Decreasing the Consumption of Foods with Sugar Increases Their Reinforcing Value: A Potential Barrier for Dietary Behavior Change

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ABSTRACT

Background The Dietary Guidelines for Americans (DGA) have recommended reducing added sugar intake since its inception in 1980. Nearly 40 years later, added sugar consumption still exceeds 2015-2020 DGA recommendations among most of the population. The reinforcing value of food influences eating behaviors, and foods high in added sugars are highly reinforcing. Restricting intake of foods high in added sugars as part of a low-sugar diet may increase their reinforcing value such that reducing consumption may be difficult to maintain. If so, this would present a mechanistic barrier to making the necessary dietary changes to meet 2015-2020 DGA recommendations.

Purpose To determine whether the relative reinforcing value of foods high in added sugars is altered when reducing intake of all foods high in sugars.

Methods Obese (n=19) and normal weight (n=23) men and woman who habitually consumed over 10% of their calories from added sugars completed the study. Reinforcing value of foods high in added sugars was measured via progressive ratio schedules of reinforcement before and on day 7 of a weeklong controlled feeding intervention where added sugars comprised 2.5% to 4.0% of daily calories and total sugars 7.3% to 8.6% of daily calories.

Results The reinforcing value of foods high in added sugars increased ($P<0.01$) after consuming a diet low in total added sugars for 1 week in both obese and normal weight participants.

Conclusion Adhering to a low-sugar diet for 1 week increases the reinforcing value of foods high in added sugars. Future studies should examine whether consuming a diet low in added sugars, but not other sugar, increases reinforcing value of foods high in added sugars and whether high–added sugar food reinforcement returns to baseline after longer-term reductions in added sugars.
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THE 2015-2020 DIETARY GUIDELINES FOR AMERICANS (DGA) focuses on five guidelines and recommendations for a healthy eating pattern.[1] One guideline is to limit energy intake from added sugars to less than 10% of calories per day. Added sugars include sugars added to foods in processing or preparation. These added sugars are almost always in the form of sucrose or high-fructose corn syrup, as opposed to naturally occurring sugars founds in foods such as fruit or milk, which are often fructose, lactose, or glucose. Foods high in added sugars such as desserts, sugar-sweetened beverages, and candy contribute little to the overall nutrient adequacy of the diet,[2] and with the average American consuming almost 91 g of added sugar per day (more than 16.5% of daily energy intake),[3] recommendations on reducing their intake are warranted.

Reducing added sugar has been a DGA recommendation since 1980.[4-6] Despite recent decreases[7] and the long-term emphasis on reducing added sugar intake, consumption continues to exceed recommended guidelines. Americans are consuming greater than 290 kcal/day from added sugars, with 59.6% of the population failing to meet 2015-2020 DGA recommendations.[8] The reinforcing value of added sugars may increase the difficulty of lowering their consumption because the reinforcing value of foods is a prime driver of eating choices and total energy intake.[9-11] Foods high in added sugars are highly reinforcing,[9,12-14] which may make it more difficult to moderate their consumption. Preference for sweet-tasting foods is considered to be an evolutionarily conserved trait, because even at initial exposures animals prefer sweetened water over plain water.[15] The hedonic value of sweet taste is mediated by the opioid system with sugar having effects similar to some drugs of abuse.[15,16] Separate from the opioid system, sugar can induce motivational effects similar to other reinforcers (ie, drugs of abuse, alcohol, sex) by increasing extracellular dopamine in the nucleus accumbens shell.[17] All of these factors contribute to greater intake of foods high in sugar, especially added sugars.

Reducing a reinforcing behavior can be challenging due to the increase in its reinforcing value that occurs when reducing access to a reinforcer below its base rate.[18] The "Disequilibrium Approach" is a theory that predicts how the circumstances of reinforcement are created or limited by changing access from the baseline.[18,19] Disequilibrium occurs in two forms, either response deficit or response excess. Response deficit occurs when access falls below the baseline amount, and response excess occurs when access is increased above baseline. According to the Disequilibrium Approach theory, the response deficit condition will result in an increase in reinforcement. For instance, one factor that increases the difficulty of maintaining energy restriction is that reducing energy intake below baseline increases overall food reinforcement.[20-24] Deprivation-related increases in the reinforcing value of food also occurs without alterations in food hedonics, indicating that the reinforcing value of food is more sensitive and a separate construct than the hedonic value, or liking, of food.[23] The same may be true for specific types of foods when total energy intake is not reduced. Studies with children, although reinforcing value was not measured, have shown that restricting access to a specific snack food when other snack foods are available during an afternoon snack time increases the attractiveness and intake of the restricted food when the restriction is removed.[25-27] It is possible that the increased intake results from an intensification in the reinforcing value of the restricted food.[25] However, it is not yet known whether reducing intake of foods high in added sugars as part of a low-sugar diet increases the reinforcing value foods high in added sugars. If so, this would present a mechanistic barrier to behavior changes required to meet 2015-2020 DGA recommendations.

