Published in final edited form as:

Obesity (Silver Spring). 2014 February ; 22(2): 441–450. doi:10.1002/oby.20563.

Neural responsivity during soft drink intake, anticipation, and advertisement exposure in habitually consuming youth

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Abstract

OBJECTIVE—Although soft drinks are heavily advertised, widely consumed, and have been associated with obesity, little is understood regarding neural responsivity to soft drink intake, anticipated intake, and advertisements.

METHODS—Functional MRI was used to assess examine neural response to carbonated soft drink intake, anticipated intake and advertisement exposure as well as milkshake intake in 27 adolescents that varied on soft drink consumer status.

RESULTS—Intake and anticipated intake of carbonated Coke[®] activated regions implicated in gustatory, oral somatosensory, and reward processing, yet high-fat/sugar milkshake intake elicited greater activation in these regions versus Coke intake. Advertisements highlighting the Coke product vs. non-food control advertisements, but not the Coke logo, activated gustatory and visual brain regions. Habitual Coke consumers vs. non-consumers showed greater posterior cingulate responsivity to Coke logo ads, suggesting that the logo is a conditioned cue. Coke consumers exhibited less ventrolateral prefrontal cortex responsivity during anticipated Coke intake relative to non-consumers.

CONCLUSIONS—Results indicate that soft drinks activate reward and gustatory regions, but are less potent in activating these regions than high-fat/sugar beverages, and imply that habitual soft drink intake promotes hyper-responsivity of regions encoding salience/attention toward brand specific cues and hypo-responsivity of inhibitory regions while anticipating intake.

Keywords

fMRI; obesity; reward learning; soft drinks; advertisements; sugar-sweetened beverages

INTRODUCTION

Sugar-sweetened beverage intake has been linked to obesity, poor diet quality, and morbidity (1–3). Adolescents' soft drink consumption has dramatically increased in the past 30 years (4), paralleling an increase in advertisements for these products (5,6). Yet, little is known about neural response to carbonated soft drink intake, anticipated intake, and

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Conflict of Interest

The authors and research staff involved with the present study declare no conflict of interest.

Data were presented at The Obesity Society annual meeting as a part of the Ethan Sims Young Investigator Award presentations.

advertisements and whether habitual soft drink consumption alters neural responsivity to these stimuli.

Obese versus lean humans show hyper-responsivity in brain regions that encode attention (visual and anterior cingulate cortices), gustatory processes (anterior insula/frontal operculum), and reward (striatum) when exposed to appetizing food images (7–10) and when anticipating palatable food receipt (11,12), theoretically increasing risk for escalated intake of energy dense foods. In contrast, obese versus lean individuals show less striatal activity during palatable food intake (12–14), which may delay meal termination if individuals are seeking the previously experienced pleasure from food intake. In support, objectively measured food intake beyond needs correlated positively with activity in attention and gustatory regions when anticipating palatable food receipt (15), and striatal response during intake correlated negatively with frequency of consumption of foods similar to those in the scan (16, 17). Collectively, data demonstrate differences in neural responsivity to food stimuli during anticipation versus intake as a function of weight status and habitual intake, suggesting that regular consumption of energy-dense, palatable foods leads to hyper-responsivity of reward valuation regions to cues that signal potential intake and hypo-responsivity of reward regions during consumption. Importantly, heightened anticipatory response followed by a reduced consummatory response, may increase risk for excess consumption in a feed forward fashion (18,19). Therefore, it is imperative to gain a better understanding of the neural processes during both anticipation and intake. However as research assessing these aspects of ingestion typically administer either a sucrose solution or milkshake, little is understood about neural response during anticipation and intake of widely consumed soft drinks.

Three studies examined neural response to intake of uncarbonated soft drinks. McClure and colleagues (20) found that logo cued intake of uncarbonated Coke® versus light cued intake, activated the hippocampus, midbrain, thalamus, and visual cortex, whereas the same contrast with Pepsi did not affect neural responsivity. Further, ventromedial prefrontal cortex (vmPFC) responsivity to the blinded delivery of these sodas related to taste preferences for these products, suggesting that the vmPFC activity was based on sensory properties during intake. Smeets and colleagues (21) used uncarbonated Orangeade to assess neural responsivity when manipulating the nutritive value of the sweetener used, whereas Filbey and colleagues (22) allowed overweight participants to select a beverages, which included uncarbonated soft drinks and analyzed data collapsing across all beverage types. Both studies showed intake of sugar-sweetened beverages elicited a reward-related response. However, little is known about the capacity of ubiquitous carbonated high-sugar soft drinks to activate brain regions associated with reward, gustatory and somatosensory processes relative to beverage types and whether habitual consumption of these beverages is related to aberrant neural responsivity.

