang Y, Wang P, et al. Neural representations of the amount and the delay time of reward in intertemporal decision making. *Hum Brain Mapp*. 2021;42(11):3450-3469. doi:10.1002/hbm.25445

121. Xu L, Liang ZY, Wang K, Li S, Jiang T. Neural mechanism of intertemporal choice: From discounting future gains to future losses. *Brain Res*. 2009;1261:65-74.

122. Zha R, Bu J, Wei Z, et al. Transforming brain signals related to value evaluation and self-control into behavioral choices. *Hum Brain Mapp*. 2019;40(4):1049-1061.

123. Zhuang JY, Wang JX, Lei Q, Zhang W, Fan M. Neural Basis of Increased Cognitive Control of Impulsivity During the Mid-Luteal Phase Relative to the Late Follicular Phase of the Menstrual Cycle. *Front Hum Neurosci*. 2020;14:568399.

PRISMA 2009 Flow Diagram

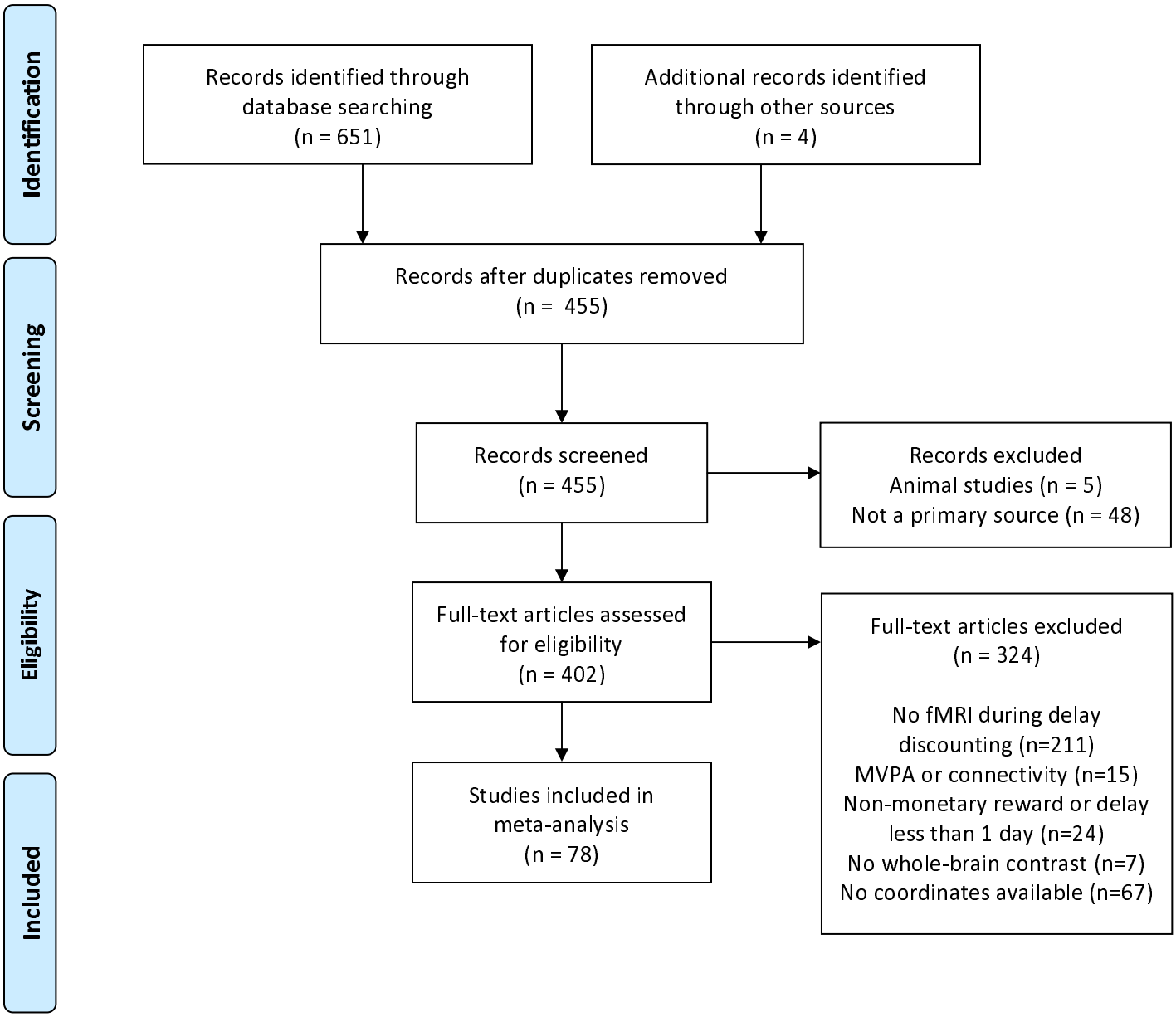

Figure 2. Whole-brain meta-analysis results for general task-related activity (*Task*) and activity related to choice difficulty (*Hard* in orange, *Easy* in blue).

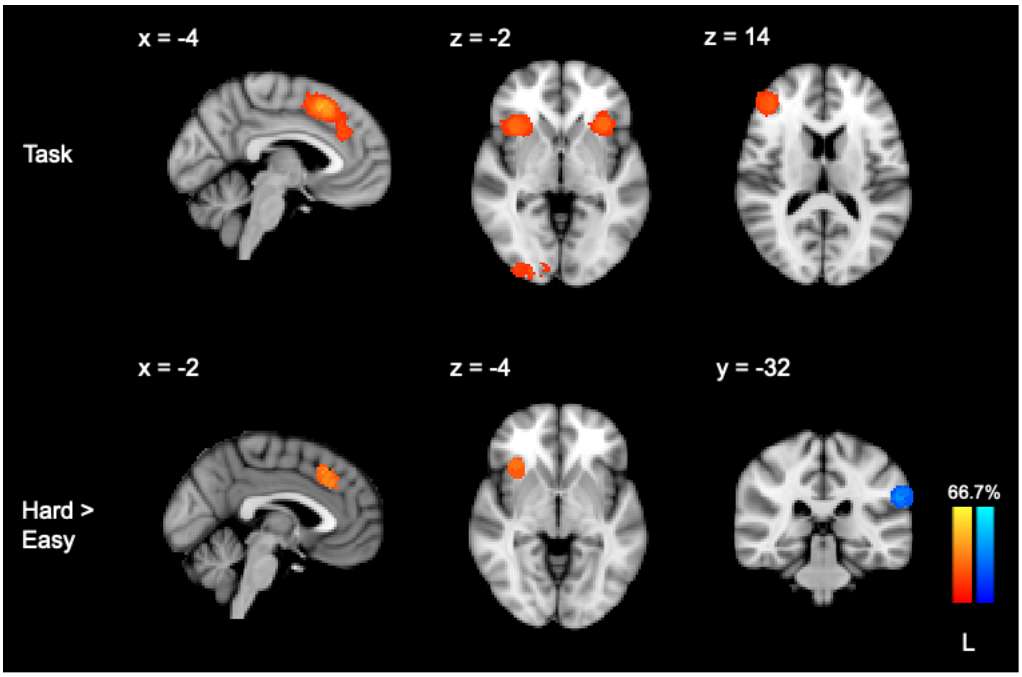

Figure 3. Whole-brain meta-analysis results for *SV*, *Magnitude*, *Delay* and *Immediacy*. Warm colors represent positive effects and cool colors represent negative effects. Effects for *SV*, *Magnitude*, and *Delay* refer to parametric correlations with the regressor.