Weight status may play a role in how attempts at dietary alteration can change food reinforcement. When asked to consume a provided favorite snack food in excess, the reinforcing value of the snack food increased among obese people, but decreased in normal weight people.[12,28] However, given the evolutionarily conserved nature of preference for sweet-tasting foods,[15] it is not clear whether sugar restriction will produce differential effects on the reinforcing value of foods high in added sugars in normal weight and obese people. In addition to body mass index (BMI; measured as kilograms per square meter), dietary restraint, dietary disinhibition, and hunger may influence the reinforcing value of foods.[29] The present study investigated the effect of adhering to a diet low in sugar for 1 week on the reinforcing value of foods high in added sugars relative to foods lower in added sugars (termed relative reinforcing value [RRV] of sugars [RRV_{sugars}]), while keeping total energy intake consistent. It was hypothesized that the RRV_{sugars} would increase after a 1-week period of restriction of foods high in both total and added sugars with obese people showing a greater increase in RRV_{sugars}. If so, this would suggest a barrier to the behavior changes required to meet 2015-2020 DGA recommendations.

MATERIALS AND METHODS

Design

A pre-post study design was employed. Initial screening visits were used to determine study eligibility. Questionnaires, resting metabolic rate (RMR), and pretreatment RRV_{sugars} were completed on subsequent visits prior to a 7-day dietary intervention designed to reduce daily intake of sugar to <10%. Participants were classified as normal weight (BMI=18.5 to 24.9) or obese (BMI≥30). All participants received the same 7-day diet intervention. Post-treatment RRV_{sugars} was completed on the final day of the dietary intervention. All study assessments and measures took place at the Grand Forks Human Nutrition Research Center and were performed by on-site staff or researchers. Upon study completion, participants were thanked and compensated $120.

RESEARCH SNAPSHOT

Research Question: Does consumption of a diet low in sugar increase relative reinforcing value of foods high in added sugar, and do obese individuals experience a greater increase in relative reinforcing value of foods high in added sugar compared with normal weight individuals?

Key Findings: Forty-two adult participants, who habitually consumed diets high in added sugars, were placed on a 7-day diet with <10% of kcal from total sugars. Relative reinforcing value of foods high in added sugar was found to be greater post-treatment for both obese and normal weight participants.

Screening. In all, 100 potential participants were screened (Figure 1). Of these, 44 met eligibility requirements and consented to be in the study. Two participants withdrew for scheduling reasons prior to completion. The final sample size included 42 participants (37 females) who were either normal weight (BMI<25; n=23) or obese (BMI>30; n=19) and between the ages of 18 and 39 years. Recruitment occurred through the greater Grand Forks, ND, metropolitan area during 2016-2017. Participants were a sample who responded to recruitment media including printed brochures and fliers and online advertisements placed on the Grand Forks Human Nutrition Center website. All participants met the entry criteria of nonsmoker, not taking medication that influenced hunger or metabolism, not diabetic (fasting blood glucose<126 mg/dL) measured by Accu-Check finger stick (Roche Diagnostics), and weight stable (have not lost or gained 2 kg in the previous 3 months).

After providing written informed consent, participants were measured for anthropometrics and completed a semi-quantitative food frequency questionnaire (Dietary History Questionnaire II)[30] to determine their habitual consumption of added sugars. Only participants who reported habitually consuming >10% of their daily calories from added sugars qualified for the study. Those who qualified were scheduled for measurement of RMR and baseline RRV_{sugars} before initiating the dietary treatment. Participants also completed the Three-Factor Eating Questionnaire (TFEQ)[31] during their baseline visit. The study was approved by the University of North Dakota Institutional Review Board and registered under ClinicalTrials.gov NCT02744001.

Dietary Intervention. Participants completed a 7-day controlled feeding dietary intervention that manipulated sugar intake. Dietary energy needs were determined via RMR

