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Reinforcer pathology: Common neural substrates for delay discounting and snack purchasing in prediabetics

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Abstract

Reinforcer pathology theory stipulates that individuals with both (a) high preference for smaller, immediate over larger, delayed rewards; and (b) high demand for unhealthy commodities are uniquely susceptible to poor health outcomes. Specifically, two behavioral economic tasks (delay discounting, assessing preference for smaller, immediate or larger, delayed rewards; and purchasing, assessing purchases of commodities over changes in price) have been independently associated with conditions such as overweight/obesity and problem substance use. In the present study, we examined possible shared neural regions involved in the processes of delay discounting and demand for snack foods in a prediabetic sample. Fifty-four participants completed both of these tasks. Conjunction between delay discounting and purchasing task results indicates substantial common neural substrates recruited during these two tasks, consistent with interpretations of executive control, interoception, and attention, in the prefrontal cortex, insula, and frontoparietal cortex (superior/middle frontal cortex and superior/inferior parietal lobules), respectively. Collectively, these results suggest possible neural substrates in which the two behavioral risk factors of reinforcer pathology may interact during real-world decision-making in prediabetes.

Keywords

Delay discounting; Purchasing; Reinforcer pathology; Prediabetes; Impulsivity

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bandc.2019.03.003>.

1. Introduction

Prediabetes is a disease supported by lifestyle choices, including overconsumption of high energy density foods and sedentary behavior. Once an individual has been diagnosed with prediabetes, they must make behavioral and lifestyle changes to reduce their risk of conversion to type 2 diabetes (Knowler et al., 2002). Complicating these changes is a rigid behavioral economic framework undergirding diseases of excessive consumption, reinforcer pathology. Reinforcer pathology stipulates that individuals who excessively prefer immediate rewards and excessively value particular commodities (e.g., snack foods or substances of abuse), will be more likely to overconsume and experience subsequent health consequences. This reinforcer pathology has been demonstrated in obesity (Carr, Daniel, Lin, & Epstein, 2011) and substance abuse (Bickel et al., 2011b; Bickel, Johnson, Koffarnus, MacKillop, & Murphy, 2014), and has two behavioral economic components: delay discounting and demand. Here, we investigate the neural substrates of both processes using functional magnetic resonance imaging (fMRI) methods to clarify their interaction.

1.1. Delay discounting

The first component of reinforcer pathology is delay discounting, which is a measure of impulsivity (Ainslie, 1975). Delay discounting is the degree to which rewards lose subjective value when received after a delay. Specifically, delay discounting tasks present individuals with choices between a smaller, immediate and a larger, delayed reward (for example, \$500 today or \$1000 tomorrow). By varying the magnitude and delay of rewards, an individual's point of indifference between the sooner and the later reward can be determined. These points of indifference may be described by a hyperbolic decay function (Mazur, 1987), representing the rate at which the subjective value of a reward decreases over time:

$$V = \frac{A}{1 + kD} \quad (1)$$

where V indicates subjective value, A is the full nominal value of the delayed reward, and D is the delay to reward receipt. The parameter describing the rate of subjective value decrement over time, *k*, varies across individuals. Higher discount rates, indicating a greater preference for immediate rewards, are commonly observed in overweight/ obese populations (Amlung, Petker, Jackson, Balodis, & MacKillop, 2016) compared to normal weight populations. Furthermore, delay discounting has been associated with an indicator of glycemic control (glycated hemoglobin, HbA1c) in a diabetic sample (Reach et al., 2011), with steeper discount rates corresponding to poorer glycemic control (Lebeau et al., 2016). Prediabetes is the state of elevated risk of conversion to type 2 diabetes during which individuals should make healthier choices. Delay discounting has also been associated in a pre-diabetic sample (Epstein et al., under review) with adherence both to healthier lifestyle choices (e.g., physical activity, dietary intake, preventive health behaviors) and to prescribed medications. For an individual who steeply discounts the future, the smaller, sooner reward of unhealthy food consumption has higher subjective value than the larger, later reward of improved health. Thus steep discount rates shed light on decision-making processes that jeopardize health and increase the risk of progressing to type 2 diabetes.

Neuroimaging methods have also been used to investigate the neural substrates of delay discounting. Each of these methods revealed areas invoked in choice difficulty and immediate choice availability conditions, including dorsolateral prefrontal cortex (DLPFC), posterior cingulate cortex (PCC) and anterior cingulate cortex (ACC). In a sample consisting of individuals with and without alcohol use disorder, bilateral DLPFC and anterior insula showed greater BOLD response in hard trials while the right inferior parietal lobule and the postcentral gyrus showed greater BOLD response for easy trials (Amlung, Sweet, Acker, Brown, & MacKillop, 2014; Wesley & Bickel, 2014). Impulsive behavior, as well as subsequent rate of weight gain, was also correlated with lower neural responses in executive function areas, such as the middle and superior frontal gyri and inferior parietal lobule, when hard trials were contrasted with easy trials (Kishinevsky et al., 2012; Stoeckel, Murdaugh, Cox, Cook, & Weller, 2013). In a study comparing trials with an immediate choice available to trials where both choices were delayed, areas that showed significantly greater BOLD responses included PCC and the medial prefrontal cortex (MPFC) (McClure, 2004).

