Supra-Additive Effects of Combining Fat and Carbohydrate on Food Reward

DIFELICEANTONIO, Alexandra G., et al.

Abstract
Post-ingestive signals conveying information about the nutritive properties of food are critical for regulating ingestive behavior. Here, using an auction task concomitant to fMRI scanning, we demonstrate that participants are willing to pay more for fat + carbohydrate compared with equally familiar, liked, and caloric fat or carbohydrate foods and that this potentiated reward is associated with response in areas critical for reward valuation, including the dorsal striatum and mediodorsal thalamus. We also show that individuals are better able to estimate the energy density of fat compared with carbohydrate and fat + carbohydrate foods, an effect associated with functional connectivity between visual (fusiform gyrus) and valuation (ventromedial prefrontal cortex) areas. These results provide the first demonstration that foods high in fat and carbohydrate are, calorie for calorie, valued more than foods containing only fat or carbohydrate and that this effect is associated with greater recruitment of central reward circuits.

Reference


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Highlights

- Fat and carbohydrate interact to potentiate reward independently of liking.
- This is reflected in supra-additive responses in the striatum during food valuation.
- Participants are able to estimate energy density from fat, but not carbohydrate.
- Accurate estimation of energy density recruits a prefrontal-fusiform gyrus circuit.

In Brief

DiFeliceantonio et al. show that foods containing fat and carbohydrate are more reinforcing than equicaloric foods containing primarily fat or carbohydrate. This effect is independent of liking and is reflected by supra-additive responses in the striatum during food valuation. This may be one mechanism driving overconsumption of high-fat/-carbohydrate processed foods.

Authors

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SUMMARY

Post-ingestive signals conveying information about the nutritive properties of food are critical for regulating ingestive behavior. Here, using an auction task concomitant to fMRI scanning, we demonstrate that participants are willing to pay more for fat + carbohydrate compared with equally familiar, liked, and caloric fat or carbohydrate foods and that this potentiated reward is associated with response in areas critical for reward valuation, including the dorsal striatum and mediodorsal thalamus. We also show that individuals are better able to estimate the energy density of fat compared with carbohydrate and fat + carbohydrate foods, an effect associated with functional connectivity between visual (fusiform gyrus) and valuation (ventromedial prefrontal cortex) areas. These results provide the first demonstration that foods high in fat and carbohydrate are, calorie for calorie, valued more than foods containing only fat or carbohydrate and that this effect is associated with greater recruitment of central reward circuits.

INTRODUCTION

Post-ingestive signals conveying information about the nutritive properties of food are critical for regulating ingestive behavior. Rats readily titrate the volume of food (i.e., portion size) they consume to hold daily caloric intake constant, indicating that rats eat for calories rather than portion (Adolph, 1947). Likewise, in humans, separate neural circuits respond to energy density compared with portion size of foods depicted in images (English et al., 2016).

Post-ingestive signals also act as powerful reinforcers in rodent models (Epstein and Tettelbaum, 1962; Miller and Kessen, 1952). In rodents, flavor-nutrient conditioning studies demonstrate that intragastric infusion of nutrients, but not saline, produces strong preferences for the flavor of a simultaneously consumed non-caloric flavored liquid (Holman, 1969; Sclafani, 2004) and these signals are both necessary and sufficient to sustain feeding via their effects on dopamine release in the striatum (de Araujo et al., 2008; Ren et al., 2010; Telliez et al., 2013a, 2013c). Accordingly, in humans, the tasteless and odorless carbohydrate maltodextrin, but not the non-caloric sweetener sucralose, conditions increased intake of sorbet (Yeomans et al., 2008), while the magnitude of the blood-oxygen-level-dependent (BOLD) signal in dopamine target areas to caloric-predictive flavors depends upon the increase in plasma glucose levels when the flavors are previously consumed with calories (de Araujo et al., 2013). Notably, neither sorbet intake nor BOLD response correlates with self-reported sorbet or flavor liking. Likewise, willingness to pay for food is associated with actual, but not estimated, caloric density and is reflected by BOLD response in the mesolimbic network (Tang et al., 2014).