Intense and specialized food marketing theoretically targets adolescents due to their purchasing power and to foster brand loyalty (23). Researchers posit that brands that have been associated with rewarding or appetitive stimuli due to marketing, engage similar brain reward-related networks (24). In support, neuroimaging studies reveal that presentation of preferred versus non-preferred brands recruited striatal, occipital, and vmPFC activity

(25,26) and exposure to familiar versus non-familiar brands resulted in precuneus and occipital cortex activity (27,28). Similarly, among healthy-weight youth, exposure to branded food logos versus non-food logos, elicited response in the posterior cingulate and occipital cortices, regions implicated in stimulus saliency, visual processing, and attention (29). When exposed to food logos (versus non-food logos), obese versus lean youth showed decreased activity in the ventrolateral prefrontal cortex (vlPFC) a region associated with cognitive control, suggesting that obese youth may be at increased vulnerability to food advertisements (30).

Little is known about the neural response to intake, anticipated intake and advertisement exposure of a carbonated soft drink or how habitual consumption may affect this responsivity. Further, it is unclear how effective high-sugar soft drinks are at activating reward regions relative to high-fat/high-sugar beverages. Given the omnipresent advertisements for soft drinks, their widespread habitual consumption and its relation to obesity and morbidity, it is vital to better understand how these events affect neural responsivity and whether habitual intake is related to aberrant neural responsivity that may perpetuate further consumption. Herein we sought to: 1) examine the effect of carbonated soft drink intake, anticipated intake, and advertisements on neural response in youth, particularly in brain regions implicated in attention, gustatory, and reward processing, 2) directly compare neural response to intake of a high-sugar/fat-free soft drink to a high-sugar/fat milkshake, and 3) test whether habitual soft drink intake moderates neural responsivity to these events.

METHODS AND PROCEDURES

Twenty-seven participants completed the study. 13 were Coke consumers and 12 were non-soda drinkers (Table 1), 2 qualified for neither consumer category and were only included in the subsample analysis. A Coke consumer was defined as consuming >5 Coca-Cola Classics® (12fl oz/Coke) per week for more than the previous month. Coke consumers could regularly drink other types of soft drinks, but remained eligible if they met the minimum (regular, not diet) Coke consumption criteria and indicated their preference for Coke above other sodas. A non-consumer was defined as an individual that drank less than two 8fl oz servings of the following beverages per month: artificially- or sugar-sweetened beverages (e.g., soft drinks, diet soft drinks, sweetened teas, added-sugar fruit juices, sweetened caffeinated beverages) or unsweetened high caffeine beverages (e.g., coffee). Additional exclusion criteria included contraindicators of MRI (e.g., braces), current major psychiatric disorders (substance use disorders, ADHD, bipolar/panic disorders, generalized anxiety disorder), serious medical complications (e.g., diabetes), current use of psychoactive drugs, smoking, and weight loss dieting. Oregon Research Institute's Institutional Review Board approved all methods.

Coca-Cola was selected for several reasons. First, Coke is the most commonly sold sugar-sweetened beverage and is heavily advertised (\$180 million spent in 2010), and Coke ads accounted for 42% of spending on ads in the regular soda category in 2008 (23,31). Coke elicited greater neural responsivity than Pepsi (20). Further, Coke accounted for three-fourths of brand appearances seen by teens (31). Lastly, the Coke brand is prominent on the

Internet; the 'MyCokeRewards.com' website is the most frequently visited sugar sweetened beverage company website with 170,000 unique youth visitors per month and Coca-Cola is the most 'liked' brand on Facebook having more than 30 million 'likes' (31).

Sensory & hedonic measures

Participants were asked to consume their regular meals but to refrain from eating or drinking for 4hr immediately preceding their imaging session for standardization (4.1 ± 0.7 hours). Just prior to the scan, hunger, and hedonic ratings of the tastants were assessed on 20cm cross-modal visual analog scales anchored by -10 'not at all', and 10 'extremely'. Participants tasted a small amount of the tastants when rating their pleasantness. Confirming participants were in a neutral hunger state during the scan, the mean hunger rated prior to the scan was neutral (0.0 ± 2.7 ; Table 1). To test the similarity of the Coke tasted before the scan to the Coke delivered during the scan, immediately after the scans participants rated: how pleasant the Coke tasted during the scan, how normal the temperature of the Coke was during the scan, how normal the carbonation of the Coke was during the scan, and, in general, how normal the Coke tasted during the scan on separate Likert scales. These scales ranged from 1 - 'not pleasant/different from normal', to 5 - 'extremely pleasant/exactly like normal' (Table 1).

