High dietary restraint improves performance on a food-motivated probabilistic selection task

Jennifer R Sadler[1], Grace E Shearrer[1], Nichollette T Acosta[1], Kyle S Burger[1,2]

[1]Department of Nutrition, University of North Carolina, Chapel Hill, NC, USA

[2]Biomedical Research Imaging Center, University of North Carolina, Chapel Hill, NC, USA

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Corresponding Author:
Jennifer Sadler
2223 McGavran Hall
135 Dauer Drive
Chapel Hill, NC, 27516 USA
jenny_sadler@unc.edu
(443) 846-3687

Abstract

BACKGROUND: Dietary restraint represents an individual's intent to limit their food intake and has been associated with impaired passive food reinforcement learning. However, the impact of dietary restraint on an active, response dependent learning is poorly understood. In this study, we tested the relationship between dietary restraint and food reinforcement learning using an active, instrumental conditioning task.

METHODS: A sample of ninety adults completed a response-dependent instrumental conditioning task with reward and punishment using sweet and bitter tastes. Brain response via functional MRI was measured during the task. Participants also completed anthropometric measures, reward/motivation related questionnaires, and a working memory task. Dietary restraint was assessed via the Dutch Restrained Eating Scale.

RESULTS: Two groups were selected from the sample: high restraint (n=29, score >2.5) and low restraint (n=30; score <1.85). High restraint was associated with significantly higher BMI (p=0.003) and lower N-back accuracy (p=0.045). The high restraint group also was marginally better at the instrumental conditioning task (p=0.066, r=0.37). High restraint was also associated with significantly greater brain response in the intracalcarine cortex (MNI: 15, -69, 12; k=35, $p_{fwe} < 0.05$) to bitter taste, compared to neutral taste.

CONCLUSIONS: High restraint was associated with improved performance on an instrumental task testing how individuals learn from reward and punishment. This may be mediated by greater brain response in the primary visual cortex, which has been associated with mental representation. Results suggest that dietary restraint does not impair response-dependent reinforcement learning.

1. INTRODUCTION

The modern food environment presents a bevy of decision-making opportunities resulting in a host of food choice behaviors. Consider a restaurant: diners choose vastly different menu items based on their expectations about the tastiness of a dish, how full it will make them feel, and whether the dish is in line with their dietary goals (Egger & Dixon, 2014; Serra-Majem & Bautista-Castaño, 2013). The expectations guiding choice require information gained through reinforcement learning (Davidson, Sample, & Swithers, 2014; Johnson, 2013). Reinforcement learning comprises two, broad categories of conditioning: Pavlovian/classical conditioning and instrumental/operant conditioning. Demonstrated by Pavlov's dogs (Pavlov, 2010), classical or Pavlovian reinforcement learning occurs when a stimulus (e.g. a logo) is paired with a food reinforcer (e.g. a sugary, palatable drink). However, Pavlovian learning inadequately explains human eating behavior, rarely is one presented an appetitive reinforcer they did not choose. Rather, reinforcement learning around food typically requires a voluntary response (e.g. choosing a food item to purchase) to get the reinforcer or avoid punishment, and therefore is defined as instrumental or operant conditioning (Ferster & Skinner, 1957). Food choices represent real-world stimulus-response pairings. In general, humans and animals alike learn to associate a logo with a palatable food and will increase behaviors to gain the palatable food; or learn to associate a logo with an unpleasant substance and decrease behaviors avoid it.

Food choices are also influenced by internal factors, such as dietary restraint can also. Dietary restraint is the intention to reduce or limit food intake (independent of actual intake reduction). Under average circumstances, a logo has been associated with a palatable food, and behavior normally would dictate choosing that palatable food. However, high dietary restraint causes one to consciously override the conditioned stimuli to avoid the rewarding behavior. Those with high restraint generally prefer high calorie foods (Houben, Roefs, & Jansen, 2010), but they are more likely to choose foods that fit their goal to limit intake (e.g. low fat or low calorie foods; (Tuschl, Laessle, Platte, & Pirke, 1990). Dietary restraint also impacts food reinforcement learning. High dietary restraint impairs flavor-flavor learning (FFL), which tests preference for a novel flavor after pairing the flavor with a tasty food (Brunstrom, Downes, & Higgs, 2001; Brunstrom, Higgs, & Mitchell, 2005). Individuals with high restraint did not form a preference for a novel flavor paired with candy (Brunstrom et al., 2001). Instead, they prefer flavors that are least frequently paired with candy (Brunstrom et al., 2005). Taken together, high restraint produces the opposite effect in FFL, where individuals learn to avoid a reward-paired flavor instead of preferring the rewarded flavor (Brunstrom et al., 2005). Results could indicate that high dietary restraint impairs learning, but there is another possible explanation. The high calorie candy may not be positively reinforcing for those with high restraint, since it's in conflict with goals to limit food intake. Instead, the candy may act as a punishment, causing participants with high restraint to avoid the reward paired flavor. However, since the FFL task is passive and participants have no choice to avoid the "reward", we cannot determine if dietary restraint impairs conditioning or if a kind of reverse conditioning drives the effects. To address this question, an instrumental conditioning task, where participants can make decisions about reinforcement is needed.