Collectively, these findings suggest that post-ingestive signals regulate neural circuits in the dopaminergic meso-striato-prefrontal system independently of other food characteristics that could influence reward, such as liking, sweetness, perceived energy density, and availability (e.g., portion size). This has important implications for understanding the human obesity epidemic because mesolimbic neural response to food cues correlate with obesity (Bruce et al., 2010; Feldstein Ewing et al., 2016; Stoeckel et al., 2008; Val-Laillet et al., 2011), genetic risk for obesity (Faroogi et al., 2007; Holsen et al., 2012; Rapuano et al., 2017), eating in the absence of hunger (Lawrence et al., 2012), food choice (Mehta et al., 2012; Schur et al., 2009), future weight gain (de Araujo et al., 2013; Demos et al., 2012; Geha et al., 2013; Kroemer et al., 2016), poorer performance on weight-loss trials (Murdaugh et al., 2012), and overfeeding (Cornier et al., 2007).

However, very little is understood about the mechanisms behind the generation of post-ingestive signals (in any species) and their regulation of mesolimbic circuits. One overlooked but
potentially important factor is the possibility that separate mechanisms evolved for fat and carbohydrate (Ritter and Taylor, 1990; Tellez et al., 2013a, 2013b). Although vagal afferent signals are critical for intra-gastrically administered lipids to increase extracellular striatal dopamine and promote appetitive behavior, dopamine release upon glucose infusion depends upon a yet-unknown metabolic signal thought to be generated during the utilization of glucose as a cellular fuel (Ren et al., 2010; Tellez et al., 2013b). Further, in rodents, vagotomy disrupts the orexigenic effects of nutrient deprivation by blocking fatty acid oxidation, but not by blocking glucose utilization (Ritter and Taylor, 1990). There is also evidence for independent gut-brain pathways for fat and sugar (i.e., carbohydrate) reward in humans. People with a genetically derived deficiency in melanocortin-4 receptors (MC4Rs) exhibit increased preference for high-fat but reduced preference for high-sucrose foods (van der Klauw et al., 2016), whereas variants in the hepatokine fibroblast growth factor 21 (FGF21) gene are associated with increased preference for sweet, but not fat, foods (Soberg et al., 2017).

The existence of independent sensing pathways for fat and carbohydrate is especially relevant when considering the human obesity epidemic. The modern food environment proffers up nutrients in doses and combinations that do not exist in nature. This contrasts sharply with our ancestors’ diet composed mostly of woody plants and raw animal meat (Balter et al., 2012). Moreover, since hunter-gatherer societies eat single dietary components at a time (Berbesque et al., 2011), even when nuts and seeds, which contain some fat, were available, consuming multiple foods in a single meal would have been a rare occurrence. One exception would be fruits containing seeds high in fat and pulp high in carbohydrate. However, such plants are rare and are very high in fiber, which would have significantly reduced the rate of carbohydrate metabolism (Murray et al., 2001). Opportunities to consume fat and carbohydrate together certainly increased following the domestication of plants and animals and development of grain and dairy production (~12,000 years ago). However, this is recent in our evolutionary past and still significantly different than the processed foods of today. For example, the nutritional content of oats with a half cup of milk and honey is only 1 g of fat and 27 g of carbohydrates. Compare this with a donut of similar calories, which contains 11 g of fat and 17 g of carbohydrate.

Since physiology is shaped by natural selection in response to environmental pressures, it is possible that the simultaneous activation of fat and carbohydrate signaling pathways produces a potentiated or perhaps extra-physiologic effect to potentiate reward and render processed foods high in fat and sugar more rewarding, calorie for calorie, than foods high in only fat or sugar. Consistent with this suggestion, rodents tightly regulate total daily caloric intake and body weight (Adolph, 1947) when given access to fat alone or carbohydrate alone; however, when given unrestricted access to fat and carbohydrate they quickly gain weight (Beilharz et al., 2014, 2016; Johnson and Kenny, 2010), suggesting that it is the combination of these macronutrients that disrupts energy balance.