Coke intake fMRI paradigm

Subjects received carbonated Coke (63kcal, 0g fat, 17g sugar/150 mL) and a tasteless solution through a gustometer designed by our research team. The tasteless solution mimicked the natural taste of saliva (32). The gustometer consists of syringe pumps dispensing tastants through beverage tubing to a manifold where a bolus of solution is dropped onto a Teflon ball that sits on the subject's tongue (8). Syringes were packed in ice bags and tubing was run through an ice bath located at the foot of the scanner bed to keep the beverages cool thereby reducing precipitation of CO₂. We also devised a 3-way 'burp' valve that allowed carbonation to escape without uncontrollably administering Coke. CO₂ inevitably exited solution within the tubing, however the manifold was designed to allow excess CO₂ to escape while Coke was delivered.

During the Coke intake paradigm a picture (bottle of Coke or water) appeared followed by a fixation cross and the corresponding tastant was delivered presented in a random order. For Coke trials, Coke was delivered as 0.5cc bolus, followed by a fixation cross, a rinse (of tasteless solution) and a jitter (Figure 1A). Tasteless solution trials were similar presenting a picture of bottled water, then delivered 0.5 cc bolus of tasteless solution followed by a jitter (Figure 1B). There were 24 repeats of each experimental events of interest (Coke and tasteless intake, anticipated Coke and tasteless). The total paradigm duration is 14min 36sec.

Milkshake intake fMRI paradigm

A subset of the sample (n=10; M=5, F=5) underwent an additional fMRI to assess neural responsivity to milkshake receipt. Participants that completed this were 3 Coke consumers, 5 non-consumers, and two additional participants were recruited that reported drinking 12froz of soft drinks 3–5 times per month. Order of the completion of these paradigms was counter-balanced separated by at least one month. Of the two additional participants included in the

subsample analyses, one was excluded due to incomplete scan data. The remaining right-handed, male subsample participant (age=17; BMI=19.9) did not differ from the sample used in primary analyses. The fMRI milkshake intake paradigm examined BOLD response to receipt of ice cream-based chocolate milkshake (270kcal, 13.5 g fat, 28g sugar/150 mL) and tasteless solution. Milkshake was selected as comparison due its highly palatability and established use in the existing literature (e.g., 8, 11, 16, 35). Milkshake was also selected given the differences from Coke in macronutrient content, thereby providing novel information about the relative effects of higher fat and sugar during intake. The design of the milkshake paradigm generally paralleled the soda receipt paradigm. Further details regarding these methods appear elsewhere (8).

Advertisement fMRI paradigm

Visual stimuli were presented with the projector/mirror system. Pictures consisted of Coke product advertisements, Coke logo advertisements, and non-food/beverage advertisements. Coke images included print Coke ads, images of Coke store displays, delivery trucks, and screenshots from Coke's website (Figure 1C). Coke product ads highlighted Coke, presenting images of the bottle/can where Coke was visible (e.g., Coke pouring over ice, bottles on display). Coke logo ads highlighted the words Coca-Cola in the branded font with wave underline and the Coke bottle silhouette (e.g., Coke poster with only Coca-Cola and bottle silhouette shown). Non-food or beverage related ads were: images of cell phone, furniture ads, parcel delivery trucks and screenshots from non-food websites. All images were matched on clarity, contrast, and brightness. Images were presented in random order and were displayed for 3.5sec followed by a fixation cross for 3–4sec. The paradigm presented 20 of each stimuli category over one run lasting 7min 30sec (Figure 1D).

fMRI data acquisition, preprocessing, & analysis

A Siemens Allegra 3 Tesla head-only MRI scanner acquired functional scans using a T2* weighted gradient single-shot echo planar imaging sequence (TE=30ms, TR=2000ms, flip angle=80°); in plane resolution = $3 \times 3 \text{ mm}^2$ (64×64 matrix; $192 \times 192 \text{ mm}^2$). Thirty-two 4 mm slices (interleaved acquisition, no skip) were acquired along the AC-PC transverse, oblique plane. Prospective acquisition correction was applied to adjust slice position and orientation, and to re-grid residual volume-to-volume motion in real-time during data acquisition to reduce motion-induced effects (33). A high-resolution inversion recovery T1 weighted sequence (FOV= $256 \times 256 \text{ mm}^2$, thickness=1.0mm, slice number 160) was acquired.