Thus, in the present study we tested how dietary restraint impacts instrumental conditioning via taste reinforcement. We used a taste-based Probabilistic Selection Task (PST; (Frank, Seeberger, & O'reilly, 2004) that examines decision making following reward and punishment, to model instrumental conditioning during a functional magnetic resonance imaging (MRI). To further understand differences in instrumental conditioning associated with dietary restraint, we examined brain response during the PST task. We hypothesized that high restraint would be associated with decreased sensitivity to reward and punishment as measured by the PST and that brain response during reward would be higher in regions important for response inhibition (e.g. dorsolateral and ventromedial prefrontal cortex) in the high restraint group.

2. MATERIALS AND METHODS

2.1 Recruitment. Ninety (n=90) male and female participants were recruited from the Chapel Hill, North Carolina area to complete a cross sectional study. Eligibility criteria included: 1) age 18-28 years, 2) body mass index between (BMI) 20.0 kg/m^2 and 32.0 kg/m^2. Exclusion criteria were: 1) counter-indications of MRI (e.g. metal implants, piercings, pregnancy), 2) current smoking, 3) self-reported current or past diagnoses of an eating disorder, 4) chronic illness or medication requirement that could affect diet, 5) diagnosis of a major psychological condition (bipolar, schizophrenia, major affective disorder), and 6) allergy or intolerance to any study foods. The Institutional Review Board of University of North Carolina at Chapel Hill approved all methods and study participants gave written consent before the start of testing. Study visits took place at the University of North Carolina at Chapel Hill's Gillings School of Global Public Health and Biomedical Research Imaging Center (BRIC).

2.2 Procedures. All measures were completed in a single study visit, lasting 2.5 hours in duration. To normalize the time since last meal in the sample, participants were instructed fast for 4-hours prior to the visit. Height (to the nearest 0.5 cm) and weight (to the nearest 0.1 kg) were measured with a wall-mounted stadiometer and a calibrated scale by trained research staff. BMI (kg/m^2) was calculated using height and weight measurements.

Participants then completed a measurement of working memory via the N-back task on a computer tablet app, PsychLab101© (Version 2.0, Neurobehavioral Systems). Participants completed one, 1-back block and one, 2-back block of the task with alphabet letter stimuli. Block order was counterbalanced across the sample. Working memory was operationalized as participants' overall accuracy on the two blocks of the task.

To select which beverages would be used in the PST, participants completed a taste test of 4 sweet and 4 bitter beverages. The most pleasantly ranked sweet beverage was selected as the reward stimuli. Whereas the least pleasantly ranked bitter beverage was selected as the punishment stimuli, excluding any beverages rated at the lowest possible score for pleasantness, anchored as “least pleasant imaginable” (-100 on a visual analog scale [VAS]). The eight beverages were made from a base of water (940mL), unsweetened Kool-Aid™ Cherry powder (4.5g), simple syrup (60 mL). Simple syrup or a quinine solution were added to the beverages to create different levels of sweetness or bitterness. The composition of the beverages can be seen in **Table 1**. The beverages will be calorically-matched by the addition of maltodextrin, a soluble and flavorless carbohydrate. Levels of sweetness and bitterness were selected from previous studies of taste preference (Charalambous, 2012). During the taste test, participants were given a 20mL sample of each beverage to rate pleasantness, desire to consume, sweetness, bitterness and intensity on VAS anchored at -100 and 100. All sweet beverages were sampled, then participants ranked the beverages from most pleasant to least pleasant. The same process was then completed with the bitter beverages. The order within sweet and bitter groups was randomized for each participant.

Following the taste test, participants completed questionnaires including the Behavioral Inhibition System and Behavioral Activation System Questionnaire scales (BIS/BAS; (Carver & White, 1994) to assess perceived sensitivity to two general motivational systems; the Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ; (Torrubia, Avila, Moltó, & Caseras, 2001) to measure perceived sensitivity to general positive and negative reinforcement; and the Block Food Frequency (BFFQ; (Block, Hartman, & Naughton, 1990) and Beverage Intake Questionnaire (BIQ; (Hedrick, Comber, Estabrooks, Savla, & Davy, 2010) to assess perceived dietary intake in the prior two weeks. Finally, the Dutch Eating Behavior Questionnaire (DEBQ; (Van Strien et al., 1986) was used to measure dietary restraint, external eating and emotional eating constructs.

2.3 Functional MRI Scanning. Anatomical and functional imaging data was collected in a Siemens Prisma 3T scanner at UNC’s BRIC. During the functional scans participants completed the Probabilistic Selection Task (Frank et al., 2004). Visual stimuli were presented with a digital projector/reverse screen display system. Tastants were delivered using programmable syringe pumps (Braintree Scientific BS-8000, Brain-Tree, MA) operated through a program written in PsychoPy (Peirce, 2007) (available at: https://github.com/niblunc/bevel_task) to ensure consistent volume, rate, and timing of taste delivery. A set of tubing attached to the scanner bed was placed into the participants' mouths and delivered the tastes. Button press response was collected via a 5-button response pad (Current Designs Pyka Response Pad, Philadelphia, PA) held in the participant's right hand.