1.2. Demand

The second component of reinforcer pathology, excessive demand for particular commodities, can be assessed with behavioral economic purchasing tasks. These tasks present options to purchase a commodity over a range of prices. Two parameters of demand can be used to understand how individuals value commodities: demand intensity (the amount an individual would like to have if a commodity were free), and demand elasticity (sensitivity of commodity purchasing to price). High demand for particular commodities has been observed in overweight and obesity (Epstein, Dearing, & Roba, 2010). Further, in discordant sibling pairs, differences in demand for food are associated with differences in normalized BMI (Feda, Roemmich, Roberts, & Epstein, 2015), with higher demand corresponding to higher normalized BMI, and this effect is moderated by delay discounting rate, with steeper discounting contributing to further increases in normalized BMI. Just as in delay discounting, high demand for food commodities can also describe decision-making in prediabetes. Prediabetes is more likely to emerge among individuals who so value high glycemic index foods that they continue to choose to purchase and consume these foods regardless of the ensuing health costs.

Neuroimaging interrogations of the reinforcing power of food among obese and overweight individuals have demonstrated greater bilateral precentral response to food cues (McCaffery et al., 2009), and greater response in reward anticipation regions (amygdala, and ventromedial prefrontal cortex; VMPFC) preceding consumption of an unhealthy food (Ng, Stice, Yokum, & Bohon, 2011). These reward valuation regions have also been commonly observed in BOLD response during standard purchasing tasks. For example, Knutson and colleagues (2007) observed that decisions to purchase were generally associated with increased BOLD response in the bilateral orbitofrontal cortex (OFC), insula, posterior cingulate, and inferior parietal lobules; and with left VMPFC and postcentral gyrus. These responses have also been used to generate classifiers to predict whether participants will purchase commodities (Grosenick, Greer, & Knutson, 2008), suggesting that in purchasing, as in delay discounting, neural differences in task performance may underlie emergent behavioral differences.

The present study represents the first investigation of the neural correlates of the components of reinforcer pathology, delay discounting and demand, using fMRI in a prediabetic sample. Within each task, we assessed concordance with previously published associations in executive control (e.g., DLPFC, Ernst & Paulus, 2005), interoception and cost-benefit decision-making (e.g., the insula, Gray et al., 2017) and attentional control (e.g., frontoparietal regions, including superior/middle frontal cortex and superior/inferior parietal lobules, Scolari, Seidl-Rathkopf, & Kastner, 2015, Culham & Kanwisher, 2001). These tasks each alter BOLD response in multiple ways, with both task-specific and potentially overlapping regions demonstrating a differential BOLD response in each case. Between tasks, we explored possible overlaps in BOLD response which may indicate neural substrates underlying behavioral interplay in reinforcer pathology using conjunction analysis. Given that each of these tasks invokes multiple processes, the precise nature of this overlap may also clarify how individuals make purchase decisions while assessing availability and difficulty of choices.

2. Methods

2.1. Participants

Fifty-four participants from two sites (37 from Roanoke, Virginia and surrounding areas; 17 from Buffalo, New York) completed an fMRI session. Data from an additional ten participants were excluded due to technical problems with data collection, excessive motion during the fMRI session, or for zero purchasing of snacks in the purchasing task. All procedures were approved by the University at Buffalo (UB) and Carilion Clinic Institutional Review Boards at Virginia Tech (VT). Apart from MRI eligibility, inclusion criteria were: a prediabetic HbA1c reading with the A1CNow + [®] (adjusted for the confidence of the system; see Epstein et al., under review, for details) at the time of consent or diagnosis of prediabetes within the past year; and diagnosis of and prescription of medication for either hypertension or hyperlipidemia. The majority of participants were female (at VT, 61% and at UB, 59%) and white (at VT, 94% and at UB, 65%). The mean age was over 50 (at VT, 54.15, SD = 10.74; at UB, 50.53, SD = 12.67). Complete demographic information is available in Appendix A, Table S1.