Data were preprocessed and analyzed using SPM8 (Wellcome Department of Imaging). After manual realignment and skull stripping, functional images were realigned to the mean and both the anatomical and functional images were normalized to the standard Montreal Neurological Institute (MNI) T1 template brain (ICBM152), resulting in a voxel size of 3 mm^3 for functional images and of 1 mm^3 for anatomical images. Functional images were smoothed with a 6mm FWHM isotropic Gaussian kernel. Anatomical images were segmented using DARTEL, a mean of the resulting gray matter was used as a base for an inclusive mask. The contrasts of interest were activation in response to intake of Coke versus tasteless solution, intake of milkshake versus Coke, and anticipated intake of Coke versus anticipated tasteless. Coke product and logo ads were compared to non-foods ads

(e.g., Coke product ads > non-food ads). Reverse contrasts were also performed. No significant effects were observed using the reverse contrasts unless otherwise noted.

Main effects were considered significant at $p < 0.05$ corrected for multiple comparisons with family-wise error rate at the cluster level across the whole brain (cluster-wise $p_{FWE} < 0.05$). For between group comparisons overall significance level of $p < 0.05$ corrected for multiple comparisons across the whole brain was calculated using the 3dFWHMx/3DClustSim modules of AFNI (34). Ten-thousand Monte Carlo simulations of random noise through the functional data at 3mm^3 were used, which indicated activity surviving $p < 0.005$ with a cluster (k) ≥ 26 was considered significant corrected for multiple comparisons. All stereotactic coordinates are presented in MNI space (Internet: <http://mni.mcgill.ca/>). Effects sizes (r) were calculated as $(Z/\sqrt{n})$. Tests of normality of distribution, descriptive statistics, correlation analyses, and tests for differences by sex were performed using SPSS (version 19, SPSS Inc.; 2011). Analyses confirmed that effects were not driven by influential outliers; presented results are not attenuated when controlling for handedness or menstrual phase.

RESULTS

Pre-scan Coke pleasantness ratings correlated with ratings of Coke pleasantness during the scan ($r = 0.43$; $p < 0.05$) and post-scan queries regarding how normal the Coke tasted during the scan (temperature, carbonation, general taste) were high (mean 3.9 out of 5; Table 1), indicating that the methods used to mimic real-world consumption of a soft drink during the scan were successful. Although no significant differences by consumer status in hedonic ratings were observed at the prescan assessments, Coke consumers rated the pleasantness of Coke during the scan significantly higher than non-consumers (Table 1).

Neural responsivity to Coke intake, anticipated intake and milkshake intake

Coke intake vs. tasteless solution intake significantly activated the bilateral postcentral gyrus (oral somatosensory cortex), midbrain extending into the insula, and central operculum (Figure 2A; Table 2). Anticipated Coke intake vs. anticipated tasteless intake activated the inferior lateral occipital cortex, ventromedial prefrontal cortex, thalamus extending into bilateral striatum including the putamen, nucleus accumbens, and caudate, bilateral postcentral gyrus, posterior cingulate cortex, and anterior cerebellum (Figure 2B; Table 2).

Milkshake intake versus Coke intake activated the bilateral postcentral gyrus (Figure 2C; Table 3) extending into the central operculum, right thalamus, and bilateral ventral pallidum extending into the putamen (Figure 2C). Coke intake versus milkshake intake activated the middle temporal gyrus, middle frontal gyrus superior lateral occipital cortex and medial prefrontal cortex extending into the anterior cingulate cortex (Table 3).

Neural responsivity to Coke advertisements

Exposure to all Coke ads vs. non-food ads activated the bilateral lingual gyrus and superior lateral occipital cortex (Table 4). Exposure to Coke product ads vs. non-food ads activated the bilateral inferior occipital cortex, bilateral postcentral gyrus, and left putamen extending

into the posterior insula (Table 4). Exposure to Coke ads with only the logo did not elicit significant activation relative to non-food ads.

Effects of consumer status

Adolescents who habitually consume Coke versus those who did not consume soft drinks, showed less activation in the ventrolateral prefrontal cortex (vlPFC/inferior frontal gyrus; Figure 3A; Table 5) during anticipated Coke intake (vs. anticipated tasteless solution intake). No significant differences by consumption status were observed during intake of Coke vs. tasteless intake.

Habitual Coke consumers showed greater activation during Coke logo ads (vs. non-food ads) in the posterior cingulate (Figure 3B; Table 5) and precuneus (Table 5) versus non-soft drink consumers. No differences in neural responsivity as a function of consumer status were observed when exposed to Coke product ads (vs. nonfood ads).

