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Research report

The effect of non-caloric sweeteners on cognition, choice, and post-consumption satisfaction ☆

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A B S T R A C T

Consumers often turn to non-caloric sweeteners (NCS) as a means of promoting a healthy body weight. However, several studies have now linked their long-term use to increased weight gain, raising the question of whether these products produce unintended psychological, physiological, or behavioral changes that have implications for weight management goals. In the following, we present the results of three experiments bearing on this issue, testing whether NCS-consumption influences how individuals think about and respond to food. Participants in each of our three experiments were randomly assigned to consume a sugar-sweetened beverage, an unsweetened beverage, or a beverage sweetened with NCS. We then measured their cognition (Experiment 1), product choice (Experiment 2), and subjective responses to a sugar-sweetened food (Experiment 3). Results revealed that consuming NCS-sweetened beverages influences psychological processes in ways that – over time – may increase calorie intake.

Introduction

The incidence of overweight and obesity in the U.S. and the rest of the world has steadily increased for more than 30 years (Flegal, 2005, Rigby, Kumanyika, & James, 2004; World Health Organization, 2006). In light of these trends, weight loss products are becoming increasingly popular among consumers seeking to lose weight or prevent weight gain. Among the most popular of these items are products containing non-caloric sweeteners (NCS), which sweeten food and drinks without adding calories. Because these sweeteners are calorie-free, using them as a replacement for sugar should facilitate weight loss. Although some studies have found evidence of this (e.g., de Ruyter, Olthof, Seidell, & Katan, 2012; Raben, Vasilaras, Møller, & Astrup, 2002) – particularly in the short-term – others have found their long-term use associated with weight gain, even after controlling for the fact that heavier people are more likely to use them in the first place (Colditz, Willett, & Stampfer, 1990; Dhingra et al., 2007; Fowler et al., 2008; Lutsey, Steffen, & Stevens, 2008; Nettleton et al., 2009; Stellman & Garfinkel, 1986).

That researchers have failed to establish a reliable association between NCS consumption and weight loss has led some to hypothesize that their consumption might produce unintended physiological, psychological, or behavioral changes that hinder, rather than help, consumers' weight management goals (see e.g., Green & Murphy, 2012; Rudenga & Small, 2012; Smeets, Weijzen, de Graaf, & Viergever, 2011; Swithers & Davidson, 2008). In the following, we present the results of three experiments that examined this possibility, testing the impact of NCS consumption (via a diet soft drink) on food-related cognition, consumer choice, and subjective responses to sugar-sweetened snacks. By measuring the impact of NCSs on processes known to impact food regulation over time, the current research seeks to provide new insights into the ongoing debate about whether NCSs help or hinder consumers' weight loss goals.

Non-caloric sweeteners (NCS) and weight regulation

For most of human history, sweetness has provided a reliable orosensory cue to a food's energy content. Sweet-tasting foods are more calorically dense than less sweet foods, making sweetness a valid predictor of subsequent energy availability. However, when the natural pairing of sweetness and caloric density is decoupled – such as when NCS-sweetened products are consumed – the mismatch between the sweet flavor and energy availability is hypothesized to disrupt the body's natural food-regulation processes, potentially causing changes that discourage rather than promote weight loss (see e.g., Rudenga & Small, 2012; Swithers, Martin, & Davidson, 2010; Wang & Dvorak, 2010). Experimental research conducted using rodent models has found support for this hypothesis (Swithers & Davidson, 2008; Swithers et al., 2010). For example, Swithers and Davidson (2008) found that rats that consumed NCS-sweetened food and drink subsequently ingested a greater number of calories and experienced an increase in body

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weight relative to rats that consumed items sweetened with glucose. Similar experiments in humans, however, have provided more mixed results (see Bellisle & Drewnowski, 2007, for a review). Although a small number of studies have found that consuming non-caloric sweeteners prior to eating a test meal increased subsequent food intake consumption (e.g., King, Appleton, Rogers, & Blundell, 1999; Lavin, French, & Read, 1997), the majority have found no relationship between these variables (e.g., Birch, McPhee, & Sullivan, 1989; Black, Tanaka, Leiter, & Anderson, 1991; Canty & Chan, 1991; Rolls, Kim, & Fedoroff, 1990).