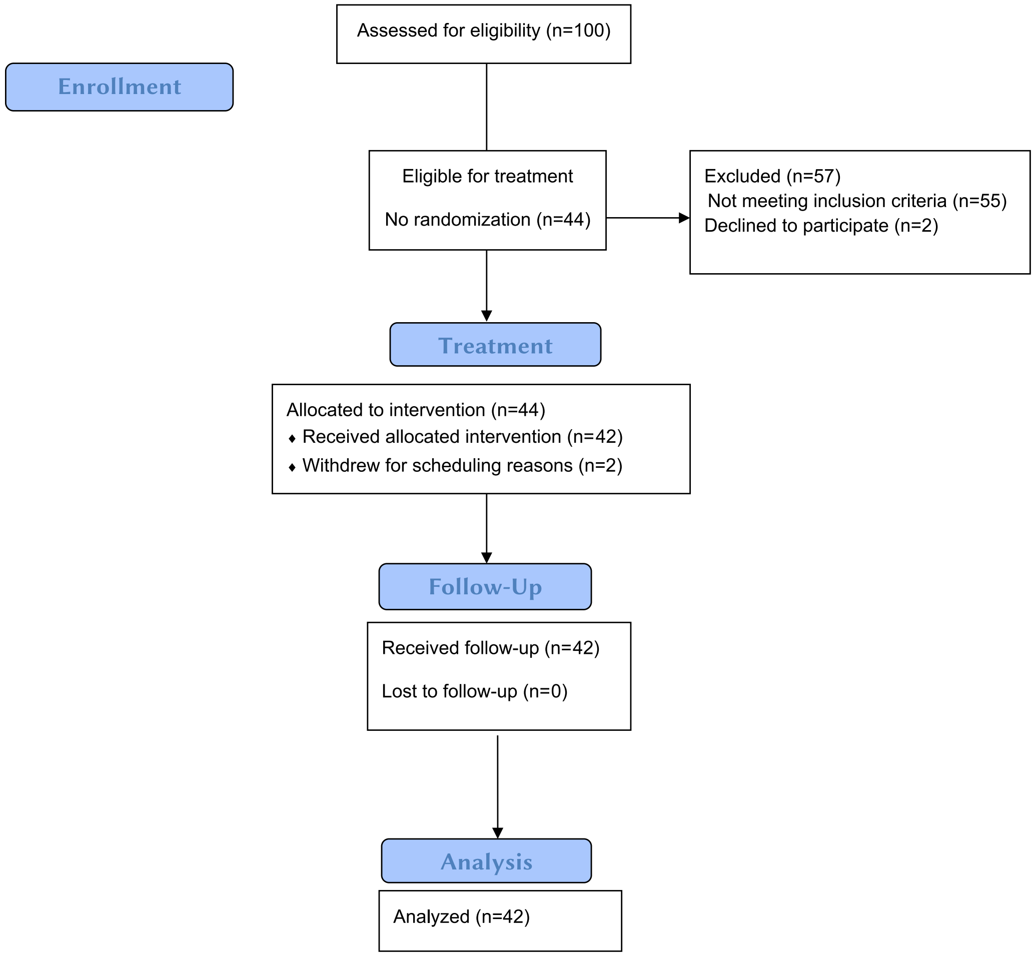

Figure 1. Enrollment, competition, and reasons for noncompletion of 100 participants screened for study.

and adjusted for physical activity amount. Total energy intake was set to keep participants in energy balance to prevent a confounding effect of energy deficit, which would increase the reinforcing value of all foods.[20-24] Participants were blinded to the purpose of the study and therefore were not aware that the diets were restricted of total sugars prior to starting the intervention. Foods high in natural sugars (ie, fruit) or nonnutritive sweeteners were also excluded as much as possible due to the similar sweet tastes many of these foods have in common with foods high in added sugars. Lactose-containing milk was included in the diet, because plain milk is not typically considered a sweet-tasting food. The experimental diet was a 3-day rotating menu that consisted of the average macronutrient distribution from the National Health and Nutrition Examination Survey "What We Eat in America 2011-2012" survey for adults over the age of 20 (approximately 16% from protein, 51% carbohydrate, 33% fat).[32] A sample day is displayed in Figure 2. The treatment diet included 2.5% to 4.0% of total energy intake from added sugars, in line with the 2015-2020 DGA recommendations, and 7.3% to 8.6% from total sugars.[1] Typical sources of added sugars (soda, candy, desserts) were replaced by food of similar carbohydrate content that contain little to no sugars or sweeteners (rice, pasta, bread). Participants returned to the Grand Forks Human Nutrition Research Center each morning during the dietary intervention and were provided with all of the food and calorie-containing beverages they were to consume for 7 consecutive days, including weekend days. Participants were strictly instructed not to consume any foods or beverages (other than water and black tea or coffee) outside of what was given to them and encouraged to consume all their daily allotment of food. If there was too much food, they were instructed to return any uneaten portions, along with empty food containers, to better monitor compliance. Prior to enrollment, participants received a detailed list of their daily diets to ensure they would be willing and able to eat the foods provided. All participants indicated willingness to comply with the study diet and none indicated deviation from protocol. The study start dates were planned so that participants completed the 7-day diet on a day that they were available for follow-up testing. No participant indicated on a postintervention debriefing questionnaire that they felt underfed, with most perceiving the amount of food given during the intervention to be greater than what they typically consume. It is therefore believed that participants were eating an adequate amount of food preventing any feelings of deprivation or hunger.