2.2. Procedure

Participants first completed behavioral data collection sessions, including behavioral assessment of initial delay discount rates using a seven-delay adjusting-amount task (Du, Green, & Myerson, 2002) and purchasing of a preferred snack food in a conventional hypothetical purchase task (Epstein et al., 2010), as well as other assessments of medication adherence, physical activity, and physiology. These results are reported in greater detail in Epstein et al., under review. In the MRI scanner, we collected a T1-weighted anatomical scan, followed by the delay discounting and then the purchase task. Participants were at least 2 h postprandial at the time of assessment.

2.3. Tasks

2.3.1. Delay discounting—The fMRI delay discounting task was an adaptation of the Individualized Discounting Task (IDT; see Koffarnus et al., 2017), in which participants are

presented with a limited series of delays allowing for examination of key components of the discounting curve. All participants were presented with intertemporal choices focused on a series of four consecutive delays out of seven including 1 day, 1 week, 1 month, 3 months, 1 year, 5 years and 25 years with a constant delayed amount of \$1000 (see Fig. 1, top panel). To determine the four individualized delays at which participants would make choices in the scanner, they first completed the seven-delay adjusting amount discounting task with a delayed amount of \$1000 (see Section 2.2 and Epstein et al., under review).

Each trial can be categorized as either “hard” or “easy” as well as “immediate available” or “immediate unavailable.” Hard and easy trials are distinguished by the proximity of a choice to an individual’s indifference point and represent the *discounting choice difficulty*. Immediate unavailable vs. immediate available trials are operationalized by the presence or absence of an amount of money available now and represent the *discounting choice availability*. For operationalization of remaining trial types, see Koffarnus et al. (2017).

2.3.2. Purchase—For this study, we used a novel discrete choice task assessing demand for food, designed specifically to examine contrasts of purchasing vs. non-purchasing decisions. Participants were presented with choices to purchase or not purchase a 10 g serving of a preferred snack food (Cheez-Its, Cheetos, Chips Ahoy, Doritos, Fritos, Lays, Oreos, M&Ms, Reese’s, or Swedish Fish) ten times per price over a list of twelve prices (\$0.01, \$0.05, \$0.10, \$0.25, \$0.50, \$1.00, \$2.00, \$5.00, \$10.00, \$20.00, \$40.00, and \$80.00 per serving, presented in random order). Participants were instructed that their choices could not be shared and that the serving sizes they purchased were to be consumed over a 20-minute period. Participants chose whether or not to purchase a serving at the given price by responding on a button box corresponding to the side of the screen on which the text “purchase a 10 g serving of [snacks] for [price]” was displayed (see Fig. 1, bottom panel). While the participant made ten choices to purchase or not purchase at a given price, with a mean inter-stimulus interval = 5 s, the screen displayed a total of the amount of money spent and the number of servings purchased at that price. Between prices, the upcoming price was displayed for 15 s. Each trial can be categorized as a purchase vs. a nonpurchase trial based on whether a participant chose to purchase a serving of snacks within that trial, representing the *purchase choice decision*.

2.4. fMRI data collection

Neuroimaging data were collected at the Virginia Tech site using a 3 T Siemens Magnetom Trio scanner and at the University at the Buffalo site using a 3 T Toshiba Vantage Titan scanner. Structural data were collected using a 3D magnetization prepared rapid acquisition gradient echo (MPRAGE) pulse sequence with parameters: repetition time = 2600 ms, echo time = 3.02 ms, field of view = 256 mm, 192 slices per slab, slice thickness = 1 mm, flip angle = 8° and duration = 4 min 49 s. Functional images were collected using an echo planar image (EPI) sequence during eight runs of approximately 8 min each (four for the delay discounting task, with 24 trials per run, and four for the purchase task, with 30 trials per run), with parameters: repetition time = 2330 ms, echo time = 30, field of view = 220 mm, 33 interleaved slices collected, slice thickness = 4 mm and flip angle = 90°. In a multi-site fMRI study such as this, the likelihood of introducing undesirable inter-site variabilities is

high and this in turn can impact the fidelity of the data (Glover et al., 2012). To minimize these variabilities, the current study utilized a communication and organization structure for stimulus presentation, data collection and quality assurance that attempted to minimize inter-site data variability. Care was taken to ensure that the scanning parameters were matched and that identical versions of the task were presented while scanning at the two sites. A quality assurance protocol scan using a spherical (17.5cm diameter) agar phantom proposed by the Functional Biomedical Informatics Research Network (fBIRN) was performed at both sites to ensure field homogeneity twice during the data collection period (Friedman & Glover, 2006; Magnotta, Friedman, & FIRST BIRN, 2006). During the fMRI analyses, a comparison between data collected at the Virginia Tech site and University at Buffalo site revealed no significant statistical differences.