The lack of experimental evidence demonstrating a meaningful causal relationship between consuming NCS-sweetened products and changes in calorie intake has led many to conclude that NCSs do not have a disruptive effect on processes influencing consumers' energy regulation. However, little remains known about the impact of NCS consumption on consumers' food regulation psychology, which guides energy regulation over longer spans of time than can be measured in the laboratory. Because consuming as little as 50 extra calories per day can lead to weight gain of 14–20 pounds over an eight year period (Hill, Wyatt, Reed, & Peters, 2003), even subtle, periodic increases in calorie intake can have implications for weight management goals. Examining the impact of NCSs on the psychological processes that guide consumption over time thus represents the important next step in the ongoing discussion about the impact of NCS-sweetened products on consumers' energy balance. In the following, we present the results of three experiments examining the effect of NCS consumption (via a diet soft drink) on food-related cognition, consumer choice, and subjective response to sugar-sweetened snacks. We predicted that, compared to participants who first consumed a sugar-sweetened or unsweetened drink, those who consumed a beverage sweetened with NCS would demonstrate: (a) increased mental accessibility of the names of high-calorie food items (Study 1), (b) increased likelihood of choosing a sugary snack food item in a consumer choice scenario (Study 2), and (c) decreased satisfaction with a subsequently consumed sweetened snack item (Study 3).

Experiment 1

The goal of our first experiment was to examine the impact of non-caloric sweeteners on the cognitive accessibility of food items with differing levels of caloric density. We predicted that – compared to participants who consumed the sugar-sweetened or unsweetened beverage – those who consumed the beverage sweetened with NCS would have shorter response-time latencies to the names of high-calorie, but not low-calorie, food items.

Method

Participants

Participants who ate or drank anything other than water less than eight hours prior to their session were excluded from all analyses (18 excluded), leaving a total of 116 undergraduates (75 women, 41 men) in our final sample (36 in the Sprite condition, 40 in the Sprite Zero condition, and 40 in the mineral water condition). Participants' ages ranged from 18 to 25 years ($M = 19.81$, $SD = 3.27$) and all received partial course credit in exchange for their participation.

Design and procedure

The design of this study was a 3 (drink condition: Sprite vs. Sprite Zero vs. mineral water, between subjects) × 3 (word type: high calorie vs. low calorie vs. non-word, within subjects) mixed factorial design. During recruitment, all participants were instructed not to eat or drink anything other than water past midnight prior to their testing session. All testing sessions were conducted between 8:00 and 11:00 a.m. After arriving in the laboratory, participants were given a participant ID number that was linked to their testing condition. Upon being seated, participants were given an unmarked, red plastic Solo cup that contained one of three 12 ounce (355 ml) beverages: (1) sugar-sweetened (Sprite), (2) non-calorically sweetened (Sprite Zero), or (3) unsweetened (Kroger brand lemon-lime sparkling mineral water) (Table 1). Participants (all condition-blind) were given five minutes to consume their drink while watching images from the Hubble Telescope on their computer screens. After this time had elapsed, participants were asked to complete a lexical decision task (described below). The study closed with participants being asked to respond to a series of questions about themselves (e.g., sociodemographic questions, height, weight) and about their compliance with the experimental procedure. After the experiment was complete, a hypothesis-blind research assistant used the ID numbers to match participants' computerized data with the drink condition to which they were assigned.

Table 1
Characteristics of the drinks used across all studies.

Drink type	Energy/100 g	Ingredients
Sprite	167 kJ/40 kcal	Carbonated water, sugar, citric acid, malic acid, acidity regulator (sodium gluconate), natural lemon-lime flavorings, sweetener (steviol glycosides).
Sprite Zero	0 kJ/0 kcal	Carbonated water, citric acid, natural lemon and lime flavorings, sweeteners (aspartame, acesulfame-K), preservative (E211), acidity regulator (E331).
Sparkling water	0 kJ/0 kcal	Carbonate water, natural flavors