With this in mind, we set out to determine if palatable familiar foods high in fat and carbohydrate are more rewarding than similarly caloric, familiar, and liked foods high in only fat or only carbohydrate. To test this we used the Becker-DeGroot-Marshall auction (Becker et al., 1964) task, in which participants bid for snacks depicted in photographs, while BOLD response was assessed using fMRI. By using familiar snack items, we ensure that participants have had the opportunity to associate these foods with their nutritional properties via flavor-nutrient conditioning in the past and, based on this conditioning, the food images represent energy-predictive conditioned stimuli.

This enabled us to test the hypothesis that pictures associated with the post-ingestive effects of fat and carbohydrate are more reinforcing than those associated with the post-ingestive effects of primarily fat or carbohydrate. As predicted, we found that participants are willing to pay more for snacks with fat + carbohydrate, compared with fat or carbohydrate alone, and that this effect was reflected by response in the dorsal striatum (caudate and putamen) and mediodorsal thalamus. Unexpectedly, we observed that participants are very accurate at estimating the energy density of fat, but not carbohydrate or fat + carbohydrate foods, an effect that is reflected by response in the fusiform gyrus and its connectivity with ventromedial prefrontal cortex (vmPFC), anterior cingulate cortex, and cerebellum. These results are the first to demonstrate that foods high in fat and carbohydrate are more rewarding, calorie for calorie, than foods high only in fat or carbohydrate and that energy density estimation accuracy differs depending on macronutrient.

RESULTS

Our first step was to create a set of pictures of small snacks falling into one of three categories of macronutrient content: those with most of their calories coming from (1) fat, (2) carbohydrate, or (3) fat + carbohydrate, but varying equally within category for liking, familiarity, and caloric content (Table 1). Testing was performed in a pilot study (n = 56) that did not include participants from the main study (STAR Methods). Examples from each group are depicted in Figure 1A. Portion sizes were adjusted across macronutrient groups to equate caloric content across snacks so that there were examples of low, medium, and high caloric values in each category with overall mean calories across categories similar (Table 1). Portion size was not significantly different across groups and pictures were chosen to have equal object size, intensity, and complexity, although they differed slightly in contrast (Table 1). This resulted in 39 stimuli with 13 in each group.

Methods and analyses are described in detail in the STAR Methods section. In brief, all participants in the main study first rated these snacks for liking, familiarity, estimated energy density, and total calories shown. On a subsequent day, they arrived fasted to the laboratory and were fed a standard breakfast of 426 kcal from orange juice, cheddar cheese, whole-wheat toast, white toast, strawberry jam, and butter (described in Tang et al., 2014). They began the fMRI session 3 hr later. Prior to scanning, participants were given €5 and told they could bid between €0 and €5 against the computer to purchase snacks depicted in pictures presented during scanning. They were also told that one item will be selected at random for auction at the end of scanning. If the participant’s bid was higher than the computer’s bid, he or she was able purchase the item and receive the remainder of the €5 in cash. Otherwise, the participant received the entire €5 but did not get the item. Participants remained in a
supervised setting following scanning, during which time they consumed the item, if one had been won. Under these circumstances the optimum strategy is to bid what one believes is the value of the item (Becker et al., 1964).

**Behavioral Results**

**Between-Category Differences in Ratings and Energy Density**

We first compared the snack macronutrient categories to test for differences in liking and estimated and actual energy density using one-way ANOVAs. By design, no differences were observed in caloric content ($F_{(2,36)} < 0.001$, $p = 0.9$; Table 1B), familiarity ($F_{(2,36)} = 0.08$, $p = 0.92$; Table 1C), or liking ($F_{(2,36)} = 1.94$, $p = 0.073$; Table 1D). Fat + carbohydrate snacks were higher in energy density ($F_{(2,36)} = 9.99$, $p = 0.0004$; Table 1E) and were accurately estimated by participants as being more calorically dense ($F_{(2,36)} = 13.132$, $p = 0.0008$). Willingness to pay was not related to portion size ($r^2 = 0.0009$, $p > 0.9$; Table 1F). Participants could not estimate the number of calories shown in each snack portion ($r^2 = 0.211$, $p = 0.82$; Figure S1B). Liking ratings were also associated with energy density overall ($r^2 = 0.122$, $p = 0.01$; Figure S1D), but this was not significant in any individual group. Liking was not related to estimated energy density for the whole group ($r^2 = 0.0003$, $p = 0.92$; Figure S1E) or any individual group.