Breakfast	Fried egg and cheese biscuit
	2% milk
	Hash brown
Lunch	Chicken noodle soup
	Ham sandwich with lettuce, tomatoes, mayonnaise
	Flavored tortilla chips
Dinner	Grilled chicken breast
	Baked potato
	Corn
	Gravy
	Wheat dinner roll with margarine
	Macaroni salad
Snack	Pretzels
Overall: 16% total kilocalories protein, 51% carbohydrate, 33% fat, 3.4% average daily added sugars.	

Figure 2. Sample daily menu for 7-day diet with 2.5% to 4.0% daily energy from added sugars.

Measures

Height and Weight. During the screening visit, height was measured in triplicate to the nearest 0.1 cm using a stadiometer (Seca). Body weight was measured using a calibrated digital scale (Fairbanks Scales Model SCB-R9000-HS) to the nearest 0.1 kg. Measures were completed with participants wearing either provided laboratory scrubs or light casual clothes (T-shirt, shorts) and not wearing shoes.

Energy Expenditure and Needs. RMR was measured using indirect calorimetry (TrueOne, 2400; Parvo Medics) and a ventilated canopy. Participants drove by automobile to the Grand Forks Human Nutrition Research Center after refraining from eating or drinking anything besides water for at least 10 hours and without exercising for the previous 48 hours. Participants completed a compliance questionnaire to ensure they met these testing criteria immediately prior to the RMR test. The TrueOne 2400 is a mixing chamber system that uses a paramagnetic oxygen analyzer (range=0% to 25%) and an infrared, single-beam, single wave-length carbon dioxide analyzer (range=0% to 10%). Before each test, calibrations were performed on the flow meter using a 3.0-L syringe and on the gas analyzers using verified gases of known concentrations. After 30 minutes of quiet rest in the supine position in a dimly lit, temperature-controlled (between 22°C and 24°C) room, RMR was measured for 30 minutes. The test was monitored to ensure participants remained awake and between 0.8% and 1.2% $feCO_2$. Criteria for a valid RMR was a minimum of 15 minutes of steady state, determined as a <10% fluctuation in oxygen consumption and <5% fluctuation in respiratory quotient. The Weir equation[33] was used to determine RMR from the measured oxygen consumption and CO_2 production. The ParvoMedics TruOne 2400 metabolic cart is reliable with across-day Pearson correlation coefficients of 0.994 and 0.991 for volume of oxygen utilized each minute (VO_2) and volume of carbon dioxide exhaled after transporting oxygen through the body (VCO_2), respectively, and coefficients of variation (CV) for VO_2 and VCO_2 of 4.7% and 5.7%, respectively.[34] An activity factor based on results from the Stanford Brief Activity Survey[35] was used to adjust dietary energy to maintain energy balance and account for individual physical activity. Energy intakes for obese and normal weight participants averaged 2,800 and 2,426 kcal/day, respectively.

Liking of Study Foods. Participants completed a taste test of the foods high in added sugars (fruit-flavored candy, chocolate-flavored taffy-like candy, low-fat cookie, sweetened corn and oat breakfast cereal) and of the foods low in added sugars and total sugars (potato chips, pretzels) used in the RRV task (Table 1). Participants rated each food in terms of overall liking on an 11-point scale anchored by "not like at all" (0) and "like very much" (11). All participants rated at least a moderate liking (liking score of ≥5) for at least one of the foods high in added sugars and low in added sugars. Participants' highest liked food in each category was used in the subsequent RRV tasks. This test was completed once, prior to the baseline RRV test.

RRV Task. Participants' RRV_{sugars} value was calculated by assessing the reinforcing value of their favorite food high in

Table 1. Energy and macronutrient information of snack foods used during task to measure relative reinforcing value of foods low and high in added sugars in a cohort of normal weight and obese adults who habitually consume >10% daily energy from added sugars

Foods used in RRV[a] task	kcal/g	CHO[b]	Fat	Protein	Sugars
		←—grams/100 g—→			
Foods high in added sugars					
Chocolate-flavored taffy-like candy[c]	3.87	87.8	3.3	1.6	56.3
Fat-free devils food cookie[d]	3.05	74.3	1.1	5.0	43.4
Fruit-flavored candy[e]	4.05	90.8	4.4	0.2	75.8
Sweetened corn and oat breakfast cereal[f]	3.98	85.5	5.1	4.4	44.3
Foods low in added sugars					
Pretzels	3.81	79.2	3.5	9.1	2.2
Potato chips[g]	5.32	53.8	34.0	6.4	0.3

[a]RRV=relative reinforcing value.
[b]CHO=carbohydrates.
[c]Tootsie Roll (Tootsie Roll Industries).
[d]Snackwell's (Back to Nature Foods).
[e]Skittles (Mars, Inc).
[f]Cap'n Crunch (PepsiCo).
[g]Lays (PepsiCo).