Cognitive accessibility of high- vs. low-calorie foods

After participants finished their beverages they completed a lexical decision task to measure the cognitive accessibility of high- and low-calorie foods. During this task, participants were presented with 28 letter strings. These letter strings, presented in random order, consisted of seven high-calorie food words (e.g., burger, cookie, pizza), 7 low-calorie food words (e.g., celery, radish, carrot), and 14 non-words (e.g., ebusun, ganeap, tigne). Each letter string flashed on the screen for 250 ms and participants had to indicate whether each letter string was a word or non-word by pressing the "z" or "m" key, respectively. The response latencies (i.e., how long it took for participants to indicate if a string of letters was a word or non-word) served as our dependent variable, with lower response latencies indicating greater cognitive accessibility. To familiarize participants with this task, before completing the experimental trials, participants completed 30 practice trials consisting of 15 neutral words and 15 non-words. A pretest conducted prior to the experiment ($n = 15$) verified that the high-calorie food items were easily recognized as being higher in calories ($M_{high} = 9.73$, $SD = .68$; $M_{low} = 1.97$, $SD = .50$, $F(1, 14) = 923.45$, $p < .001$), more fattening ($M_{high} = 9.84$, $SD = 1.04$; $M_{low} = 1.25$, $SD = .32$, $F(1, 14) = 759.57$, $p < .001$), and more sugary ($M_{high} = 7.28$, $SD = 1.48$; $M_{low} = 1.24$, $SD = .38$, $F(1, 14) = 266.27$, $p < .001$) than the low-calorie food items. Lastly, participants were thanked, debriefed, and dismissed.

To determine whether drink type affected cognitive accessibility of high-calorie food items, we examined participants' response latencies to the names of high- and low-calorie food items. We first calculated the mean reaction time RT for each correct response within each response category (i.e., high-calorie foods, low-calorie foods, and non-words). This measure reflects the average amount of time (in milliseconds) that it took participants to correctly identify a string of letters as being a word (the name of either a high- or low-calorie food item) or a non-word. Because outliers can distort RT measures (Fazio, 1990; Fazio, Sanbonmatsu, Powell,

& Kardes, 1986), we adopted a priori cut-off standards at 100 ms and 1000 ms, per research convention (Bargh & Chartrand, 2000; Garcia, Weaver, Moskowitz, & Darley, 2002). Participants with RTs falling outside of these cut-offs (i.e., which exceeded 3 *SD*s from the mean) were thus excluded from our analyses (a total of 7 participants were excluded for this purpose).

Analysis plan

Because participants' RT scores reflect their speed in correctly identifying a string of letters as a word or non-word, we will first conduct a preliminary multivariate ANOVA to determine whether drink condition influences the number of words participants correctly identified as a word or non-word so that we can control for these differences in subsequent analyses if necessary. Although participant sex is not predicted to impact our results, we will also conduct a preliminary 2 (Participant Sex) × 3 (Drink) × 3 (Response Category) mixed model ANOVA to determine whether participant sex moderates the impact of any of our manipulated variables.

To test the prediction that consuming the NCS-sweetened beverage will increase cognitive accessibility of high-calorie, but not low-calorie food items, we will conduct a 3 × 3 mixed-model ANOVA with drink type as the between-subjects factor and response category as the within-subjects factor. If we find a significant interaction between drink type and response category, it will be probed by running three separate ANCOVA models, each of which will examine the effect of drink condition on a specific response category (high calorie food words, low calorie food words, non-words) while controlling for response times to each alternative response category. Because we will be conducting three follow-up analyses (one for each response category), we will use Bonferroni's correction ($\alpha = .017$) to preserve alpha level and reduce the likelihood of Type 1 error. If the results of these follow-up ANCOVAs reveal a main effect of drink condition on participants' RT, we will conduct orthogonal planned contrasts ($\alpha = .025$) to examine the differences in RT scores between participants who consumed the NCS-sweetened drink and those who consumed the sugar-sweetened or unsweetened drink (Helmert, SPSS v. 22). Contrast 1 will examine the differences between participants who consumed the NCS-sweetened drink and those who consumed the sugar-sweetened and unsweetened drinks. Contrast 2 will examine the differences between participants in the two control conditions (i.e., the sugar-sweetened and unsweetened drink conditions).