Blood-oxygen-level-dependent (BOLD) signal was collected during functional runs under the following scanning parameters: TR = 2000 ms, TE = 20ms, flip angle = 80°, with a spatial resolution of 3.0mm. Images were collected with whole-brain coverage; 32 4mm slices (interleaved acquisition) were acquired along the AC-PC transverse, oblique plane as determined by the midsagittal section. Anatomical scans were acquired with a TR/TE of 2100ms/2.4ms, flip angle of 15°, TI of 1100ms, matrix size of 256x256, FOV of 22cm, and slice thickness of 1mm.

2.4 Probabilistic Selection Task. Participants completed the Probabilistic Selection Task (Frank et al., 2004), measuring response to reward and punishment. The task was composed of training and testing phases. In the "training" phase, participants were presented with pairs of novel shapes (similar to logos), and asked to select the "correct" shape to receive a reward. Participants were instructed that when they choose "incorrectly", they would receive a punishment. Feedback was probabilistic; each shape was reinforced at a prespecified probability. For example, the A shape was rewarded 80% and punished 20% of the times selected. A visual representation of the task and the reward and punishment frequencies of each shape can be found in **Figure 1**. In the present version of the task, reward and punishment feedback was given in the form of 3mL of sweet (reward) or bitter (punishment) taste to indicate if they chose correctly. Tastes were delivered for 5 seconds, followed by a 1mL rinse of a tasteless solution made to mimic the taste of saliva, delivered over 2 seconds. The next trial proceeded following a 3-7 (mean=5) second jitter. In total, participants completed 104 training trials over four runs, each 6 minutes and 44 seconds in length. Following the training phase during the fMRI scan, participants completed the behavioral testing phase of the task outside of the scanner. During the behavioral testing phase, participants were presented novel pairings of the shapes and asked to select the shape that is more likely to be “correct”. The pairings included one shape from the AB set (A: 80% correct, B: 20% correct), as this set is the most reliable predictor of positive/negative outcome. The proportion of trials in which that participant selects the A shape represented their sensitivity to reward, and the proportion of trials in which that participant avoids the B shape represented their sensitivity to punishment. Participants were grouped by their sensitivity to reward and punishment into four groups: those who selected A and avoided B on >50% of behavioral testing phase trials were considered “Sensitive to Reward and Punishment”, those who selected A on >50% of posttest trials, but did not avoid B were considered “Sensitive to Reward”, those who avoided B on >50% of posttest trials, but did not select A were considered “Sensitive to Punishment” and those who did not select A or avoid B on >50% of posttest trials were considered “Insensitive to Reward and Punishment”. Categories were selected to group participants on both sensitivity to reward and sensitivity to punishment.

2.6 Group Selection and Statistical Analysis. Scoring and Statistical analyses of behavioral data were carried out using the R statistical software package (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria). DEBQ dietary restraint, emotional eating, and external eating subscale scores were calculated in the sample by averaging 1-5 Likert Scale responses on items in each subscale. As no consensus regarding cutoffs for high or low dietary restraint scores exists, dietary restraint groups were selected by splitting the sample by DRES tertiles. Participants with DRES scores in the top tertile were selected as the high restraint group, and those with scores in the lowest tertile were selected as the low restraint group. High restraint and low restraint groups were compared on the psychological and behavioral measures described above (see 2.2) including emotional eating, external eating, working memory, taste test beverage ranking, PST training performance, and sensitivity to reward and punishment groups as assessed by PST posttest. Between group differences were calculated using two samples T-tests and Chi-Squares tests for continuous and categorical variables, respectively. Significance for behavioral/questionnaire group differences was considered at $p < 0.05$.

2.7 Neuroimaging Data Analysis. Neuroimaging data was processed and analyzed primarily using FSL (FMRIB Software Library, www.fmrib.ox.ac.uk/fsl) following an established pipeline. In brief, DICOMS were converted to the Brain Imaging Data Structure (Gorgolewski et al., 2016) (BIDS file structure; http://bids.neuroimaging.io), then, preprocessing was performed via the fMRIPrep pipeline (Esteban et al., 2018) (http://fmriprep.readthedocs.io/en/latest/index.html) which includes: first, skull stripping using Advanced Normalization Tools (ANTs); FSL's Automated Segmentation Tool (FAST) for tissue segmentation; spatial normalization to Montreal Neurological Institute (MNI) 152-Asymmetrical space is performed using ANTs' registration option. FreeSurfer was used to reconstruct surfaces from structural images. Functional images will be motion corrected using FSL's MCFLIRT, corrected for field map distortion, and spatially smoothed using a 6mm Gaussian full width half maximum. Analyses will be performed via recolonized approaches in FSL including accounting autocorrelation and highpass filtering and nuisance regressors (the 6 motion parameters, their squares and high motion time points (> 0.9). Further details of the pipeline are available here: https://fmriprep.readthedocs.io/en/latest/workflows.html.