DISCUSSION

Intake of a branded carbonated soft drink recruited several brain regions implicated in oral somatosensory (postcentral gyrus) and reward (midbrain) processing. Anticipation of intake elicited robust activity in regions implicated in reward/incentive properties of food (striatum), gustatory processing (insula), visual processing (occipital cortex), salience of stimuli (posterior cingulate) and oral somatosensory processes. Replicating results from McClure (20), during brand-cue Coke intake, we observed midbrain activity. Interestingly, midbrain activity during palatable food intake has predicted subsequent *ad lib* consumption (35). Responsivity in oral somatosensory regions, the thalamus, pallidum, and striatum appear to be more sensitive to high-fat/-sugar milkshake intake, indicating that foods with greater energy density or fat/sugar content produce greater neural response in these regions that are frequently associated with food reward. It is unclear if the greater activation from the milkshake vs. Coke was a response to the increased energy density or differences in macronutrient of the milkshake. When assessing neural responsivity to Coke versus milkshake intake, we observed activity in the vmPFC. This region has been shown to correlate with soft drink preferences during intake irrespective of brand knowledge (20). The present data extend this finding by demonstrating that intake of soft drink stimulated greater activity in this region relative to an energy-dense milkshake.

All Coke ads relative to non-food ads resulted in activity in the lingual gyrus and occipital cortex, replicating activation patterns reported by Bruce and colleagues (29) in response to food logos vs. non-food logos. We, however, observed differences in the type of Coke ad presented; ads highlighting the product elicited more activity relative to ads highlighting the logo, suggesting that presentation of the product in food ads may be more effective in eliciting attention in the lay public. Exposure to Coke product ads resulted in activity in gustatory and oral somatosensory related regions, while the brand did not, suggesting that presentation of actual food items recruited activity in regions associated with ingestion.

We observed some differences in neural responsivity as a function of habitual consumption, in a manner that may theoretically encourage further intake. Specifically, we observed

greater response to Coke logo ads in the posterior cingulate and decreased vIPFC activity when anticipating intake. The posterior cingulate cortex is thought to encode stimulus salience (36), and responds during selection of a favorite brand during a forced choice paradigm (37), and during purchasing decisions (38). The present data suggest that the Coke logo is more salient to regular consumers of the product, which may increase the susceptibility for additional purchase. Interestingly, consumer status did not affect neural response to Coke product ads, hinting that this sweetened beverage is an unconditioned cue, whereas the logo is a conditioned cue. This notion is supported by the fact that the Coke product conveys little information via image alone beyond the fact it is a dark brown, carbonated liquid. Therefore the product itself is less distinctive (e.g., Pepsi®, Dr. Pepper® appear similar), however the Coke logo is far more unique and specific, conveying considerably more information regarding the brand upon viewing. Bruce and colleagues (30) found overweight youth showed less vIPFC activity to food logos vs. non-food logos, echoing our finding that Coke consumers vs. non-consumers showed less vIPFC activity when anticipating Coke intake. The vIPFC has been associated with inhibition and theoretically relates to real-world instances of self-control (39,40). Thus, decreased activity in this inhibition-related region during anticipation may increase risk for excessive intake. Collectively, a heightened salience response to the Coke logo, and decreased inhibitory response during anticipation may, in theory, work in tandem to perpetuate habitual consumption.

It is important to note the study limitations. First, the cross-sectional design makes it unclear whether the neural responsivity identified herein represents initial vulnerability factors that increase risk for habitual intake of sweetened beverages or are a result of this behavior. Second, the moderate sample size reduced sensitivity and could have led to false negative findings, particularly in the reduced sample size in the subsample. However, many results are supported by previous, independent work, we used rigorous thresholds to account for multiple comparisons, and insured that the observed findings were not a result of influential outliers, suggesting the presented results are valid. Further, the within-subject nature of the subsample analyses is a strength, and those included in the subsample did not statistically differ from those not included in the subsample in all variables presented in Table 1 (p 's = 0.16–1.00). Third, only one soft drink was investigated; results may not generalize to others and information as to why the non-consumers did not drink Coke was not obtained. There is also a possibility the present results do not reflect a similar response in adults (e.g., adults may differ on the length of habitual consumption; and may have different purchasing power). Fourth, whereas Coke contains caffeine and was carbonated, the tasteless solution and milkshake were not; it is possible that this difference contributed to the observed effects. Lastly, subjective valence ratings of the advertisement images and pre-scan thirst were not collected. Valence ratings may have provided support for the observed results in the advertisement paradigm, and differences in thirst may have impacted the present findings.