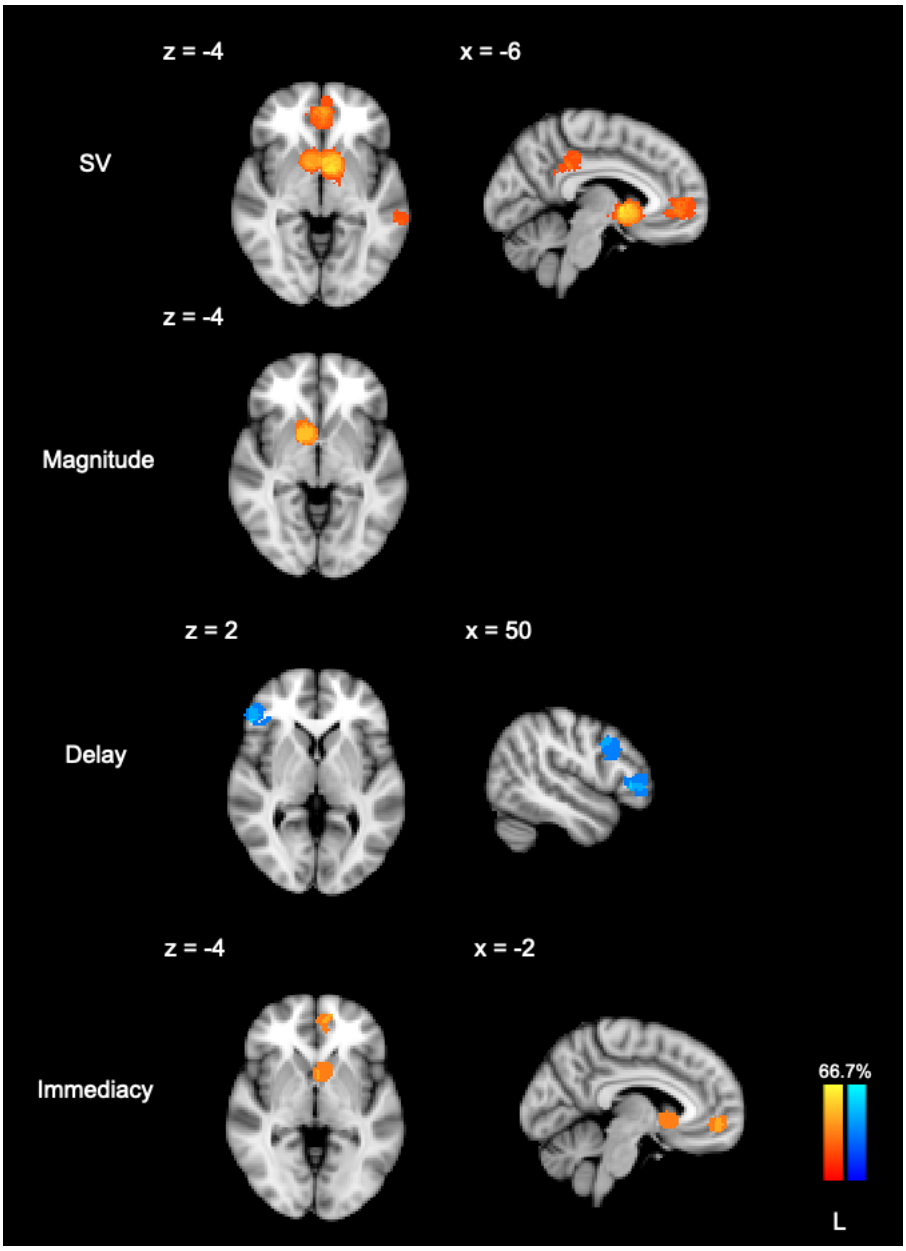

Figure 4. Whole-brain meta-analysis results for choice-related activity (*SSR* in warm colors, *LLR* in cool colors).