Results

See Table 2 for descriptive statistics. No between-condition differences were found for the number of letter strings participants correctly categorized ($p = .25$) and participant sex did not interact with any of our manipulated variables ($ps \geq .28$). These variables were therefore not included in our main statistical model. The results of our 3 × 3 mixed-model ANOVA revealed a significant interaction between drink type and RT-category, $F(4, 224) = 2.98$, $p = .02$. Results of our follow-up tests indicated no significant main effect of drink type on participants' RT to low-calorie food words ($F(2, 111) = 1.93$, $p = .15$) or non-words ($F(2, 111) = .90$, $p = .41$). However, results revealed a significant main effect of drink type on participants' RT to high-calorie food words, $F(2, 111) = 6.03$, $p = .003$. Orthogonal planned comparisons revealed that participants who consumed the NCS-sweetened beverage responded more quickly to the names of high-calorie food items compared to those who consumed either the sugar-sweetened or unsweetened drink ($p = .001$, CI: –84.89, –20.11). No differences were found between the sugar-sweetened drink and those who consumed the mineral water ($p = .28$).

Table 2
Descriptive statistics for total number and the reaction time (in milliseconds) of words categorized correctly during a lexical decision task. Longer reaction time latencies indicate lower cognitive accessibility.

	High calorie		Low calorie		Non-word	
	M	*SD*	M	*SD*	M	*SD*
Words correct						
Sprite	6.97	0.17	6.83	0.38	13.42	1.02
Sprite Zero	6.98	0.16	6.88	0.34	13.33	1.23
Water	6.85	0.36	6.75	0.44	13.33	1.42
Reaction time						
Sprite	631.74	118.59	652.27	92.12	817.78	186.97
Sprite Zero	589.40	67.11	648.78	111.16	878.17	376.04
Water	643.80	109.14	635.96	98.13	817.42	255.25

Experiment 2

The goal of our second experiment was to extend the results of Experiment 1 by testing the effects of NCS-sweetened beverages on people's decision-making in a consumer choice scenario. In particular, we were interested in whether NCS consumption influences the types of consumer products people choose when offered their choice of either a high-calorie food item (M&M chocolate candies) or one of two low- or zero-calorie, non-food items (a bottle of Ozarka spring water or a pack of Trident sugar-free gum). We predicted that participants who consumed the NCS-sweetened beverage would choose to take the high-calorie candy at a greater frequency than would those who consumed the sugar-sweetened or unsweetened drinks.

Method

Participants

As in Experiment 1, participants who ate or drank anything other than water less than eight hours prior to their arrival at the testing were excluded from all analyses (20 excluded), leaving a total of 115 undergraduates (64 women, 51 men) with ages ranging from 18 to 22 years ($M = 19.10$, $SD = 1.63$) to participate in return for course credit (39 in the Sprite condition, 40 in the Sprite Zero condition, and 36 in the mineral water condition).

Procedure

Participants in Experiment 2 were told that they would be participating in a consumer products study. The procedure for beverage dispersal and consumption was the same as in Experiment 1. After the five-minute consumption period, participants were asked to answer questions about their impressions of the drink they consumed, as well as some additional questions about product preferences (e.g., how much they like specific brands of shampoo) to help reinforce the cover story.

After answering the distracter questions, participants were instructed to take the lid off of an opaque (6" × 10") green IKEA box that was located on the far right of their partitioned computer space. Inside the box were three consumer products: (a) a 12 ounce bottle of Ozarka natural spring water, (b) a pack of Trident gum (18 sticks, original flavor), and (c) an 8 ounce bag of plain chocolate M&M candies. Participants were prompted by the computer to pick each product up one at a time (order was randomized via Qualtrics) and evaluate the product's logo, packaging, and their familiarity with the product. At the end of the experiment, participants were told that they could choose one of the products to take with them when leaving. Participants were then thanked, debriefed, and dismissed. After participants exited the lab, the research assistant inspected each of the boxes and made note of which product was chosen by each participant using their ID number.

Table 3
Percent of participants in each drink condition who chose a specific food option to take home. The raw numbers of participants who chose each option are in parentheses. Three participants took none of the items (Sprite: $n = 1$, Sprite Zero: $n = 2$).