In conclusion, the present study found that intake and anticipated intake of Coke activated regions implicated in gustatory and reward processing, yet high-fat/sugar milkshake intake elicited greater activity relative to Coke. Advertisements highlighting the Coke product activated gustatory and visual processing regions, whereas the Coke logo did not. However,

habitual Coke consumers versus non-consumers showed greater posterior cingulate responsivity to Coke logos while also exhibiting less vIPFC responsivity during anticipated Coke intake. Results indicate that soft drinks activate reward and gustatory regions, but are less potent in activating these regions than high-fat/sugar beverages, and imply that habitual soft drink consumption may be related to hyper-responsivity of regions encoding salience/attention toward brand specific cues and hypo-responsivity of inhibitory regions while anticipating intake.

Acknowledgments

The authors would like to thank Scott Watrous at the Lewis Center for Neuroimaging at the University of Oregon for his assistance in designing the methods for controlled administration of a carbonated beverage in the scanner. Support for this work was provided by internal funding mechanisms at Oregon Research Institute. Both authors were involved in writing the manuscript and provided final approval for the submitted version.

Abbreviations

fMRI	Functional magnetic resonance imaging
MNI	Montreal Neurological Institute
vmPFC	ventromedial prefrontal cortex
vIPFC	ventrolateral prefrontal cortex

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What is already known about this subject

- Functional magnetic resonance imaging (fMRI) studies indicate that obese vs. lean human show: hyper-responsivity to food cues in reward, gustatory and attention regions and a reduced reward-related response during palatable food intake.
- A similar pattern of neural response has been shown as a function of habitual food intake.
- Soft drinks are heavily advertised toward youth and widely consumed, and are linked with obesity and poor health.

What this study adds

- This is the first study to examine neural response to carbonated soft drink intake, anticipated intake & advertisements in youth.
- Coke anticipation & intake elicited activity in reward & somatosensory regions, yet reward-related response of a high-fat/sugar milkshake intake was greater when compared to Coke.
- Habitual Coke consumers had greater response to Coke logo ads in a region associated with salience and less activity in a behavioral control region when anticipating Coke intake.

Figure 1.

Sample timeline and images from the advertisement Coke intake fMRI paradigm. Timing is shown for (A) Coke and intake and (B) tasteless solution cue and intake. Sample images (C) and timeline (D) from the advertisement fMRI paradigm.

Figure 2.

Column A) Activation in response to Coke intake (Coke intake > tasteless solution intake) in oral somatosensory regions (top circles) and midbrain (bottom circle). Column B) Activation in response to anticipated Coke intake (anticipated Coke intake > anticipated tasteless solution intake) in oral somatosensory regions (top circles) and striatum including the caudate, putamen & nucleus accumbens (top & bottom oval). Column C) Activation in response to milkshake intake relative to Coke intake (milkshake intake > Coke intake) in oral somatosensory regions (top circles) and ventral pallidum and thalamus (bottom oval). Additional detail can be seen Tables 2–4. Color bars indicate the *T*-value of the activation.

Figure 3.

Column A) Habitual Coke consumers showing *less* activation in response to anticipated Coke intake (anticipated Coke intake > anticipated tasteless) relative to non-consumers in the ventrolateral prefrontal cortex (vlPFC; circles). Column B) Habitual Coke consumers showing *greater* activation in response to Coke logo ads (Coke logo ads > non-food ads) relative to non-consumers in the posterior cingulate cortex (circles). Additional detail can be seen Table 5. Color bars indicate the T -value of the activation.

Table 1

Participant characteristics and sensory and hedonic measures

	Coke consumers n = 13	Non-consumers n = 12	Full sample n = 25
Age (years)	15.0 ± 0.9 ^a	15.4 ± 0.6	15.2 ± 0.8
Sex	M = 8, F = 5	M = 5, F = 7	M = 13, F = 12
BMI (kg/m ²)	22.0 ± 3.4	23.6 ± 5.2	22.8 ± 4.4
BMI percentile	63.9 ± 23.4	71.0 ± 21.9	67.4 ± 22.5
Handedness (# right handed)	12	12	24
Pre-scan Hunger (−10 to 10) ^b	−0.2 ± 3.0	0.2 ± 2.4	0.0 ± 2.7
Pre-scan Coke pleasantness (−10 to 10) ^b	4.1 ± 3.9	1.8 ± 3.3	3.0 ± 3.8
Pre-scan Tasteless solution pleasantness (−10 to 10) ^b	−1.9 ± 3.2	−0.6 ± 2.6	−1.3 ± 2.9
Scan Coke pleasantness (1 to 5) ^c	4.3 ± 0.7*	3.1 ± 1.1	3.7 ± 1.0
Scan Coke temperature normality (1 to 5) ^d	3.2 ± 1.0	3.3 ± 1.0	3.3 ± 1.0
Scan Coke carbonation normality (1 to 5) ^d	4.2 ± 0.8	4.0 ± 0.9	4.1 ± 0.8
Scan Coke taste normality (1 to 5) ^d	4.6 ± 0.7	3.9 ± 0.9	4.3 ± 0.9