2.5. Analyses of fMRI data

Analyses of the discounting task were performed in the 54 participants. Behavioral data were analyzed in R, and AFNI (Cox, 1996) was used for all MRI data processing and analyses. Trials were modeled beginning at the moment of task presentation, and ending when the participant indicated their response selecting from one of the two presented options. Preprocessing of functional data was performed using `afni_proc.py`, and included slice timing correction, motion correction, spatial smoothing (6 mm FWHM) and scaling to percent signal change (Cox, 2012). Anatomical volumes were skull-stripped and aligned to the first functional volume before co-registration to the MNI 152 template. The resulting functional-to-MNI transformation matrices were applied to the statistical maps generated by the following GLM analyses. Time points containing motion spikes and time series outliers were censored from the analysis. Apart from baseline and task-related regressors, six additional nuisance regressors were included to account for head motion (roll, pitch, yaw, X, Y, Z).

For first-level analyses, discounting trial contrasts included *hard* trials vs. *easy* trials (discounting choice difficulty condition) and *immediate unavailable* trials vs. *immediate available* trials (discounting choice availability condition), as described in Koffarnus et al. (2017). On average, the number of trials per participant in the delay discounting task were 11.8 control, 38.4 easy, 28.3 hard, 66.7 immediate available, and 17.7 immediate unavailable trials per participant. The demand task included *purchase* and *nonpurchase* trials (purchase choice decision). Because participants made many more nonpurchase choices, only trials at prices which led to some purchasing were included in this contrast to balance trial counts. On average, approximately 46 trials were excluded per participant, leaving approximately 74 trials (excluding 38% of the trials). This improved the ratio of purchase to nonpurchase trials from 20% to 50%. This yielded an average of 44.5 non-purchase (at purchase prices) and 22.0 purchase trials per participant. Elastic and inelastic trial types were also compared, as in other purchase tasks for commodities associated with poor health outcomes (e.g., Gray et al., 2017), but no significant differences between these trials were observed and they are not reported here. A mixed-effects meta-analysis model, the 3dMEMA command in AFNI (Chen, Saad, Nath, Beauchamp, & Cox, 2012), was used for group analyses for each condition. This model accounts for variability within and across participants.

A set of conjunction analyses were performed to indicate overlapping regions of statistically significant changes in BOLD response in the three conditions of interest. The results of the separate 3dMEMA t-statistic maps were combined using conjunction analyses for all three conditions (discounting choice difficulty, discounting choice availability, and purchase choice decision) as well as for each pair of conditions. All of these conjunction analyses were performed conservatively using the minimum statistic conjunction analysis method (Friston, Penny, & Glaser, 2005; Nichols, 2005). Each conjunction was thus defined as a logical ‘and’ null hypothesis, yielding only those voxel clusters that are significant for each of the base contrasts included in the analyses. The result of every conjunction analysis thus represents voxels where all of the base contrasts were independently significant. We used a threshold of $p < 0.05$, FDR corrected for each base contrast (absolute $t = 3.19$ for discounting choice difficulty, $t = 3.20$ for discounting choice availability, and $t = 2.33$ for purchase choice decision) in all of the conjunction analyses.

To indicate differences in BOLD response between pairs of conditions, a mixed-effects analysis of variance was conducted using the 3dANOVA2 command in AFNI, with condition as a fixed effect and subject as a random effect. Next, post-hoc comparisons of two conditions at a time were performed to generate t-statistic maps indicating regions where BOLD response is significantly different between the given conditions paired, FDR corrected at $p < 0.05$ with a minimum cluster size of 20 voxels.

3. Results

3.1. Behavioral data

In the discounting task, all participants exhibited some discounting of \$1000 (i.e., some choices of smaller, sooner over larger, later rewards) over the four individualized delays presented. Eq. (1) was fit to out-of-scanner discounting data (mean RMSE = 0.119). The naturallog-normalized discount rate between the two sites did not differ (see Table S1). The median number of servings of snacks purchased at the lowest price presented (or demand intensity) was 3 (IQR = 2–5). The median breakpoint (indicating the price at which participants cease making purchases) was \$2.00 (IQR = \$2–\$5). The median price of maximum output was \$1.00 (IQR = \$0.50–\$4.25). A median of 18 purchasing decisions (IQR = 12–27) were made, with no differences observed across sites. Neither standard behavioral economic parameters describing these tasks (e.g., hyperbolic discount rate), nor behavioral variables relevant to prediabetes (HbA1c, dietary intake, and usual daily activity) were significantly associated with BOLD response in the neuroimaging analyses.