added sugars relative to their favorite food low in sugar. Reinforcing value was assessed by evaluating the amount of operant responding (mouse button presses) a participant performed to gain access to each alternative (foods high in added sugars and low in sugar; Table 1).[9,36,37] The testing environment included two workstations with computers in the same room. One computer had a game that was set up for participants to earn points toward their highest liked food high in added sugars, and the other computer had the same game that participants could use to earn points toward the highest liked food low in sugar. Participants could switch between stations as much as they chose. The computer programs present a game that mimics a slot machine; a point is earned each time the shapes match. For every 5 points, a session is completed and the participant received an approximately 57-calorie portion of the reinforcer that was earned (either food high in added sugars or low in sugar). The game was performed until the participant no longer wished to work for access to either food. At first, points were delivered after every four presses, but then the schedule of reinforcement doubled (4, 8, 16, 32, [. . .] 1,024) each time 5 points were earned. For instance, the participant initially had to click the mouse four times to earn each point for schedule 1. After the first 5 points were earned, schedule 1 was complete and the participant earned an approximately 57-calorie portion of food for the reinforcer earned. Then eight clicks were required to earn each of the next 5 points for schedule 2 before another portion of the reinforcer was earned. Schedule 3 required 16 clicks to earn 1 point, schedule 4 required 32 clicks to earn 1 point and so on.[9,36] Participants received the food earned after completing the game, which ended when the participant no longer wished to earn points for eating either type of food. Participants were not allowed to take food out of the laboratory with them but were not required to consume all the food they earned in the event a participant earned more food than they could eat in one sitting. RRV tests were conducted 2 to 4 hours postprandial between usual lunch and dinner times when snack foods are likely to be consumed. Similar button-pressing tasks have been shown to be valid predictors of the RRV of eating behaviors.[9-12,38] The breakpoint, or P_{max},[36] was the total number of schedules completed for the high- or low-sugar foods. RRV_{sugars} was the proportion of P_{max} for food high in added sugars compared with the food low in sugar calculated as (P_{max} food high in added sugars) / (P_{max} food high in added sugars + P_{max} food low in sugar). As constructed, an RRV_{sugars} score over 0.5 indicates a greater reinforcing value for the food high in added sugars.[9,36]

Hunger and Satiety. Before each RRV task, participants rated how hungry, how full, and how satisfied they were, as well as how much they thought they could eat and how strong their desire to eat was on a visual analog scale[39] to be used as potential covariates for RRV.

Food Attitudes and Beliefs. The TFEQ is a validated instrument used to evaluate cognitive restraint, uncontrolled eating, and emotional eating.[31,40]

Analytic Plan

Demographic, physical characteristics, and baseline RRV_{sugars} of the obese and normal weight groups of participants are reported as means and standard deviations (SDs) and BMI group differences were tested using Student's *t* tests for unequal variance. Differences across time for RRV_{sugars}, the primary outcome, were tested using a generalized linear mixed model with BMI group (normal weight, obese) as a between-subjects factor and time (baseline, post-treatment) as a within-subjects factor. Because RRV_{sugars} is a ratio in the range of 0 to 1, the data were assumed to follow a β distribution. Correlations were assessed between the change in RRV_{sugars} and baseline liking of the test foods, baseline RRV_{sugars}, cognitive restraint, uncontrolled eating, emotional eating, and demographic characteristics found to differ between groups. Correlations were also assessed between RRV_{sugars} and hunger on each test day. Items found to be significantly correlated with RRV_{sugars} were added as a covariate in the final model. Because participants did not always consume all of the food they earned, paired sample Student's *t* tests and mixed models were used to test differences in the percentage of earned calories consumed of the foods low in sugar and high in added sugars at the baseline and post-treatment RRV tests. All

Table 2. Demographic characteristics and difference scores at baseline of normal weight and obese study participants who habitually consume >10% energy from added sugars and participated in a study on the reinforcing value of added sugars following a 7-day diet low in total sugar and added sugars

Participant characteristics	All subjects (n=42)	Normal weight (n=23)	Obese (n=19)	*P* value
	←——	*mean±SD*[a]	——→	
Age (y)	25.6±5.6	23.3±3.7	28.5±6.4	0.004
Weight (kg)	82.1±25.1	63.6±7.5	104.4±20.0	<0.001
Height (cm)	167.8±6.9	167.2±6.2	168.4±7.7	0.578
BMI (kg/m^2)[b]	29.1±8.6	22.7±1.7	36.8±7.0	<0.001
Energy/day (kcal)[c]	2,595±568.2	2,426±543.8	2,800±541.6	0.032
% kcal from added sugars	18.2±12.0	17.5±12.9	19.0±11.0	0.675

[a]SD=standard deviation.
[b]BMI=body mass index; calculated as kg/m^2.
[c]Average energy intake during the 7-day controlled feeding intervention.

statistics were run on SAS 9.3. The primary outcome was RRV_{sugars} differences over time; therefore, only participants with both pre- and post-treatment data could be analyzed. Only two participants withdrew prior to completion. We hypothesized that obese subjects would show a twofold increase over normal weight subjects in RRV_{sugars} responses based on previous work with these populations.[12,41] To test for a differential response in obese and normal weight subjects assuming α=.05 and a between subject SD=10, 15 subjects were needed to have 90% power to detect an increase in responses (RRV task) for intake within a treatment group based on the initial increases in RRV_{sugars} during a short-term deprivation period.[23] Because our sample size exceeded n=15 for both obese and normal weight participants, it was judged to have adequate power.