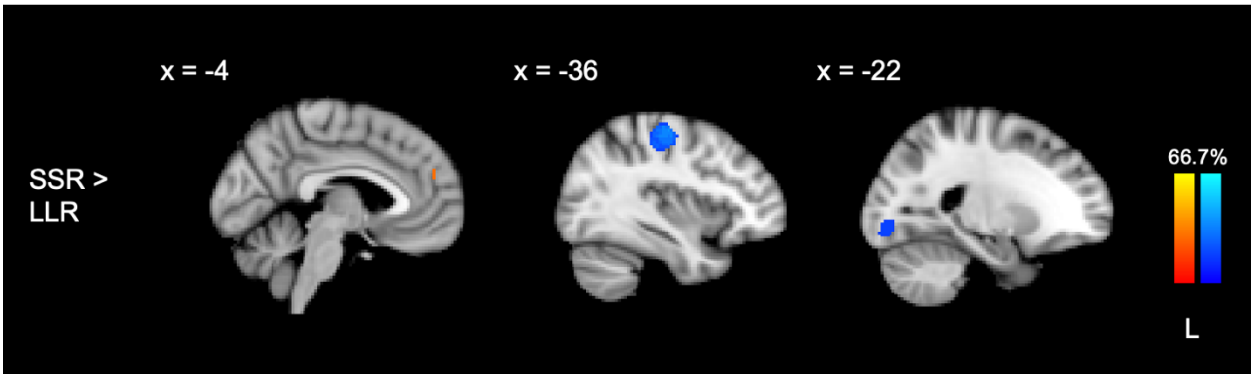

Table 1. Meta-analytic sample (N=78 studies; 146 contrasts).

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Albert et al., 2012[43]	40	NS	Choice evaluation > baseline Positive effects of differential magnitude	4				6				
Albrecht et al., 2011[78]	28	NS	Today trials > delay trials									18
Albrecht et al., 2013[79]	30	HC	SS > LL			3						
Avsar et al., 2013[69]	14	HC	Task > SMC trials Easy > hard	18							9	
	14	Schizophrenia	Task > SMC trials Easy > hard	8							9	
Ballard et al., 2009[80]	16	HC	Magnitude Negative effect of delay					3	3			
Banich et al., 2013[81]	29	HC	Task > fixation Now > later	22		17						
Bickel et al., 2009[82]	30	HC	Discounting > control (real money)	21								
Blain et al., 2019[83]	37	NS	Hard > easy							18		
Chantiluke et al., 2014[84]	18	HC	Delayed > immediate choices		2							
Christakou et al., 2011[46]	40	HC	Delay > immediate Immediate > delay		13	4						
Claus et al., 2011[27]	160	Heavy drinkers	Later > now Now > later		17	18						
Clithero et al., 2009[85]	11	HC	Delay task	3								
Cox et al., 2014[86]	20	HC	SV (narrow and wide)				4					
Deshpande et al., 2019[72]	54	Prediabetics (high BMI)	Hard > easy Easy > hard Immediate available vs. unavailable							6	11	18
Eppinger et al., 2012[87]	30	NS	All choice > baseline Immediate options > delayed options	5								2
Eppinger et al., 2018[88]	50	NS	SV Hard > easy Easy > hard				3			2	4	
Fröhner et al., 2019[89]	126	NS	SV				3					

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Fu et al., 2022[90]	48	HC	Want > control	5	6							
Gardiner et al., 2018[91]	177	NS	Hard > easy							4		
Halcomb et al., 2022[92]	29	Heavy drinkers	Choice > baseline	7								
Hamilton et al., 2020[55]	27	HC	All choices vs. baseline	8								
Hare et al., 2014[93]	25	HC	SV Del > imm		24		11					
Hoffman et al., 2008[66]	36	Methamphetamine dependence[1]	DD task > magnitude estimation task	11								
Ikink et al., 2019[94]	24	NS	Conjunction of ambiguous and exact DD	7								
Kable et al., 2007[17]	10	NS	SV using HDR Objective value Inverse delay Delayed > immediate Negative effects of SVD		1		14	2	4	8		
Kable et al., 2010[28]	25	NS	NOW – 60 DAY									9
Kishinevsky et al., 2012[71]	19	Obese women	Hard > easy							2		
Koffarnus et al., 2017[95]	18	NS (excluded substance use disorder)	Hard > easy Easy > hard							1	5	
Laube et al., 2020[96]	70	HC	Delayed > immediate Immediate > delayed Now-Later options		8	8						8
Lempert et al., 2017[13]	35	NS	SV (memory and control choice)				24					
Lim et al., 2017[26]	17	Alcohol use disorder	SS > LL			3						
Liu et al., 2012a[97]	19	HC	Free choice > forced choice SV	11			17					
Liu et al., 2012b[98]	18	NS	Task > baseline during valuation	7								