On average, in the delay discounting task, response times were 2.86 s (SD = 1.38) for control, 2.83 s (SD = 1.26) for easy, 3.60 s (SD = 2.28) for hard, 3.16 s (SD = 1.81) for immediate available, and 4.06 s (SD = 2.01) for immediate unavailable trials. In the purchasing task, response times were 1.87 s (SD = 1.59) for nonpurchase and 2.40 s (SD = 2.16) for purchase trials. In all conditions for both discounting and purchasing, contrasting trial types were of significantly different duration in three pairwise tests corrected for multiple comparisons ($p < 0.05$).

3.2. BOLD responses for discounting and purchasing task conditions

Within the discounting tasks, we contrasted two main trial types: *immediate unavailable* vs. *immediate available* and *hard* vs. *easy*. Consistent with past results (Koffarnus et al., 2017), *immediate unavailable* trials showed a preferential BOLD response in parts of bilateral superior parietal and middle frontal regions (comprising parts of DLPFC), as well as left inferior frontal gyrus compared to *immediate available* trials. *Immediate available* trials showed a preferential BOLD response in the left insula, left superior frontal, bilateral cingulate gyrus, and parts of the bilateral inferior parietal lobule. (Fig. 2, Panel A; see Appendix A, Table S2). Furthermore, the *hard* vs. *easy* contrast (Fig. 2, Panel B; see Appendix A, Table S3) identified preferential BOLD response in *hard* trials of medial frontal, bilateral superior frontal, middle frontal gyrus (comprising parts of DLPFC), and bilateral inferior parietal lobules. In *easy* trials, right insula and bilateral middle temporal showed a relatively greater BOLD response. We did not observe significant differences in BOLD response between immediate and delayed choices in this task.

For the demand task, the contrast of *purchase* compared to *non-purchase* trials at prices where purchases were made was examined (Fig. 2, Panel C; see Appendix A, Table S4). These trials were taken to represent contrasting choices between snacks valued higher than the price presented and those additional snacks valued lower than the price presented. In *purchase* trials, relatively greater BOLD response was seen bilaterally in superior parietal lobules, inferior frontal and medial frontal gyrus (including parts of DLPFC), and thalamus. In *nonpurchase* trials, relatively greater BOLD response was seen bilaterally in the inferior frontal gyrus, insula, caudate, superior temporal gyrus, anterior and posterior cingulate cortex, and parahippocampal gyrus. A comparison was also made for each of the three contrasts and showed no significant differences between data collected from both sites.

3.3. Overlap between tasks

3.3.1. Overlap between all conditions—Across both discounting conditions and the purchasing condition, significant common BOLD response was observed in frontoparietal regions (superior/middle frontal cortex and superior/inferior parietal lobules or Brodmann areas B6, B8, and B40, where B indicates bilateral; see Fig. 3). This null-hypothesis conjunction analysis map indicates regions of significant common BOLD response across all three conditions as well as for each pairwise combination of conditions. Pairwise conjunction analyses indicated additional overlap in frontoparietal, right middle temporal, bilateral medial frontal, and left insula between the discounting choice availability and purchase choice decision conditions (in Brodmann areas B40, R37, B8, and B6); and in frontoparietal, right middle temporal, left medial frontal, and right insula between the discounting choice difficulty and purchase choice decision conditions (in Brodmann areas B40, R39, R13, B9, B8, and B6; see Table 1 for summary and Tables S5–S8 for complete results). Overall, the conjunction analyses showed commonalities in direction of BOLD response between specific trial types underlying each condition. That is, preferential BOLD response for purchase, hard, and immediate unavailable trials versus nonpurchase, easy, and immediate available trials was observed in areas of conjunction. The complete conjunction analysis results, including overlaps between both discounting conditions, are provided in Tables S5–S8. The results of the analyses performed to indicate directionality or difference

in BOLD response between pairs of conditions (a contrast of contrasts) are also included in Tables S9–10 and Fig. S1–2.

4. Discussion

Overall, both delay discounting and snack food purchasing tasks recruited overlapping regions in a prediabetic sample. Conjunction analysis revealed common patterns of BOLD response in specific trial types within these tasks. Pairwise conjunction of purchase choice decision and discounting choice availability indicated significant overlap in Brodmann areas B40, R37, B8, and B6. Pairwise conjunction of purchase choice decision and discounting choice difficulty indicated significant overlap in Brodmann areas B40, R39, R13, and B9. These regions have been functionally linked with executive control, direction of attention, quantitative processing, interoception, and visual processing. Furthermore, directionality of BOLD response in conjunction areas was similar between hard discounting trials, immediate unavailable discounting trials, and purchase demand trials, compared to easy discounting trials, immediate available discounting trials, and non-purchase demand trials, respectively. Here, we will compare these results to others who have studied delay discounting and purchasing in other populations; discuss specific commonality between the types of trials in the delay discounting and purchasing tasks, and interpret overall similarity of BOLD responses in all conditions.