RESULTS

As expected, the normal weight group had a lower ($P<0.001$) body weight and BMI than the obese group (Table 2). Participants endorsed a slightly greater liking of sweet foods (mean=9.95; SD=1.38) than savory foods (mean=9.05; SD=2.24) (P=0.010), but the absolute difference was small and liking scores were correlated (r=0.36, P=0.0178). Baseline RRV_{sugars} did not differ across BMI ($P>0.20$). Obese participants were slightly, but significantly older than normal weight participants (Table 2). However, age was not correlated (r=0.11, $P>0.48$) with changes in RRV_{sugars}, so it was not included as a covariate. As shown in Table 3, there was a significant main effect of time for both normal weight and obese participants, in that RRV_{sugars} increased by 32.7% after the dietary intervention. The main effect of BMI on the RRV_{sugars} was not significant (P=0.85). "How strong is your desire to eat?" was significantly associated (r=0.33, P=0.032) with post-treatment P_{max} of foods low in added sugars, and "How full do you feel?" was inversely associated (r=−0.32, P=0.048) with post-treatment P_{max} of foods low in added sugars. These items are highly collinear (r=−0.65, $P<0.001$), so only "How strong is your desire to eat?" was included as a covariate. Cognitive restraint, uncontrolled eating, and emotional eating were not correlated (all $P>0.11$) with the pre- to post-treatment change in RRV_{sugars}. However, liking of the foods high in added sugars was inversely associated (r=−0.31, P=0.044) with change in RRV_{sugars} and was therefore included as a covariate. Inspection of the data revealed that all but one participant rated a liking of >7 for their most liked food high in added sugars. The exception was a normal weight participant who rated a modest (5 of 11) liking value. This value met the definition of an outlier,[42] and when removed, liking of foods high in added sugars was not correlated (P=0.41) with RRV_{sugars}. There were no differences (P=0.93) in the caloric percentages of food high in added sugars earned that were subsequently consumed between pretreatment (73% of earned kilocalories consumed) and post-treatment (73% of earned kilocalories consumed). Percentage of foods low in sugar was significantly greater (P=0.001) pretreatment (69% of earned kilocalories consumed) than post-treatment (40% of earned kilocalories consumed). Mixed models confirmed that weight status had no effect on this pattern (P=0.21). Because there were so few male participants, comparisons across sexes were not possible. To examine the effect of female sex, separate analysis excluding male participants were performed. Results indicated the increase in added sugar reinforcement held for females with RRV_{sugars} increasing (P=0.024) from 0.22 at baseline to 0.80 post with no differences between weight status.

Table 3. Comparisons of mean and standard error of the RRV[a] and percentage of foods high and low in energy (kcal) from added sugars earned during pre- and post-treatment RRV task that were consumed[b]

Variables compared	Baseline	Post-treatment	P value
	←——mean±SE[c]——→		
RRV[bd]			
All subjects	0.55±0.04	0.70±0.04	0.002
Normal weight[d]	0.50±0.05	0.73±0.05	
Obese[d]	0.58±0.04	0.68±0.07	
	←——%——→		
% kcal consumed—low sugars[de]			
All subjects	68.92	40.17	0.001
Normal weight[d]	69.06	42.68	
Obese[d]	68.76	37.14	
% kcal consumed—high sugars[f]			
All subjects	72.51	72.88	0.932
Normal weight	77.10	78.07	
Obese	66.95	66.60	

[a]RRV=relative reinforcing value.
[b]RRV of foods high in added sugars calculated as schedules of reinforcement completed for foods high in added sugars / (schedules of reinforcement for foods high in added sugars+schedules completed for foods low in added sugars).
[c]SE=standard error.
[d]Time effect, $P<0.01$, both groups. No interaction.
[e]Percent kilocalories of foods low in added sugars consumed out of total amount of foods low in added sugars earned after completion of RRV task, baseline and post-treatment.
[f]Percent kilocalories of foods high in added sugars consumed out of total amount of foods high in added sugars earned after completion of RRV task, baseline and post-treatment.