	Candy	Water	Gum
Drink condition			
Sprite	23.1% (9)	41% (16)	33.3% (13)
Sprite Zero	42.5% (17)	40.0% (16)	12.5% (5)
Water	16.7% (6)	58.3% (21)	25.0% (9)

Analysis plan

Although participant sex is not predicted to impact our results, we will first conduct a preliminary 2 (Participant Sex) × 3 (Drink) binary logistic regression model to determine whether participant sex moderates the impact of drink condition on participants' likelihood of choosing the candy (coded: Yes = 1, No = 0). If sex does not have an impact on our dependent measure (either by way of a main effect or interaction), it will be dropped from the model and the resulting model will be used to test our prediction ($\alpha = .05$). If the results reveal a main effect of drink condition on participants' RT, we will conduct two Bonferroni corrected orthogonal planned contrasts of the same kind as used in Experiment 1 ($\alpha = .025$ for each contrast).

Results

The results of our first statistical model revealed that participant sex did not interact with drink condition to influence participants' likelihood of taking the candy ($p = .50$) and was therefore dropped from the model. The resulting model revealed a significant main effect of drink condition on participants' likelihood of choosing the candy, *Wald* $\chi^2(2) = 7.12$, $p = .03$, $R^2 = .08$ (see Table 3 for descriptive statistics). Participants in the NCS drink condition were 2.93 times more likely to take the candy than those who had consumed either the sugar-sweetened or unsweetened drinks, $b = 1.08$ ($SE = .41$), *Wald* $\chi^2(1) = 7.02$, $p = .008$. No differences we found between those who consumed the sugar-sweetened or unsweetened drinks ($p = .62$).

Experiment 3

The goal of our third experiment was to build on the results of Experiments 1 and 2 by examining whether consuming NCS disrupts individuals' subjective responses to subsequently consumed sweetened foods. Much research has found that NCS consumption does not influence the number of calories consumed in a subsequent meal or snack (see Bellisle & Drewnowski, 2007 for a review). However, because consuming NCSs disrupt the natural pairing of sweet taste and energy availability, consuming them may degrade the hedonic response to sucrose-sweetened food, impairing the body's ability to regulate energy and body weight (Swithers & Davidson, 2005, 2008). Study 3 was designed to test this possibility experimentally by examining the impact of NCS-consumption on participants' satisfaction with a subsequently-consumed, sugar-sweetened snack.

Method

Participants

Because Experiments 1 and 2 did not find drink condition to interact with participant sex, we only tested using female participants in Experiment 3 to minimize variance in our dependent measure. As in Experiments 1 and 2, participants who ate or drank anything other than water less than eight hours prior to their study session were excluded from all analyses (13 excluded). This left a total of 77 participants (all female) with ages ranging from 18 to 23 years ($M = 19.38$, $SD = 1.57$) to participate in return for course credit (26 in the Sprite condition, 23 in the Sprite Zero condition, and 28 in the mineral water condition).

Design and procedure

Participants came into the laboratory one at a time ostensibly to participate in a consumer products study. The procedure for beverage dispersal and consumption was the same as in Experiments 1 and 2. After the five-minute consumption period had elapsed, participants answered the same distracter questions used in Experiment 2, and were then told that they were going to be evaluating how consumers evaluate food items when they are presented either in or out of their packaging. After clicking the continue button, participants were all told that they were in the 'no packaging' condition and that they would be evaluating a popular brand of cookies that would be brought to them in a serving bowl. At this point, a trained research assistant (all female) brought the participants the contents of a one ounce bag of mini Oreo cookies served in a disposable bowl. Participants were then instructed to sample the cookies so that they could answer some questions about them. Participants were told to eat at least one cookie, but that they could eat as many as they liked. Once participants finished sampling the cookies, they were instructed to answer questions about them. Participants were asked how good/bad they thought the cookie tasted and how satisfied they felt after eating them. Participants were then thanked, debriefed, and dismissed. A suspicion probe revealed that none of the participants guessed the true purpose of the experiment.

After participants exited the lab, the research assistant weighed the food remaining in the bowls. This amount was then subtracted from the pre-consumption weight to control for the amount consumed when examining participants' satisfaction after eating.