Following preprocessing, individual and group level analyses were carried out in FSL's FMRI Expert Analysis Tool (FEAT; (Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004; Woolrich, Ripley, Brady, & Smith, 2001). Within subject models assessed both brain response to reward was defined as sweet taste compared to neutral taste; and brain response to punishment was defined as bitter taste compared to neutral taste. Motion parameters were included as nuisance regressors at the individual level. At the group level, the analysis followed a two sample T-test, comparing brain response in both the reward contrast and the punishment contrast between the high restraint and low restraint groups. Multiple comparisons were controlled for by using the threshold free cluster enhancement, nonparametric thresholding algorithm in FSL's randomize (n permutations = 5000) resulting in a family-wise error rate corrected significance threshold of $p_{fwe} < 0.05$ (Smith & Nichols, 2009).

3. RESULTS

*3.1 Dietary Restraint Groups***.** In the main sample (n = 90), the mean$\pm$SD of DRES score was 2.24 $\pm$ 0.75. The Participants with DRES scores in the lowest tertile of the sample (< 1.84) were classified as low dietary restraint (low DR), and participants with DRES scores in the highest tertile of the sample (> 2.50) were categorized as high dietary restraint (high DR). The resulting sample included n=30 participants in the low restraint group and n=29 participants in the high restraint group. To confirm, the high restraint group reported significantly higher DRES scores than the low restraint group (Low DR: $\bar{x} = 1.4 \pm 0.3$; High DR: $\bar{x} = 3.1 \pm 0.4$; $t = 19.0$; $p < 0.001$). Participants were primarily Caucasian (64.4%) or Asian/Pacific Islander (25.4%), and non-Hispanic (94.9%).

3.2 Behavioral, Physiological, and Self-Reported Differences between Dietary Restraint Groups. Significant differences between the high restraint and low restraint groups were identified in behavioral, physiological, and self-reported measures (summarized in **Table 2** and visualized in **Figure 2**). The groups also reported significant difference in the DEBQ emotional eating subscale (Low DR: $\bar{x} = 1.9 \pm 0.7$; High DR: $\bar{x} = 2.2 \pm 0.6$; $t = 2.0$; $p = 0.046$). The two groups did not show significant differences in the external eating subscale ($t=0.3$; $p = 0.8$). As predicted, the high restraint group had a significantly higher BMI than the low restraint group (Low DR: $\bar{x} = 23.2 \pm 2.5$; High DR: $\bar{x} = 25.5 \pm 3.0$; $t = 3.2$; $p = 0.0026$). The low restraint and high restraint groups significantly differed in the sweetness of the reward selected during the taste test, such that a greater proportion of the high restraint group chose the less sweet beverages (level 1 or 2: 55%) compared to the low restraint group (level 1 or 2: 16%; X^2 = 11.6, *p* = 0.0087). A similar effect was observed with the bitterness of the punishment selected, where a greater proportion of the high restraint group ranked the bitterest beverage or next most bitter beverage (93%) as the least palatable compared to the low restraint group (70%; X^2 = 8.5, *p* = 0.037). Finally, the groups performed differently on the N-back task, where the low restraint group had a significantly higher percent accuracy than the high restraint group (Low DR: $\bar{x}$ = 91% ± 6%; High DR: $\bar{x}$ = 86% ± 11%; t = 2.1; *p* = 0.045).

On self-report dietary intake measures, the high restraint group reported consuming lower daily intake than the low restraint group (Low DR: $\bar{x}$ = 2015 ± 805 kcals; High DR: $\bar{x}$ = 1666 ± 517 kcals; t = 2.0; *p* = 0.052). The high restraint group also reported consuming fewer 12oz servings of sugar sweetened beverages per day (inclusive of sodas, root beer, and fruit flavored beverages; Low DR: $\bar{x}$ = 2.0 ± 1.2; High DR: $\bar{x}$ = 1.6 ± 0.7; t = 1.8; *p* = 0.083). Finally, the two groups showed different performance on the posttest of the probabilistic selection task (X^2 = 7.8, *p* = 0.066, effect size (*r*) = 0.36). The high restraint group had a higher proportion of individuals who were sensitive to reward and punishment (n=10; 34%) or sensitive to reward (n=8; 28%), whereas the low restraint group had a higher proportion of individuals who were sensitive to punishment (n=9; 30%) or insensitive to reward and punishment (n=12; 40%).

The dietary restraint groups did not show significant differences in sex distribution (X^2 = 0.85, *p* = 0.13), age (t = 1.3, *p* = 0.20), DEBQ External Eating Subscale scores (t = 0.26, *p* = 0.79), or taste test VAS scores for any of the sweet and bitter beverages (*p's* = 0.15-0.98). Also, the two groups did not differ in their overall accuracy in avoiding punishment in the PST posttest (t = 1.37, *p* = 0.18) or overall accuracy in selecting reward in the PST posttest (t = 1.6, *p* = 0.12).