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Luo et al., 2012[99]	21	HC	LL > SS		7							
Marco-Pallarés et al., 2010[51]	17	HC	Indifference > non-indifference Non-indifference > indifference							1	11	
Martin et al., 2015[58]	19	Poor quality sleepers[1]	Immediate > baseline	12								
Massar et al., 2015[100]	23	HC	SV Negative effects of delay level				21		12			
Mavrogiorgou et al., 2017[53]	20	HC	Immediate > delay			8						
McClure et al., 2004[18]	14	NS	Delta system Beta system	8								5
Meade et al., 2011[67]	39	Cocaine dependence[1]	Task > baseline Hard > easy	1						9		
Meade et al., 2016[101]	35	HC	Task > baseline Hard > easy	8						8		
Miedl et al., 2012[34]	32	Pathological gamblers[1]	SV				25					
Miedl et al., 2015[45]	15	HC	LDR > SIR		2							
	15	Pathological gamblers	LDR > SIR		8							
	30	Pathological gamblers[1]	Indifferent > sure Sure > indifferent							20	13	
Monterosso et al., 2007[49]	29	Methamphetamine users[1]	Hard > easy	6						2		
Morys et al., 2018[54]	36	Obese[1]	Delay discounting > perceptual decisions SS > LL	7		4						
Murawski et al., 2012[102]	13	NS	Task > baseline SV Easy > hard	13			6				5	
Neukam et al., 2019[103]	90	HC	Parametric amount Negative effects of delay					7	32			

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Norman et al., 2017[22]	20	HC	Delay > immediate (both directions)		2	1						
	26	ADHD	Delay > immediate (both directions)		2	7						
	20	OCD	Delay > immediate (both directions)		2	3						
O'Connell et al., 2018[104]	26	NS	DEL > IMM Positive effects of net SV		3						14	
Peters et al., 2009	22	NS	SV Reward magnitude Inverse delay				25	15	13			
Peters et al., 2010[106]	30	HC	SV (control and episodic condition)				15					
Pine et al., 2009[107]	24	HC	Discounted utility (V) Undiscounted utility (U) Temporal discount factor (D) Hard > easy				7	16	22	7		
Pine et al., 2010[108]	14	HC	Discounted utility (V) Undiscounted utility (U) Temporal discount factor (D)				9	25	28			
Pinger et al., 2022[57]	30	HC	Reward decision > baseline	21								
Piva et al., 2019[109]	20	NS	Hard > easy Positive effect of relative SV							13	2	
Rodriguez-Moreno et al., 2021[110]	102	HC	Now > Not-Now									6
Ripke et al., 2012[111]	222	HC	Task SV	18			19					
Samanez-Larkin et al., 2011[112]	25	NS	SV				19					
Sasse et al., 2015[113]	23	HC	SV (episodic condition)				12					
Sasse et al., 2017[114]	22	HC	SV				8					
Schneider et al., 2014[115]	48	HC	SV				4					
Souther et al., 2022	81	Mood and psychotic disorders[1]	SV SVD (positive and negative)				6			28	12	