Unlike in prior work, where willingness to pay was unrelated to ratings of liking (Tang et al., 2014), we observed a strong positive association with liking for the total number of tests run (32). Replicating prior work by Tang et al. (2014), willingness to pay was highly associated with energy density ($r^2 = 0.225$, $p < 0.001$; Figure 2A) across all snacks. Interestingly, participants could very accurately estimate energy density for fat snacks ($r^2 = 0.688$, $p = 0.016$; Figure 2C). In contrast to fat snacks, participants were unable to accurately estimate energy density of carbohydrate ($r^2 = 0.012$, $p > 0.9$) and fat + carbohydrate snacks ($r^2 = 0.22$, $p > 0.9$; group × estimated energy density $F_{(1,37)} = 13.132$, $p = 0.0008$).

\[ \text{For the snack images: object size is the proportion of non-white pixels, brightness is the differences between the mean luminance of all non-white pixels, and complexity is the proportion of outline pixels to the white background, contrast is the SD of the luminance of the non-white pixels, and familiarity is the proportion of outline pixels (Blechert et al., 2014b). Means (n = 39 pictures) with SEM are given with the range below each mean. C, carbohydrate; F, fat; FC, fat + carbohydrate.} \]

\[ \text{\textsuperscript{a}Significant } p \text{ values } (p < 0.05) \]
correlation between liking and willingness to pay for all foods ($r^2 = 0.69$, $p < 0.0001$; Figure S1C) and in fat ($r^2 = 0.89$, $p = 0.00003$) and fat + carbohydrate ($r^2 = 0.70$, $p = 0.011$) categories, but not carbohydrate ($r^2 = 0.58$, $p = 0.077$). To test if energy density and liking are independent predictors of willingness to pay, we performed a mediation analysis by constructing models with both variables entered as predictors. Significance improved with both variables entered ($p = 0.002$ to <0.001), but each contributed uniquely to the effect, with energy density remaining a significant predictor when liking was included ($b = 0.207$, $p = 0.03$) and liking remaining a significant predictor when energy density was included ($b = 0.763$, $p < 0.001$), indicating both predictors contribute independently.

**Between-Group Differences in Willingness to Pay**

Next, we generated a linear mixed effects model with bid as the outcome variable; subject as a random effect; and macronutrient group, true energy density, estimated energy density, liking, estimated portion calories, portion size, and calories shown in each picture as fixed effects to test our prediction that participants would pay more for the fat + carbohydrate foods compared with the fat or carbohydrate foods. As predicted, participants were willing to pay significantly more for foods

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**Figure 1. Stimulus Characteristics and Examples**

Examples of each macronutrient group are displayed in (A). Averages across macronutrient groups for the scanned participants in calories shown (B), familiarity (C), liking (D), energy density (E), estimated energy density (F), and reaction time (G). Following pre-testing on a separate day, participants viewed a fixation cross for approximately 9 s (H). A picture of a food item to be bid on was displayed for 5 s. Participants then had 5 s to make a bid on the item. They moved a trackball inside the scanner to move a cursor back and forth between 0 and 5 euros. After they submitted their response it remained on screen for the remainder of the 5 s. Data are represented as means ± SEM. C, carbohydrate; F, fat. *$p < 0.05$. 

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with fat + carbohydrate compared with fat ($t_{1,774} = -5.024$, $p < 0.0001$; Figure 4A) or carbohydrate ($t_{1,774} = -4.9021$, $p < 0.0001$; Figure 4A) foods. Importantly, liking, actual energy density, and estimated energy density were in this model and therefore were adjusted for. To test if the effect was supra-additive, we generated a second model in which macronutrient categories were coded as containing fat or carbohydrate, with the other random and fixed factors identical to the previous model. The interaction term was significant ($F_{(1,773)} = 20.383$, $p < 0.0001$), showing that bids for fat + carbohydrate were greater than would be expected from summing the bids for fat and carbohydrate foods.