3.3 Differences in Brain Response between Dietary Restraint Groups.

Brain response during the PST training demonstrated differences between the high restraint and low restraint groups. Significant group differences in response to punishment (bitter > tasteless) was found in the high restraint compared to low restraint group comparison in the right intracalcarine cortex (MNI coordinates: 15, -69, 12; k = 35, t = 3.98) (**Figure 3)**. When comparing brain response to reward (sweet > tasteless) between the dietary restraint groups, no significant differences in activity was observed under the high restraint > low restraint comparison or the low restraint > high restraint comparison.

4. DISCUSSION

How we learn from taste is an important determinant of future eating behavior. Compared to studies of passive reinforcement learning, our study demonstrates that high dietary restraint does not confer deficits on a response-dependent reinforcement learning task. Rather, in our sample, individuals reporting high dietary restraint were more likely than individuals reporting low dietary restraint to successfully learn from reward and punishment on the probabilistic selection task. Our results demonstrate the nuanced ways in which dietary restraint influences reinforcement learning.

The goal of high dietary restraint is to limit caloric intake, and this goal affects how individuals with high dietary restraint respond to food rewards. Sugar and fat are inherently rewarding tastes (Ventura & Mennella, 2011), and independent of degree of restraint, people report these foods as palatable (Houben et al., 2010). However, when given a choice, those with high restraint choose against palatability for the less palatable low-calorie foods over full-fat/sweetened foods (Tuschl et al., 1990). This conflict between what individuals with high restraint want to eat versus what they choose to eat affects reinforcement learning. When reinforcement learning tasks use an energy dense reward, high restraint individuals do not undergo reinforcement learning in the same way as low restraint counterparts (Brunstrom et al., 2001). Candy rewarded Pavlovian conditioning is impaired in individuals with high restraint

(Brunstrom et al., 2001), but when Pavlovian conditioning is rewarded with money, high restraint individuals show stronger conditioning than low restraint individuals (Coppin, Nolan-Poupart, Jones-Gotman, & Small, 2014). This suggests that high dietary restraint does not disrupt all conditioning, but rather, top-down cognition reverses the reward derived from highly energy dense foods, leading participants avoid them. Our data supports this idea as well. The high restraint group ranked lower sweetened beverages as their most preferred. The beverages were calorically matched, but sweetness conveys information about caloric content (De Araujo et al., 2008), so the high restraint group preferred a beverage they possibly thought had fewer calories. Participants with high dietary restraint may not have felt the need to avoid the low sugar reward, and thus performed better on the task than the low restraint group. Of note, this difference was marginally non-significant with a p-value of 0.066. This corresponded to a medium effect size (r = 0.37). With a larger sample, we may have seen a significant effect between dietary restraint groups.

When we examined brain response to reinforcement during instrumental conditioning, we found that in response to punishment via bitter taste, the high dietary restraint group had significantly stronger activity in the primary visual cortex as compared to the low dietary restraint group. Traditionally, the intra-calcarine cortex is involved in mental representation of imagery and abstract words (Lambert, Sampaio, Scheiber, & Mauss, 2002). Activity in the intra-calcarine cortex during punishment via taste may reflect participant’s forming a mental image of the shape they selected while receiving feedback. Individuals with high dietary restraint show a stronger response in the intra-calcarine cortex during punishment, suggesting they may form mental representation of the shapes more strongly during punishment than those with low dietary restraint. However, this difference in brain response during punish does not clearly correspond with behavioral sensitivity to punishment, as the high dietary restraint group was less likely to be sensitive to punishment on the PST posttest. Together, results suggest that while the high dietary restraint group may have responded more strongly in a brain region involved in mental representation during punishment, this did not contribute to greater behavioral sensitivity to punishment. Despite rating the bitter beverage as equally sub-palatable as the low dietary restraint group, it is possible that the bitter beverage was not as strongly aversive to the high dietary restraint group.

Comparing the dietary restraint groups resulted in effects consistent with prior research. First, the high dietary restraint group also showed lower working memory capacity as measured by an N-back task than the low dietary restraint group. Dietary restraint is theorized to increase cognitive load, which in turn impacts working memory (Green & Rogers, 1998) and other cognitive task performance (Kemps & Tiggemann, 2005). Our results suggest the same effect, where the cognitive load associated with high dietary restraint potentially reduced participants' accuracy on the N-back task, compared to the low dietary restraint group. Second, the high restraint group had significantly higher BMI than the low restraint group. This result add to the other reports positive correlations between DEBQ restraint scale scores and BMI in college aged populations (Labbe, Rytz, Brunstrom, Forde, & Martin, 2017) and in adolescents (Goldfield et al., 2010). Together, results support that BMI and dietary restraint are positively associated. Of note, the direction of the relationship between BMI and dietary restraint is contentious. Dietary restraint is associated with cyclical overeating during lapses in control (Polivy & Herman, 1985; Stice, 2002). Lapses in control and subsequent overeating contribute to weight gain and eventual overweight or obesity (Polivy & Herman, 1985), suggesting that high dietary restraint causes elevated weight status. However, this relationship is not consistently supported in longitudinal studies (Lowe, Doshi, Katterman, & Feig, 2013), and other research demonstrates that BMI increases may proceed change in dietary restraint, where BMI increases contribute to increased restraint with the intention of changing weight status (Snoek, van Strien, Janssens, & Engels, 2008). The present study includes cross-sectional assessment of this relationship, so we cannot test the direction of the relationship between BMI and dietary restraint in our sample.