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Sripada et al., 2011[63]	20	HC	LL > SS Immediacy		15							6
Stanger et al., 2013[50]	30	Substance abuse	LL > control task SS vs. LL	14		2						
Steinbeis et al., 2016[116]	20	HC	SV during valuation				4					
van den Bos et al., 2014[117]	22	NS	Choice > baseline LL-SS	7	5							
Van de Groep et al., 2023[61]	96	HC	Delay > Control	10								
van den Bos et al., 2015[59]	50	NS	LL-SS		4							
Vanyukov et al., 2016[70]	48	Major depression[1]	Task > fixation SIR-DDR Negative effect of longer vs. shorter delay Difficult > easy Negative effect of difficult > easy	11				1	1	3	1	
Vetter et al., 2017[118]	174	HC	Decision phase > baseline	1								
Waegeman et al., 2014[47]	41	HC	Delayed > immediate		41							
Wang et al., 2014[119]	28	HC	Amount of delayed reward Positive effects of SVD					7			11	
Wang et al., 2017[21]	21	HC	Delay - Immediate		3							
	18	Internet gambling disorder	Delay - Immediate		1	2						
Wang et al., 2021[120]	19	HC	Amount					10				
Weber et al., 2008[56]	23	NS	Delayed > immediate		1							
Wiehler et al., 2017[35]	48	Pathological gamblers[1]	SV (conjunction of HC and gamblers)				3					
Wittmann et al., 2007[60]	13	HC	<1 versus >1 year Delayed vs. immediate		7				1			
Xu et al., 2009[121]	20	HC	Temporal discounting (gains) > baseline Available immediately (G-TD)	19								12

				Number of foci								
Study	n	Diagnosis	Contrast	Task	LLR	SSR	SV	Mag	Del	Hard	Easy	Imm
Zha et al., 2019[122]	46	HC	SV Difficulty				10			8		
Zhuang et al., 2020[123]	24	HC	Delayed > immediate Immediate > delayed		3	8						

Notes: HC = healthy controls, NS = not specified, Task = Task activations, LLR = larger later reward > smaller sooner reward, SSR = smaller sooner reward > larger later reward, SV = positive correlation with subjective value, Mag = positive correlation with objective (undiscounted) magnitude of reward, Del = negative correlation with delay or positive correlation with inverse delay, Hard = hard > easy, Easy = easy > hard, Imm = trials with immediate option > trials with both options delayed. [1] includes HC (pooled across the entire study sample.

Table 2. Meta-analytic test statistic (% of studies that reported a peak within a 10mm radius).

#	Volume (mm^3)	MNI coordinates X	Y	Z	Value	Brain area
Task						
1	1567	0	22	44	51.7	Bilateral dmPFC
2	678	-46	12	30	34.5	L. middle frontal gyrus
3	827	34	-60	46	31.0	R. occipital cortex
4	776	36	20	-2	31.0	R. insula
5	748	-28	-58	46	31.0	L. occipital cortex
6	539	-32	22	0	27.6	L. insula
7	440	46	40	14	27.6	R. frontal pole
8	523	28	-92	-4	24.1	R. occipital pole
Hard						
1	609	2	24	42	47.1	Bilateral dmPFC
2	168	34	22	-4	29.4	R. insula
Easy						
1	375	-62	-32	28	38.5	L. supramarginal gyrus
SV						
1	1303	-2	8	-4	66.7	Bilateral striatum
2	829	0	46	2	45.8	Bilateral vmPFC
3	254	-4	-38	36	37.5	L. Posterior cingulate
4	141	-62	-36	-4	29.2	L. Middle temporal gyrus
Magnitude						
1	496	10	8	-4	50	R. striatum
Delay						
1	363	50	38	2	55.6	R. frontal pole
2	335	52	16	32	44.4	R. middle frontal gyrus
Immediacy						
1	253	-4	10	-2	44.4	L. striatum
2	236	-6	50	-6	44.4	L. vmPFC
SSR						
1	18	-4	50	24	28.6	L. dmPFC
LLR						
1	545	-36	-22	54	39.1	L. Precentral gyrus
2	137	-24	-86	-8	17.4	L. occipital fusiform gyrus

Notes: Task = Task activations, Hard = hard > easy, Easy = easy > hard, SV = positive correlation with subjective value, Magnitude = positive correlation with objective (undiscounted) magnitude of reward, Delay = negative correlation with delay or positive correlation with inverse delay, Immediacy = trials with immediate option > trials with both options delayed, SSR = smaller-sooner reward > larger-later reward, LLR = larger-later reward > smaller-sooner reward, L = left, R = right.