4.1. Comparison to existing literature

4.1.1. Discounting—Our fMRI results for the conditions in the discounting task (choice availability and choice difficulty) are consistent with results obtained using the same individualized discounting task in Koffarnus et al. (2017) while also manifesting a few additional regions. The additional regions may be a result of increased power due to a larger sample size as well as the fact that the participants in the present study were pre-diabetic as opposed to healthy controls in Koffarnus et al. (2017). In the discounting choice availability condition, the present study replicated the results of Koffarnus et al. (2017). Additionally, immediate choice unavailable trials also preferentially activated parts of the left DLPFC (inferior and middle frontal gyri). Parts of the bilateral cingulate, bilateral medial frontal gyrus, bilateral postcentral gyrus and left fusiform gyrus along with the left insula and bilateral cuneus were also preferentially activated by immediate choice available trials in the present study but not in Koffarnus et al. (2017). The present study also showed findings similar to McClure (2004) that parts of the paralimbic cortex (cingulate gyrus) are preferentially activated by immediately available choices as well as to Sripada, Gonzalez, Phan, and Liberzon (2011) where the superior frontal gyrus showed preferential activation when an immediate choice was available and the superior parietal lobule showed preferential activation when an immediate choice was unavailable.

The discounting choice difficulty condition also indicated that the regions associated with hard and easy trials were consistent with Koffarnus et al. (2017). In our prediabetic sample, bilateral DLPFC (inferior and middle frontal gyri), right superior frontal and parts of the bilateral inferior parietal lobules also showed preferential activation for hard trials while parts of the bilateral cingulate gyri, right insula and right postcentral gyrus showed

preferential activation for easy trials. These findings replicated preferential activation for hard trials in the bilateral DLPFC in a previous study by Amlung et al. (2014). Furthermore, these results replicate past findings of relatively greater activation in bilateral DLPFC and intraparietal sulcus when contrasting hard vs. easy trials in both methamphetamine users and a control population (Monterosso et al., 2007).

We note that we did not observe significant differences in BOLD response in the striatum in either discounting condition. The striatum is often cited as a part of a ??-network (immediate options vs. all choice options) frequently associated with delay discounting processes (Carter, Meyer, & Huettel, 2010). However, this network is typically observed in contrasts between all discounting trials irrespective of delay against baseline conditions or in contrasts between immediate choice options against all choice conditions (Eppinger, Nystrom, & Cohen, 2012; as in McClure, 2004; McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007), rather than in the discounting conditions explored here.

4.1.2. Purchase—The present study employed both a novel purchasing task and a novel population (of individuals with prediabetes), and results are thus less directly comparable to previously published datasets. Furthermore, the reported results of the *purchase* vs. *nonpurchase* contrast are based on analyses of trials only at prices where participants purchased at least one serving of snack food. We also performed this same contrast including all prices presented, yielding largely similar results. However, by limiting contrasts to only prices at which some purchasing occurred, nonpurchase decisions may more specifically reflect the decision against additional food options at a given price, especially given the very high range of prices (up to \$80 for a 10 g serving of snacks) at which servings of food were possibly available in the present purchasing task, increasing interpretability of results. Furthermore, while all participants were instructed to be at least 2 h postprandial at the beginning of the scanning period, we did not control for self-reported variation in hunger or other sources of food motivation in the present analyses.

Some prior work (Knutson, Rick, Wimmer, Prelec, & Loewenstein, 2007) has also directly contrasted decisions to purchase against decisions to not purchase various desired products (including some food commodities), specifically in a sample of 26 healthy controls. In accordance with their results, we observed the preferential BOLD response in purchase decisions in left middle and inferior frontal gyri, right posterior cingulate, and left superior parietal lobule. In non-purchase decisions, we replicate all of Knutson and colleagues' results showing a preferential BOLD response in bilateral insula, left post-central gyrus, bilateral inferior parietal lobules and left paracentral lobule. However, in contrast to this study, the present results did not reveal preferential right orbitofrontal cortex and left posterior cingulate activation in purchasing; rather, these regions were associated with nonpurchasing in our prediabetic sample purchasing only food. Future research is needed to clarify whether these distinctions can be attributable to differences in commodities, populations, or task presentation when making purchasing decisions.