Finally, high dietary restraint was associated with marginally lower self-reported caloric intake and lower self-reported consumption of sugar sweetened beverages. Importantly, this effect is derived from a self-report measure of perceived dietary intake, and not an objective measure of intake. High dietary restraint does not consistently show an inverse effect on caloric intake (Stice, Cooper, Schoeller, Tappe, & Lowe, 2007). In our sample, the high restraint group may perceive that they consume fewer calories/SSBs compared to the low restraint group, but likely are not accurately assessing their intake (Westerterp & Goris, 2002).

One caveat, our sample in general did not perform well on the PST task training or posttest. Compared to prior studies (Coppin et al., 2014; Frank et al., 2004), our sample was less accurate on the posttest (the average sensitivity to reward & punishment was about 50%), suggesting that they may not have learned the reinforcement contingencies presented during training as well as prior samples. This difference could be the result of differences in the training paradigms. Our training was completed during a MRI scan to gather data on brain response to the taste reinforcers during learning. This provided novel data, but confined the training to a set number of trials. In the original task, was completed on a computer and allowed participants to completed up to 240 training trials, stopping if participants they reached an performance criterion of 75% accuracy across trials (Frank et al., 2004). Our sample may not have had enough exposure to the training trials, which would result in low overall accuracy in the posttest. To date, this is the first study to use taste, a primary reinforcer, as stimuli on the PST instead of monetary reinforcers. This innovation may have been counterproductive to training however, since repeated exposure to taste can lead to sensory specific satiety (Hetherington & Rolls, 1996), where a rewarding food becomes less palatable as it is consumed repeatedly. This sensation would decrease the rewarding value of the sweet taste over the course of the scan, narrowing the reinforcer value contrast between the sweet reward and bitter punishment. In combination with the comparatively low number of training trials, this downward shift in the value of the reward could further contribute to training disruptions within the sample. Future studies applying this task with food reinforcement should consider the role of sensory specific satiety on reinforcer value when designing their task and setting the number of training trials.

5. CONCLUSIONS

In summary, our results demonstrate that high dietary restraint is associated with decreased working memory capacity, elevated body mass index, and improved performance on an instrumental conditioning task with taste reinforcers. Compared to prior reports that high dietary restraint reduces the capacity for food-motivated reinforcement learning (Brunstrom et al., 2001; Coppin et al., 2014), the present results suggest that when the food reinforcer is thought to be congruent with dietary goals, high dietary restraint may improve conditioning. This discrepancy is possibly driven by the perception that the reinforcer selected is less calorically dense than other available reinforcers, thus preventing the top-down change in reinforcer value seen with more calorically dense, traditionally rewarding foods used previously as stimuli.

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Table 1. Beverage Recipes (per 300 mL)

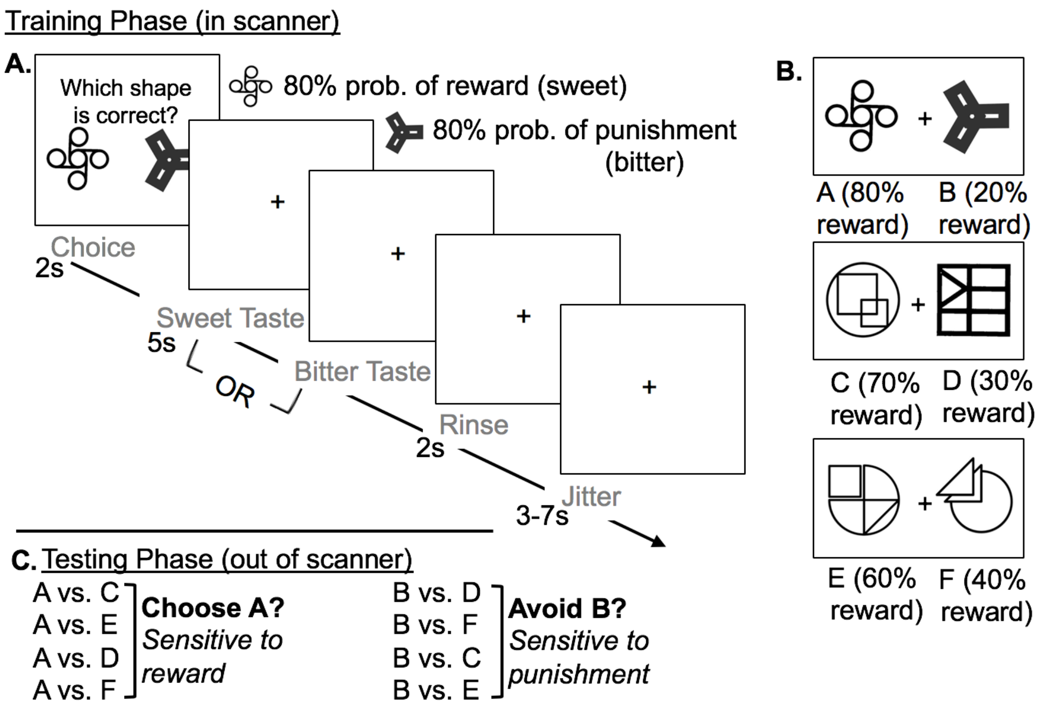
Flavor	kcal	Sugar (g)	Quinine (mg)	Maltodextrin (g)
Sweet Level 1	104.6	14.2	--	20.9
Sweet Level 2	105.4	21.2	--	10.5
Sweet Level 3	105.4	28.2	--	5.3
Sweet Level 4	105.4	35.1	--	0.0
Bitter Level 1	105.3	7.0	12.0	7.0
Bitter Level 2	105.3	6.8	24.0	7.1
Bitter Level 3	105.3	6.3	48.0	7.2
Bitter Level 4	105.3	5.5	72.0	7.4