DISCUSSION

The current study is the first to assess whether an imposed restriction of a specific type of food (foods high in sugars) to promote a healthy eating pattern that meets the 2015-2020 DGA increases the RRV of the restricted food. The present study extends the literature by being the first to demonstrate that reducing foods high in sugars for 1 week increased RRV_{sugars} by 33%. Such an increase in the RRV_{sugars} could actually lead to greater initial intakes than before the restriction of the less healthy food when the food is no longer restricted.[25] Thus, restricting foods high in added sugars as part of a total low-sugar diet may have the unintended consequence of increasing the RRV of foods high in added sugars, and at least initially, increase the difficulty of adhering to the 2015-2020 DGA. Whether RRV_{sugars} returns to baseline after a longer period of dietary sugar restriction is not yet known.

Reduction of the intake of foods high in sugars increased the RRV_{sugars} in both normal weight and obese adults. Moreover, baseline RRV_{sugars} did not differ between BMI groups despite previous work showing obese subjects having a greater RRV of food and energy intake than nonobese.[9,11,43] That the current study did not show a greater RRV response in obese participants compared with normal weight participants may be due to sweet taste's naturally reinforcing effect, thought to be an evolutionarily conserved trait[15] causing foods high in added sugars to be highly reinforcing[9,12,14] regardless of a person's BMI. Several results in the present study provide evidence that the reinforcing values of foods high in added sugars are conserved across subjects. First, the Law of Initial Values[44] suggests that the magnitude of response to an experimental stimulus is related to the prestimulus value, such that greater initial values are associated with smaller increases. Yet, despite the high baseline RRV_{sugars}, the current study demonstrated that restriction of sugar further increased the RRV_{sugars} and that eating behaviors assessed by the TFEQ that are often considered important factors to predict intake[31,40] were not associated with changes in RRV_{sugars} after sugar restriction. Furthermore, although foods low in sugar lost their appeal post-treatment, as evidenced by the significant decrease in percentage of earned calories ultimately consumed, foods high in added sugars remained appealing. To standardize the timing of the RRV tests, all but one of the participants performed each test 2 to 4 hours postprandial during the afternoon hours between typical lunch and dinner times. Satiety scores assessed prior to each RRV task did not affect the results, suggesting that participants were responding for food during the RRV task not out of hunger, but rather out of a motivational drive to eat.

Our results indicate that the relative reinforcing value of a behavior (eg, eating sweet-tasting foods such as those high in added sugars) is increased when the rate of that behavior is decreased below the baseline rate, which has strong theoretical underpinnings in Disequilibrium Approach Theory.[18] Applied to the current study, Disequilibrium Approach Theory accurately predicted that lowering the consumption of sugar would increase the RRV_{sugars}. Disequilibrium Theory has also accurately predicted an increase in reinforcing value and intake of snack foods among preschool-aged children.[25-27]

Americans are consuming greater than 290 kcal per day from added sugars, with 59.6% of the population failing to meet 2015-2020 DGA recommendations.[8] Dietary changes are needed at the whole diet level to increase the diet quality of Americans. The current results add to the growing body of evidence of how to implement dietary change that may most effectively promote healthy dietary habits. Great and abrupt energy restriction produces obsessive preoccupations with sweet foods, increased hedonic ratings of food, and an increased rewarding value of food.[20,21] Just as is the case for energy restriction, it is now apparent that restricting foods high in sugars will increase their RRV. Abruptly restricting foods high in added sugars may therefore not be the most effective means of producing habitual reductions in added sugar consumption. 2015-2020 DGA stresses food choices that can be maintained long term for optimal nutrition. Although a decrease in added sugars is recommended, a gradual decline such as reducing calories from added sugars by 10% to 25% per week until 2015-2020 DGA is reached may not provoke as extreme a response. Because RRV is an important determinant in behavioral choice,[9,11,41,45-47] increasing the RRV_{sugars} would impose a barrier to meeting 2015-2020 DGA recommendations for added sugar intake. Behavioral change strategies are therefore needed that will help Americans reduce their added sugar intake while limiting the increase in RRV_{sugars}. One strategy could be focusing on substitution—including foods higher in natural sugars such as fresh fruits in the diet while reducing consumption of foods high in added sugars. Perhaps repeated exposures to foods low in added sugars (fresh fruits, vegetables, whole grains, for example) may increase their RRV so that they act as more effective alternatives for foods high in added sugars, resulting in increased consumption without focusing on restricting foods high in added sugars.[48] The potential of using incentive sensitization to increase RRV of certain foods shows promise[12,28,41]; this mechanism for increasing RRV of food is currently being investigated in the context of foods low in added sugars.[48] Focusing on consumption of healthier foods instead of restricting less healthy options may be more successful for implementing the dietary changes necessary to meet 2015-2020 DGA recommendations.[49]

This study is not without limitations. The sample was skewed in terms of sex (88% female). This is due to the difficulty in recruiting males who consumed greater than 10% of their calories from added sugars; a full 70% of male applicants did not qualify. When analyzing females separately, the overall results did not differ. Inadequate power prevented the analysis of males separately because there were only two normal weight and three obese male subjects. Future studies should focus on middle-aged adults, older adults, and especially children, to determine whether similar relationships are present between RRV and restricting sugars.