^aData presented in mean ± standard deviation unless otherwise noted.^bVisual analog scale range −10 to 10; −10 – ‘not at all’, 0 – ‘neutral’, 10 – ‘extremely’.^cScale range 1 to 5; 1 – ‘not pleasant’, 5 – ‘extremely pleasant’.^dScale range 1 to 5; 1 – ‘different from normal’, 5 – ‘exactly like normal’.*Indicates significant differences between Coke consumers and non-consumers $p < 0.05$.

Table 2

BOLD responsivity to Coke intake and anticipated intake

		<i>x, y, z</i>	<i>k</i>	Peak <i>Z</i> value	Peak <i>r</i>	Cluster-wise <i>pFWF</i> ^a
<i>Coke intake vs. tasteless solution intake</i>						
Postcentral gyrus	R	48 -13 34	128	4.98	>0.98	0.001
		51 -13 43		4.95	>0.98	
Midbrain		42 -4 40		3.87	0.77	
	R	6 -31 -2	89	4.90	0.98	0.006
		9 -31 -20		3.97	0.79	
Postcentral gyrus		-3 -40 -23		3.67	0.79	
	L	-51 -13 43	64	4.80	0.96	0.024
		-45 -16 34		3.95	0.79	
Central operculum		-57 -7 25		3.60	0.72	
	R	48 -10 13	72	4.69	0.94	0.015
		57 2 7		4.61	0.92	
		63 -7 13		3.54	0.71	
<i>Anticipated Coke intake vs. tasteless solution intake</i>						
Inferior lateral occipital cortex	L	-57 -61 4	180	5.02	>0.98	1.2 e-5
		-45 -73 -8		4.46	0.89	
Ventromedial prefrontal cortex (vmPFC)		-33 -88 -5		4.34	0.86	
	L	-3 38 -14	191	4.94	>0.98	7.0 e-6
		0 53 19		4.53	0.91	
Thalamus		0 59 7		4.46	0.89	
	R	12 -16 7	285	4.94	>0.98	9.2 e-8
Putamen	R	30 -22 1		4.50	0.90	
Putamen/Nucleus accumbens	R	18 8 -11		4.49	0.90	
Anterior Cerebellum	L	-18 -58 -26	141	4.85	0.97	9.4 e-5
		-36 -55 -29		4.10	0.82	
		-6 -49 -23		3.44	0.69	
Postcentral gyrus	R	36 -25 40	654	4.85	0.97	1.0 e-13
		48 -16 37		4.76	0.95	

		x, y, z	k	Peak Z value	Peak r	Cluster-wise pFWE ^a
Postcentral gyrus	L	57 2 31		4.71	0.94	
		-54 -16 37	311	4.83	0.97	3.0 e-8
		-54 -13 19		4.61	0.92	
Putamen/Nucleus Accumbens	L	-54 -4 34		4.54	0.91	
		-24 -1 -5	161	4.74	0.95	3.2 e-5
		-18 14 -5		4.52	0.90	
Caudate	L	-9 2 7		4.08	0.82	
Thalamus	L	-9 -16 7	103	4.69	0.94	0.001
		-9 -22 -2		4.61	0.92	
		-12 -31 1		4.04	0.81	
Superior parietal cortex	L	-30 -46 49	64	4.59	0.92	0.011
		-36 -40 46		3.56	0.71	
		0 -52 34	294	4.47	0.89	6.3 e-8
Posterior cingulate cortex/precuneus		12 -67 22		4.29	0.86	
		-6 -46 13		4.01	0.80	
		-60 -52 19	59	4.30	0.86	0.015
Angular gyrus	L	-51 -67 28		3.84	0.77	
		-57 -58 25		3.69	0.74	
		21 -67 -32	137	4.23	0.85	0.0001
Cerebellum	R	9 -64 -14		4.19	0.84	
		27 -61 -26		4.07	0.81	
		45 -64 -5	42	3.74	0.75	0.056
Inferior lateral occipital cortex	R	57 -61 -5		3.67	0.73	

^a Data considered significant at $p < 0.05$ corrected for multiple comparisons using with family-wise error rate at the cluster level.