Past research has also examined purchasing of specific commodities in relevant populations, both tobacco purchasing among cigarette smokers (Gray et al., 2017) and alcohol purchasing among drinkers (MacKillop et al., 2014). Common activation patterns for cost-benefit

comparison while purchasing both of these commodities were present in the anterior insula, caudate, anterior cingulate, medial frontal gyrus, and dorsolateral prefrontal cortex (Gray et al., 2017). In the present prediabetic sample, each of these regions was preferentially activated in either purchasing (bilateral thalamus, DLPFC) or nonpurchasing (bilateral anterior insula, bilateral caudate, medial frontal gyrus, anterior cingulate cortex, posterior cingulate, and bilateral lingual gyrus) of snack foods, with different portions of precuneus activated in both purchase and nonpurchase conditions. However, their particular role in cost-benefit comparisons cannot be determined using the present purchasing task. The cuneus, which in their smoking sample was associated with price, was in the present prediabetic sample associated with not purchasing trials. We also attempted to define trials as elastic and in-elastic (Gray et al., 2017; MacKillop et al., 2014) but did not observe significant differences between these trial types in the present sample. This may have been due to the differences between our novel purchasing task and the alcohol and cigarette purchase tasks previously used, specifically an imbalance of trial types.

4.2. Interpretation of overlaps

Both delay discounting and purchasing tasks have been previously implicated in the development of challenging health conditions through reinforcer pathology (Bickel et al., 2011a). Specifically, steep delay discounting (indicating higher impulsivity), and high demand for particular commodities in purchase tasks may represent a distinctly greater risk state for obesity (Carr et al., 2011). Overlap in BOLD response between delay discounting and snack food purchasing could represent recruitment of common areas in these two processes, suggesting possible substrates for reinforcer pathology. Both tasks involve making hypothetical choices: about whether you would choose between immediate and delayed rewards that differ in value; or about how much you would pay for a commodity that differs in value now. The precise nature of these overlaps suggests that components of the delay discounting and purchasing tasks correspond in distinct ways.

Relatively extensive overlaps in BOLD response were observed between the purchase choice condition and each discounting condition. The discounting difficulty condition and purchase choice condition both significantly altered BOLD in frontoparietal regions, right middle temporal, bilateral medial frontal, and right insula. Notably, the common regions in bilateral medial frontal are also observed in common between delay discounting, working memory, and response inhibition tasks (Wesley & Bickel, 2014). Between the discounting availability condition and purchase choice condition, overlaps in BOLD response were found in more lateral portions of left middle frontal, and more rostral portions of bilateral medial frontal, and left insula. Overall, regions commonly influenced between the purchasing condition and either discounting condition were distributed through established executive control networks (including bilateral prefrontal); impulsive regions associated with craving, reward anticipation, and interoception (including insula); as well as in attentional, visual, and task-positive networks (including frontoparietal regions).

Furthermore, conjunction analyses revealed commonality between trial types contrasted in each condition. Specifically, regions demonstrating relatively greater BOLD response in purchase trials versus nonpurchase trials also showed preferential response in immediate

unavailable versus immediate available discounting trials. These overlaps suggest choices to purchase snacks may be similar to comparing between only delayed options in a discounting task, requiring co-involvement of executive function and reward anticipation regions. Similarly, purchase trials (versus nonpurchase trials) commonly recruited regions also responding to hard (versus easy) discounting trials. This may suggest additional deliberation during purchasing trials, providing context for recruitment of executive control regions. Overall, purchase, hard, and immediate unavailable trial types may also represent instances of greater cognitive load during task performance. This was supported by significantly longer response times during each of these trial types versus nonpurchase, easy and immediate available trials respectively.

The possibility also exists that the overlap between the delay discounting and purchasing tasks is driven by methodological similarities between the two activities in the scanner (e.g., their hypothetical nature). However, the distinct regions of conjunction between each discounting condition and the purchase condition indicate some specificity of overlap. Although other conditions within these tasks (e.g., the comparison of immediate versus delayed choices in the delay discounting task) exist, we did not observe a significant BOLD response in base contrasts of these trial types. Additionally, future research can best clarify the extent of correspondence between delay discounting tasks and purchasing tasks by comparison with other tasks not commonly explored in reinforcer pathology, as the lack of a comparator task in the present study provides a substantial limitation to the interpretation of the present findings.

4.3. Future directions and conclusions

These results provide a substantial contribution both to the understanding of reinforcer pathology as a theory and to the development of future research. In the present study, BOLD responses in each task did not correspond to task performance. This could be due to the selection of particular features of both delay discounting and purchasing (e.g., hard vs. easy trials, purchase vs. nonpurchase trials) which may not tend to be correlated with task performance. Future research examining additional features of each task may clarify how BOLD response during delay discounting and purchasing corresponds to task performance, and future research into other populations may indicate how this degree of overlap differs between groups with and without possible reinforcer pathologies (Boettiger et al., 2007; e.g., Claus, Kiehl, & Hutchison, 2011). Overall, however, these results provide some insight into how delay discounting and purchasing may interrelate at the level of neural activation. The co-involvement of prefrontal cortex, insula, and frontoparietal regions may suggest an interplay between executive control, interoception, and attention, candidate processes that regulate the selection of rewards over both delay and cost. Each of these interactions may then shed light on the emergence of reinforcer pathology.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Disclosures and conflicts of interest

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Individualized Discounting Task

Purchase Task

Fig. 1.