Analysis plan

Before examining the impact of drink condition on participants' satisfaction with the sugar-sweetened snack, we will first conduct an exploratory MANOVA to determine whether drink condition influences how tasty participants find the cookies and the number of calories they consume during the testing session. Although no differences are predicted on these measures, this analysis will allow us to rule out the possibility that any changes in self-reported satisfaction are the result of between-group differences on these measures. To test the prediction that consuming the NCS-sweetened beverage will decrease participants' satisfaction with a subsequently-consumed sugar-sweetened snack, we will then conduct a univariate ANCOVA with drink type as the between-subjects predictor, number of calories consumed as the covariate, and self-reported satisfaction as the dependent measure ($\alpha = .05$). If the results reveal a main effect of drink condition on participants' reported satisfaction, we will conduct Bonferroni corrected orthogonal planned contrasts ($\alpha = .025$) of the same kind as used in Experiments 1 and 2.

Results

The results of our exploratory multivariate analysis of variance (MANOVA) revealed that drink type did not influence how good/bad participants thought that the cookies tasted ($p = .51$) nor how much product participants consumed ($p = .65$) (see Table 4 for descriptive statistics). The results of our target univariate analysis of covariance (ANCOVA) revealed a significant main effect of drink condition on our dependent measure, $F(2, 73) = 5.15$, $p = .008$. Orthogonal planned comparisons revealed that participants who consumed the NCS-sweetened drink reported feeling less satisfied with what they had eaten compared to those who consumed either the sugar-sweetened or unsweetened drink ($p = .004$, CI: −1.46, −.297, see

Table 4
Descriptive statistics for participants' food ratings and calorie consumption by drink condition.

	Calories consumed		Taste		Satisfaction	
	M	*SD*	M	*SD*	M_{adj}	*SD*
Drink condition						
Sprite	57.94	43.18	6.00	0.82	4.91	1.12
Sprite Zero	66.75	53.47	5.70	1.33	3.84	1.66
Water	70.47	51.10	6.00	0.94	4.53	1.22

Table 4). No differences were found between the sugar-sweetened drink and those who consumed the mineral water ($p = .24$).

General discussion

Researchers frequently observe an association between regular consumption of non-caloric sweeteners (NCS) and weight gain, raising the question whether consuming products sweetened with NCS facilitate or impede weight loss goals (Colditz et al., 1990; Dhingra et al., 2007; Fowler et al., 2008; Lutsey et al., 2008; Nettleton et al., 2009). Although the majority of experimental studies examining the impact of NCS on subsequent calorie intake have failed to establish a causal link between these variables (Bellisle & Drewnowski, 2007), it remains possible that NCS consumption might influence individuals' food regulation psychology in more subtle ways that have the potential to influence weight management goals over time. In a series of three experiments using diverse methods and measures, we sought to examine this possibility, testing whether NCS consumption causes changes in individuals' food regulation psychology that may have implications for energy intake and weight management goals.

The results of our three experiments found support for this hypothesis. Experiment 1 found that participants who consumed a beverage sweetened with NCS– compared to those who consumed a sugar-sweetened or unsweetened beverage –had shorter response latencies to the names of high-calorie food items. No such differences were found for the names of low-calorie food items or non-words, suggesting that drinking non-caloric sweeteners may increase cognitive preoccupation with foods that have a relatively high calorie content. Experiment 2 extended these results, demonstrating that participants who consumed a NCS-sweetened beverage – relative to those who consumed a sugar-sweetened or unsweetened beverage –were more likely to choose a high-calorie food item in a consumer choice scenario. When offered their choice of either a high-calorie food item (M&M chocolate candies) or one of two low- or zero-calorie items (a bottle of Ozarka spring water or a pack of Trident sugar-free gum), participants who consumed the NCS-sweetened beverage were 2.93 times more likely to take the candy than those who had consumed the sugar-sweetened or unsweetened drink. Together, these results suggest that consuming NCSs may influence implicit desires for calorie dense foods and promote behaviors that encourage increased calorie consumption over time.