Table 2. Dietary Restraint Group Characteristics and Comparison

	Low Dietary Restraint (n=30)	High Dietary Restraint (n=29)	Between-Group Statistic	*p*-Value
BMI (kg/m^2)	23.21 ± 2.53	25.47 ± 2.95	t = 3.16	0.0026*
Age (years)	20.93 ± 2.27	21.69 ± 2.19	t = 1.30	0.20
Sex	14 F (46.7%)	17 F (58.6%)	X^2 = 0.85	0.13
DEBQ - Dietary Restraint	1.44 ±0.25	3.12 ±0.41	t = 18.97	< 0.001*
DEBQ - External Eating	3.02 ± 0.68	2.98 ± 0.5	t = -0.26	0.79
DEBQ - Emotional Eating	1.89 ± 0.65	2.22 ± 0.59	t = 2.04	0.046*
FFQ – Daily total kcals	2015.0 ± 804.8	1666.4 ± 516.5	t = -1.99	0.052†
BIQ – Daily portions of SSB	2 ± 1.15	1.56 ± 0.68	t = -1.77	0.083†
N-Back Accuracy	0.91 ± 0.06	0.86 ± 0.11	t = -2.07	0.045*
Preferred Sweet Reinforcer	1: 3 (10.0%) 2: 2 (6.7%) 3: 7 (23.3%) 4: 18 (60.0%)	1: 5 (17.2%) 2: 11 (37.9%) 3: 6 (20.7%) 4: 7 (24.1%)	X^2 = 11.63	0.0087*
Pleasantness Rating of Sweet Reinforcer	37.5 ± 20.2	41.5 ± 16.0	t = 0.83	0.41
Preferred Bitter Reinforcer	1: 3 (10%) 2: 5 (17%) 3: 3 (10%) 4: 19 (6%)	1: 1 (3%) 2: 1 (3%) 3: 11 (38%) 4: 16 (55%)	X^2 = 8.48	0.037*
Pleasantness Rating of Bitter Reinforcer	-42.8 ± 32.8	-49.7 ± 21.5	t = -0.96	0.34
PST Training Phase - Accuracy	0.51 ± 0.05	0.5 ± 0.05	t = -0.72	0.47
PST Posttest - Reinforcer Sensitivity Groups	S: 3 (5%) SR: 6 (10%) SP: 9 (15%) InS: 12 (20%)	S: 10 (17%) SR: 8 (14%) SP: 5 (8%) InS: 6 (10%)	X^2 =7.18	0.066†

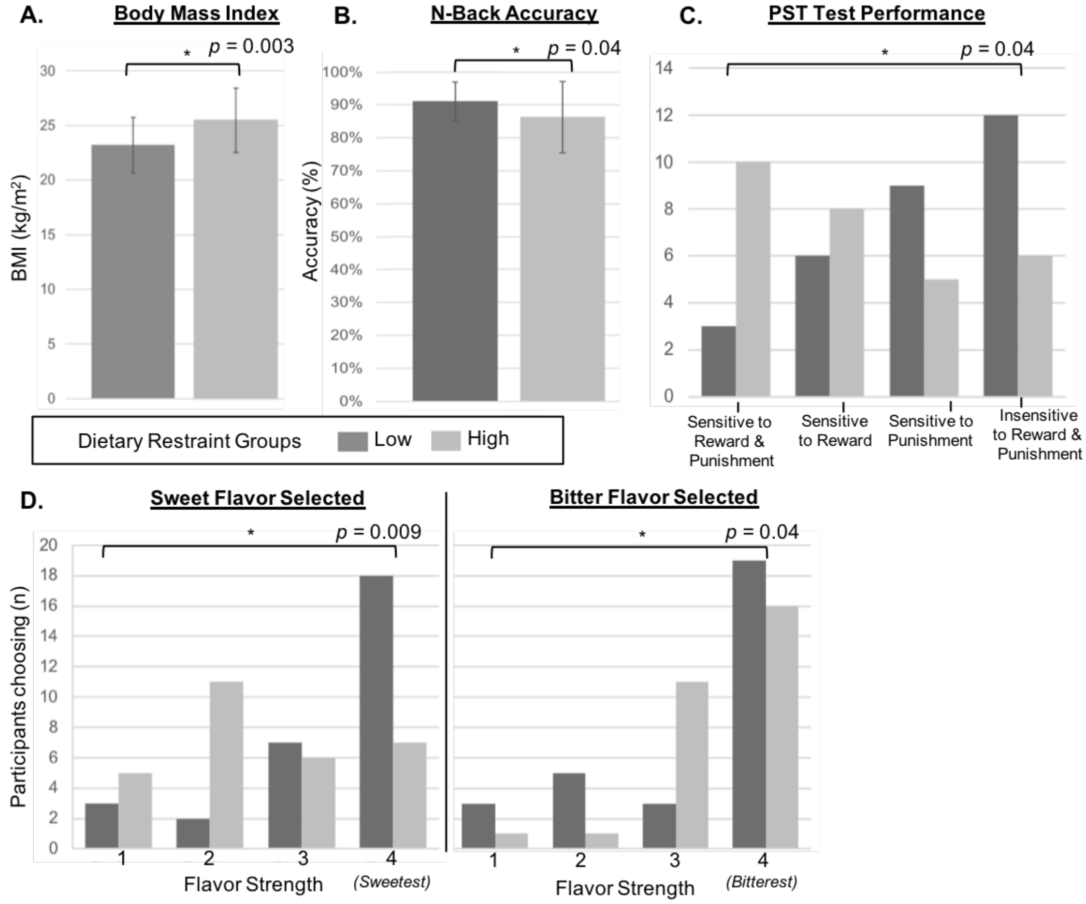
S = Sensitive to Reward and Punishment; SR = Sensitive to reward only; SP = Sensitive to Punishment only; InS = Insensitive to Reward and Punishmnet
* = significant ($p < 0.05$)
† = trending significance ($p < 0.10$)