Task Presentation. Tasks are depicted with whitespace removed. The top panel represents a trial in the individualized discounting task, and the bottom panel represents a trial in the discrete choice demand task.

Fig. 2.

Significant contrasts across discounting and purchasing tasks at $q = 0.05$. Panel A depicts significant results for the immediate unavailable (orange) vs. immediate available (blue) contrast (Discounting choice availability) for the IDT. Panel B depicts significant results for the hard (orange) vs. easy (blue) contrast (Discounting choice difficulty) for the IDT. Panel C depicts significant results for the purchase (orange) vs. nonpurchase (blue) contrast at purchase prices (Purchase choice decision) for the purchasing task. L indicates the left side of the brain with results FDR corrected at $p < 0.05$, minimum cluster size = 20 voxels. ACC = Anterior Cingulate Cortex, CD = Caudate, CG = Cingulate Gyrus, IFG = Inferior Frontal Gyrus, INS = Insula, IPL = Inferior Parietal Lobule, ITG = Inferior Temporal Gyrus, MFG = Middle Frontal Gyrus, MeFG = Medial Frontal Gyrus, MTG = Middle Temporal Gyrus, MOG = Middle Occipital Gyrus, PCC = Posterior Cingulate Cortex, PHG = Parahippocampal Gyrus, SFG = Superior Frontal Gyrus, SPL = Superior Parietal Lobule,

STG = Superior Temporal Gyrus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Fig. 3.

Conjunction analysis between conditions. Minimum statistic conjunction analysis map displaying regions of common activation for each combination of the discounting choice difficulty, discounting choice availability, and purchase choice decision conditions; all three conditions in red, purchase choice and discounting availability in yellow, purchase choice and discounting difficulty in blue, discounting availability and discounting difficulty in pink. *CG* = Cingulate Gyrus, *IFG* = Inferior Frontal Gyrus, *IPL* = Inferior Parietal Lobule, *MeFG* = Medial Frontal Gyrus, *MFG* = Middle Frontal Gyrus, *MOG* = Middle Occipital Gyrus, *MTG* = Middle Temporal Gyrus, *PCG* = Postcentral Gyrus, *SFG* = Superior Frontal Gyrus, *SOG* = Superior Occipital Gyrus, *SPL* = Superior Parietal Lobule, *INS* = Insula. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Summary results of pairwise conjunction analyses between the purchase choice condition and each discounting condition.

Center of mass			Condition T statistic		Extents		BAs	
Size	x	y	z	IU > IA	H > E	P > NP		Regions
Discounting choice difficulty and purchase choice decision								
305	3.4	-24.8	51.5	-	6.99	4.71	L medial frontal*, L superior frontal, L middle frontal; R superior frontal, R medial frontal	L8*, L32, L6; R9, R6
134	-55.8	25.6	28.0	-	-3.46	-5.96	R inferior parietal*, R postcentral, R superior temporal	R40, R3, R2, R1
67	-52.6	61.5	7.6	-	-5.55	-3.15	R middle temporal*, R superior temporal	R39, R37
54	45.3	60.2	48.4	-	4.88	3.53	L inferior parietal*, L superior parietal	L40, L7
43	-24.9	-20.6	59.6	-	4.76	3.60	R middle frontal, R superior frontal	R6*, R8
40	43.3	-29.6	35.2	-	5.79	3.74	L middle frontal*	L9*
27	-43.2	-33.7	39.6	-	3.41	2.80	R middle frontal*, R superior frontal	R9
18	-44.7	-0.2	14.3	-	-4.08	-3.50	R insula*, R precentral	R13
Discounting choice availability and purchase choice decision								
127	-60.7	30.2	27.5	-3.33	-	-6.06	R inferior parietal*, R postcentral	R40*
49	-48.2	64.3	6.0	-4.09	-	-2.64	R middle temporal*	R37
39	36.7	-13.8	57.1	3.96	-	3.67	L superior frontal*, L middle frontal	L8*, L6
33	-0.4	5.3	59.7	-4.13	-	-4.57	L medial frontal*, R medial frontal	L6; R6
27	46.3	20.6	24.7	-3.71	-	-4.31	L postcentral*, L inferior parietal	L40
23	43.0	2.2	17.1	-4.15	-	-3.53	L insula*	
17	-25.4	-22.2	55.9	3.62	-	3.63	R superior frontal*, R middle frontal	R8*, R6
14	5.6	18.0	53.4	-4.12	-	-2.53	L medial frontal*, L paracentral	L6