Experiment 3 built on the results of experiments 1 and 2 by examining the impact of NCS-sweetened beverages on participants' subsequent responses to a sugar-sweetened snack. The results of this experiment found that drink type did not influence the number of calories consumed; however, participants who consumed a NCS beverage felt less satisfied after eating a sugar-sweetened snack than those who had consumed a sugar-sweetened or unsweetened beverage. These results are consistent with recent fMRI studies demonstrating that regular consumption of NCSs can alter the neural pathways responsible for the hedonic response to food (see, e.g., Green & Murphy, 2012; Smeets et al., 2011). For example, research indicates that frequency of NCS consumption negatively predicts amygdala and insula responses to sucrose (Rudenga & Small, 2012), which is consistent with a diminished pleasure response to sweet foods (Kringelbach, 2005). Taken together with the results from Experiment 3, such research suggests that NCS-consumption may have an impact on patterns of hedonic-based consumption over time, but perhaps in more subtle ways than can be captured using traditional experimental pre-load designs (see e.g., Birch et al., 1989; Black et al., 1991; Canty & Chan, 1991; Rolls et al., 1990). For example, it is possible that these changes may increase one's likelihood of seeking out additional food items as a means of gratifying consumption desires (Bornet, Jardy-Gennetier, Jacquet, & Stowell, 2007; Harrold, Dovey, Blundell, & Halford, 2012; Kristensen & Jensen, 2011). Alternatively, this effect may decrease the intake of sugar-sweetened food items, given their lower reward-value. Whatever its ultimate impact on consumption, this research suggests that the effects of NCS on energy balance are likely more nuanced than many have previously thought. Rather than causing sweeping psychological, physiological, and behavioral changes – NCS consumption may produce smaller, subtler changes in the ways that consumers think about and respond to food, making their impact on energy balance only apparent over time (i.e., over a longer span of time than measured in the laboratory and short-term longitudinal studies).

The current results contribute to a growing body of research on the impact of NCS-sweetened food and drink on energy intake and body weight maintenance, many of which have found conflicting results (see Bellisle & Drewnowski, 2007 for a review). In some studies, the consumption of NCS-sweetened products is associated with increased food intake and weight gain (e.g., Colditz et al., 1990; Dhingra et al., 2007; Fowler et al., 2008; Foreyt, Kleinman, Brown, & Lindstrom, 2012; Lavin et al., 1997; Nettleton et al., 2009). Others find that they have no impact on energy consumption and body weight (e.g., Newby et al., 2004; Porikos, Booth, & Van Itallie, 1977; Van Wymelbeke, Beridot-Therond, de La Gueronniere, & Fantino, 2004; Wilson, 2000), while others find that they decrease food intake and can prevent weight gain or promote weight loss (e.g., Blackburn, Kanders, Lavin, Keller, & Whatley, 1997; de Ruyter et al., 2012; Raben et al., 2002). Although these studies differ in their research design, sample composition, and the specific nature of their dependent measures, it seems unlikely that the variability in the results obtained could emerge simply as the result of these differences. Instead, it is plausible that NCSs have multiple or even conflicting behavioral effects on food intake and weight management. For example, it is possible that NCS-sweetened products may facilitate an initial decrease in body weight if consumers use them as a replacement for higher-calorie products. Over time, however, they may promote weight gain either as the result of psychological changes similar to those demonstrated in our studies or through calorie compensation (i.e., consumers adding additional calories to their diet to make up for those they eliminated by using of NCSs). Another possibility is that the impact of these products on energy intake and energy balance may differ inter-individually, depending on one's experiences with them, one's metabolism, and the composition of the foods and drinks in which they are contained. There is evidence supporting each of these possibilities (see e.g., Green & Murphy, 2012; Griffioen-Roose et al., 2013; Hogenkamp, Stafleu, Mars, Brunstrom, & de Graaf, 2011). The results of the current research – particularly when considered in the context of these other studies – suggest that discussions about the impact of NCSs on energy regulation are far from over. Novel approaches to studying its impact may be necessary to fully understand the complex interplay between sweetened drink consumption, energy intake, and weight management.

The current research also contributes to a growing literature on the impact of NCS-consumption of cognition, more broadly. Researchers have hypothesized that the mismatch between a sweet taste and lack of energy availability may activate adaptive cognitions that promote survival in the context of bodily energy shortfall (Aarøe & Petersen, 2013; Wang & Dvorak, 2010). Consistent with this hypothesis, researchers found that participants who consumed a soft drink sweetened with NCS – but not those who consumed a sugar-sweetened drink – subsequently experienced a decrease in blood glucose, which was associated with a greater preference for immediate compared to delayed monetary rewards (Wang & Dvorak, 2010). Others have found that it produces increased support for social welfare programs (Aarøe & Petersen, 2013). The result of the current experiments lend additional support for this hypothesis, demonstrating that NCS-sweetened products may also influence processes that influence food regulation in ways that would help promote survival in the face of a perceived energy shortfall.