Figure 1: Probabilistic Selection Task



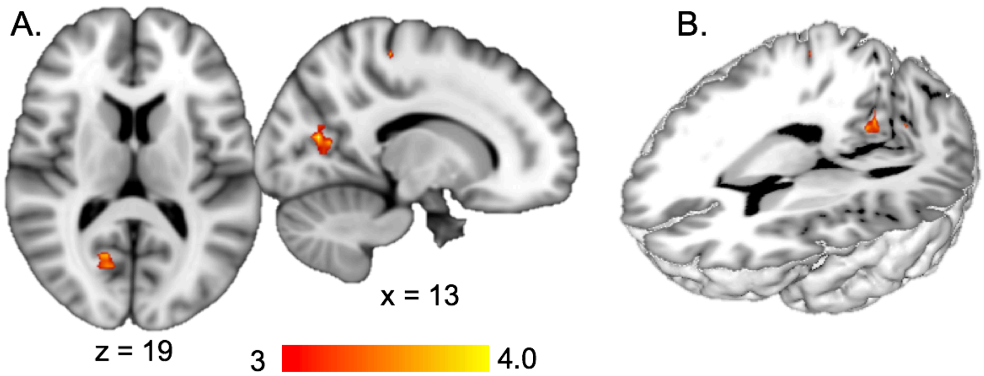
Caption: **A.** Visual representation of one trial of the Probabilistic Selection Task. Boxes represent what is presented to participants. On each trial, participants are first presented with a pair of shapes and instructed to select the shape they think is correct. Based on their selection, they receive either a reward (sweet taste) or punishment (bitter taste). After either taste, they receive a rinse of neutral solution, then there is a jitter of 3-7 seconds between trials. **B.** The reinforcement probabilities associated with each shape pair. Probabilities shown reflect the likelihood a shape is rewarded with a sweet taste when selected. For example, shape C is rewarded with a sweet taste 70% of times selected, but punished with a bitter taste 30% of times selected. **C.** Following training in the scanner, participants' sensitivity to reward and punishment is tested by presenting the A and B shapes against all other shapes to test if participants have learned to choose the A shape (highest reward likelihood), and avoid the B shape (highest punishment likelihood).

Figure 2: Differences between high dietary restraint and low dietary restraint groups in physiological and behavioral measures



Caption: Behavioral and physiological differences between the dietary restraint (DR) groups is summarized here: **A.** Participants reporting high restraint had significantly higher BMI than those reporting low DR. **B.** High restraint was significantly associated with decreased working memory performance as measured by N-back task accuracy, compared to low DR. **C.** The distribution of participants' sensitivity to reward and punishment on the Probabilistic Selection Task (PST) posttest was significantly different between high restraint and low restraint groups, such that high restraint was. **D.** RESTRAINTgroups also significantly differed in the flavor strength selected from the sweet and bitter beverage stimuli, such that high restraint selected less of the sweetest flavor and selected a greater proportion of the two most bitter flavors.

Figure 3: High dietary restraint is associated with brain response to punishment via bitter taste



Caption: Brain response to punishment via bitter taste (contrasted against neutral solution) is stronger in the right intra-calcarine cortex (MNI coordinates: 15, -69, 12; *k* = 35, t = 3.98) in the high dietary restraint group (n=29) compared to the low dietary restraint group (n=30). A) Response is shown in horizontal and sagittal planes. MNI space coordinates of each slice are presented below the image. B) Three-dimensional rendering of same response.