Although a variety of common foods were made available during the RRV task, the available choices may have influenced how much participants were willing to work for the food choices. It is possible that participants did not dislike or have low RRV for the foods high or low in added sugars per se, but that their preferred food options were not provided. A potential avenue for future RRV studies would be to ask participants open-ended questions regarding their favorite foods instead of asking them to choose from a narrow list. Also, of potential future interest is how a diet low in sugar influences participant's motivation toward nonsweet flavors, such as savory, umami, or sour. Participants were consuming a great deal of other foods low in added sugars and low in total sugars during the intervention diet so it is possible that a "response excess" scenario occurred, in that the increasing of access of foods low in sugars above baseline decreased their reinforcing value.[18] However, the specific test foods low in added sugars and low in total sugars during the RRV test (pretzels, chips) were not consumed the day of or the day before the RRV test, so it is unlikely that participants were not responding for the option low in added sugars due to being tired of eating these particular foods. Furthermore, it is possible 7 days of a low-sugar diet increased RRV_{sugars} in the short term, but had the diet been maintained longer, RRV_{sugars} would have returned to baseline values.[50] Future studies should investigate long-term changes in sugar reinforcement when following a diet low in sugar.

PRACTICE IMPLICATIONS

- The reinforcing value of food is a prime determinant in eating behaviors and choices.
- The reinforcing value of high–added sugar foods is increased after restricting sugar for 1 week.
- A potential barrier to maintaining a reduction in added sugar consumption could be related to the increase in its reinforcing value that is observed upon restriction.

Participants in the current study were not informed that added sugar and other sweet-tasting foods were removed from the experimental diet. A total of 17 of the 42 participants were able to disclose that they were placed on a diet that restricted sugars for 1 week, with the remaining 25 unaware that they were placed on a diet low in sugars. This was despite 29 out of the 42 participants reporting that they craved sweet-tasting foods during the diet. This attempt to blind the study purpose and dietary restriction may have reduced participants' preoccupations of sweet foods when added sugar and sweet-tasting foods are reduced.[20,21] Future studies on restriction may inform participants of what the intervention is and what foods will be restricted to better replicate the restriction in an actual setting, which would be expected to increase the reinforcing value of foods high in added sugars to a greater extent.

During the intervention diet, all foods with any types of sugars were restricted to an average of 3.4% kilocalories from added sugars and 8.2% from total sugars per day, along with artificial sweeteners. The exclusion of natural sugars and other sweeteners was in place to further promote the sense of restriction, because some people may have similar perceptions between foods high in added sugars and foods with artificial sweeteners or natural sugars. It is therefore possible that it was not necessarily the RRV of added sugars that was increased rather the RRV of sweet taste. However, people consume more high–added sugar foods than sweet-tasting foods low in added sugars (such as fruit, artificial sweeteners),[51] so increasing the RRV of sweet-tasting foods may impact the intake of foods high in added sugars more than sweet-tasting foods low in added sugars. Current follow-up studies are underway analyzing the RRV of naturally occurring sugars, such as fruit. Non–added sugars were excluded in the current study diet and added sugar was restricted to amounts below 2015-2020 DGA, but it may be possible that by providing natural sugars or added sugars up to but not exceeding 10% of calories would attenuate the RRV of foods high in added sugars.

CONCLUSIONS AND FUTURE DIRECTIONS

The consistent recommendations in the DGA across decades to lower added sugar intake without a population change points to the difficulties Americans have had in reducing added sugar intake.[4-6] The current investigation establishes for the first time that following sugar-restricted diet for 1 week results in an increase in RRV_{sugars} in adults, which may act as a barrier for reducing the consumption of these very reinforcing foods.[9,12-14] Reinforcement for sweet taste may be an evolutionarily conserved trait,[15] which may promote the increase in RRV_{sugars} that occurs across people of lower and greater BMI class when sugars are restricted. However, a reduction of foods high in added sugars below base rate is needed for the vast majority of US adults to adhere to 2015-2020 DGA recommendations. Future studies are needed to investigate the potential for increasing the RRV of healthy foods and how to avoid increasing the RRV of nondesirable foods as a strategy for improving Americans' adherence to the 2015-2020 DGA added sugar recommendations.

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STATEMENT OF POTENTIAL CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors. The mention of trade names, commercial products, or organizations does not imply endorsement from the US government. USDA is an equal opportunity provider and employer.

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AUTHOR CONTRIBUTIONS

K. D. Flack, S. Casperson, L. Jahns, and J. Roemmich designed the study. K. D. Flack and K. Ufholz collected the data. K. D. Flack, K. Ufholz, and L. Johnson analyzed the data. K. D. Flack and K. Ufholz drafted the manuscript, with substantial contributions from other authors. All authors have approved the final version.