One important limitation of the current research is that we didn't measure participants' experience with either sugar- or NCS-sweetened beverages and, as such, did not control for this experience in any of our statistical analyses. Although some have found that repeated exposure to NCS does not influence how people respond to either sugar- or NCS-sweetened food and drinks (see e.g., Griffioen-Roose et al., 2013), others have found that they do (Appleton & Blundell, 2007; Rudenga & Small, 2012). Future research would benefit from including these variables in their experimental design so that they could be appropriately controlled for, if necessary. A related limitation is that we didn't ask participants to try to identify what they were drinking. Accordingly, there is no way to determine what role their beliefs about the energy composition of the drink they consumed played in our results. One possibility, for example, is that the differences observed between those in the NCS-sweetened drink condition compared to the other two drink conditions emerged as a by-product of more conscious-level processes related to calorie compensation. That is, because each of these drinks has a different taste profile, it is possible that participants were aware of what they were drinking and that this could have impacted how they responded. For example, it is possible that those in the NCS-sweetened beverage condition recognized that they were consuming a non-caloric drink, which in turn led them to exhibit compensation behaviors (i.e., changes that would promote increased calorie consumption). Although future research is needed to address these limitations, the present results contribute to the ongoing discussion about the impact of sweetened drinks on energy regulation and energy balance.

Although not the focus of the current research, it is worth noting that across each of our three experiments, there were no differences found between participants who consumed the sugar-sweetened drink (Sprite) and those who consumed sparkling water. That this pattern was observed in each of our experiments suggests that sugar-sweetened drinks may not elicit compensation-related cognitions (i.e., cognitive responses to food that would promote diminished calorie intake to make up for the energy consumed in the drink), potentially leading to increased total calorie consumption. This result is consistent with others' research examining the effect of sugar-sweetened drinks on hunger and energy intake (see e.g., de Castro, 1993; de Graaf, 2011; Maersk et al., 2012; Mattes, 1996; Sørensen, Vasilaras, Astrup, & Raben, 2014) and provides novel evidence bearing on the hypothesis that liquid calories fail to trigger the normal suite of mechanisms that promote satiety and regulate appetite (see also Anton et al., 2010). Future research into this issue is potentially warranted given the consistency with which this pattern was observed.

Lastly, although the results of the current research have found support for the hypothesis that NCS consumption causes psychological changes that may encourage increased calorie consumption, the specific mechanism guiding the reported effects is admittedly speculative. As of this writing, we do not have direct causal evidence from which we can draw final conclusions about whether the demonstrated shifts are guided by perceptions of a bodily energy crisis based on the decoupling of sweetness with energy availability, as hypothesized (Aarøe & Petersen, 2013; Wang & Dvorak, 2010). One alternative explanation for our results, for example, is that these effects emerge from temporary changes in neuronal signaling in response to the chemical composition of key ingredients found in NCSs. For example, research finds that high levels of aspartate – a key ingredient in aspartame – influence neurons in the arcuate nucleus of the hypothalamus (Bouret, Draper, & Simerly, 2004; Dawson, Pelleymounter, Millard, Liu, & Eppler, 1997; Olney, 1993; Olney & Ho, 1970; Schainker & Olney, 1974). Accordingly, one potential alternative hypothesis is that these changes occur in response to temporary disruptions in leptin signaling in the brain (e.g., Olney & Ho, 1970; Rudenga & Small, 2012; Schainker & Olney, 1974). Future research is needed to address the precise mechanisms that are responsible for the demonstrated effects and whether these effects are specific to changes in food regulation psychology, or if they extend to predict more general changes in the ways that consumers think about and respond to hedonic stimuli more generally. Nonetheless, the current research contributes to the growing body of research on the impact of psychological processes on factors that play a role in energy regulation.

Conclusions

The results of our three experiments revealed that consuming NCS-sweetened beverages may impact the psychological processes that influence energy regulation in ways that have not been accounted for in previous testing paradigms. Although further research is needed to fully understand the mechanisms guiding these effects, the reported results nonetheless contribute to the growing discussion about the roles played by NCS- and sugar-sweetened beverages in energy regulation.

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