Table 3

BOLD responsivity to milkshake intake and Coke intake

	x, y, z	k	Peak Z value	Peak p value (uncorrected) ^a
<i>Milkshake intake vs. Coke intake</i>				
Postcentral gyrus	L -63 -16 22	186	4.70 ^b	1.3 e-6
	-54 -10 28		4.56	2.6 e-6
	-48 -16 34		4.44	4.5 e-6
Postcentral gyrus	R 60 -4 28	213	4.62	1.9 e-6
	57 -16 16		4.57	2.4 e-6
Central operculum	63 -16 22		4.56	2.6 e-6
Thalamus	R 15 -16 4	43	4.42	5.0 e-6
Ventral pallidum/putamen	L -27 -13 -8	24	4.16	1.6 e-5
	-24 -4 -2		3.66	0.0001
Ventral pallidum/putamen	R 27 -10 -8	25	3.79	7.5 e-5
	21 -4 -2		3.69	0.0001
<i>Coke intake vs. milkshake intake</i>				
Middle temporal gyrus	R 60 -10 -11	43	4.27	9.8 e-6
	48 2 -20		3.99	3.2 e-5
	63 -16 -5		3.90	4.7 e-5
Middle frontal gyrus	L -27 17 40	30	3.87	5.3 e-5
Superior lateral occipital cortex	R 27 -73 40	37	3.72	1.6 e-5
	24 -67 34		3.54	0.0002
	36 -73 31		3.18	0.0007
Medial prefrontal cortex/Anterior cingulate cortex	R 3 47 22	41	3.49	0.0002
	3 47 7		3.43	0.0003
	-6 53 7		3.25	0.0006

^a Data considered significant at $p < 0.05$ corrected for multiple comparisons ($p < 0.005$; $k = 26$) derived using 3DClustSim.

^b All effect sizes ($r > 0.98$)

Table 4

BOLD responsivity to Coke Advertisements

		<i>x, y, z</i>	<i>k</i>	Peak <i>Z</i> value	Peak <i>r</i>	Cluster-wise <i>p</i> FWE
<i>All Coke ads vs. non-food ads</i>						
Lingual gyrus	L	-30 -55 -11	483	7.27	>.98	1.0 e-11
		-27 -61 -5		6.55	>.98	
		-24 -73 -5		6.26	>.98	
Lingual gyrus	R	30 -52 -11	523	6.73	>.98	1.1 e-12
		30 -61 -8		6.22	>.98	
		24 -67 -5		6.12	>.98	
Superior lateral occipital cortex	R	24 -58 52	49	4.14	0.82	0.019
		24 -52 46		3.83	0.77	
<i>Coke product ads vs. non-food ads</i>						
Inferior lateral occipital cortex	L	-42 -67 4	58	6.68	>.98	0.027
	R	48 -58 -2	64	6.16	>.98	0.002
Postcentral/supramarginal gyrus		39 -67 -8		3.50	0.70	
	L	-54 -28 37	140	5.08	>.98	1.1 e-4
		-42 -31 40		4.71	0.94	
Postcentral/supramarginal gyrus	R	45 -37 49	245	5.07	>.98	4.6 e-8
		42 -34 40		5.01	>.98	
		51 -25 37		4.86	0.97	
Putamen	L	-33 -10 4	54	4.99	>0.98	0.013
Insula		-33 -10 13		4.22	0.84	
		-36 -4 -2		4.09	0.82	

^aConsidered significant at *p*FWE < 0.05 corrected for multiple comparisons using with family-wise error rate at the cluster level.

Table 5

Differences in BOLD responsivity to anticipated Coke intake and Coke advertisements by consumer status

	<i>x, y, z</i>	<i>k</i>	Peak <i>Z</i> value	Peak <i>r</i>	Peak <i>p</i> value (uncorrected) ^a
<i>Anticipated Coke vs. tasteless solution; Coke consumers vs. non-consumers</i>					
Inferior frontal gyrus (ventrolateral prefrontal cortex)	L -51 29 4	81	-4.14	-0.83	1.7 e-5
	-45 47 4		-3.58	-0.72	0.0002
	-45 38 -8		-3.39	-0.69	0.0003
<i>Coke logo ads vs. non-food ads; Coke consumers vs. non-consumers</i>					
Posterior cingulate cortex	R 6 -55 19	31	3.38	0.68	0.0003
	9 -43 13		2.78	0.56	0.003
	12 -61 16		2.69	0.53	0.004
Precuneus	15 -61 34	26	2.93	0.59	0.002

^aConsidered significant at $p < 0.05$ corrected for multiple comparisons ($p < 0.005$; $k = 26$) derived using 3DClustSim.