Although we controlled for liking in all analyses, fat + carbohydrate items were liked slightly, but not significantly, more, and liking and bid amount were highly correlated. We therefore took an additional step to verify that effects were not related to liking. More specifically, we re-ran all analyses after removing the two least liked items from the carbohydrate and fat categories and the two most liked items from the fat + carbohydrate category. In so doing, the fat category became most liked (carbohydrate = 7.655 ± 3.342, fat = 17.12 ± 3.267, fat + carbohydrate = 14.59 ± 3.06, $p < 0.0001$), showing that bids for fat + carbohydrate were greater than expected from summing the bids for fat and carbohydrate foods. We next tested whether bid amount modulated connectivity with the striatum differentially as a function of macronutrient category by performing a psychophysiological interaction (PPI) analysis with the seed defined as a 5 mm sphere surrounding the caudate and putamen. To test our hypothesis that response in dopamine target areas would be greater for fat + carbohydrate compared with fat or carbohydrate foods during bidding, we created a GLM with estimated calories, true energy density, liking, and bid amount for each item in each group. This was done to control for factors that differed across groups to ensure any effects seen were due to the bid amount alone. A contrast of fat + carbohydrate combination (FC) > fat + carbohydrate was modeled on the first level to account for within-subject variance. As predicted, response in the caudate and putamen was more strongly associated with bid amount for fat + carbohydrate compared with fat or carbohydrate alone (caudate, $[14–20]$, $z = 3.82$, $p < 0.001$; Table 2; Figure 4C; putamen, $[−28–2–2]$, $z = 3.37$, $p < 0.001$; Figure 4D). A similar effect was also observed in the thalamus ($[−10–12]$, $z = 3.87$, $p < 0.001$; Figure 4E). No significant effects for the reverse analysis (fat + carbohydrate > fat + carbohydrate) were found.

We next tested whether bid amount modulated connectivity with the striatum differentially as a function of macronutrient category by performing a psychophysiological interaction (PPI) analysis with the seed defined as a 5 mm sphere surrounding the caudate peak ($[14–20]$). Group difference in bid amount modulated striatal connectivity were observed with insular cortex bilaterally ($[38–12]$, $z = 2.719$, $p < 0.0001$; $[−40–8–10]$, $z = 2.615$, $p < 0.0001$; Figure 4F) and with the anterior medial temporal lobe (hippocampus and amygdala, $[26–2–26]$, $z = 2.718$, $p = 0.00106$; Figure 4G), although this cluster was just above our threshold of $p < 0.001$. More specifically, striatal...
but not carbohydrate or fat + carbohydrate snacks (Figure 2A). Able to accurately estimate the energy density of fat snacks, but not carbohydrate or fat + carbohydrate snacks (Figure 2A). To further confirm this relationship, we performed regressions such that beta values were generated for each subject for each snack type. Here, we controlled for portion size across groups to ensure it was not driving the effects. We found an overall group difference (Friedman’s statistic = 9.1, p = 0.0106; Figure 5A) using a non-parametric test, as beta values were not normally distributed. Further, participants were better able to estimate the energy density of fat snacks over carbohydrate snacks (p = 0.0144) and over fat + carbohydrate snacks (p = 0.0228).

Having confirmed this relationship in the behavioral data, we sought to isolate the neural circuit reflecting the differences in the ability to estimate energy density of fat compared with carbohydrate and fat + carbohydrate by regressing brain response against estimated energy density of fat compared with carbohydrate and fat + carbohydrate foods. We found a negative relationship with estimated energy density in the fusiform cortex when viewing fat pictures, in contrast to a positive response when viewing carbohydrate or fat + carbohydrate pictures ([-26 – 72 – 8], z = 3.25, p < 0.00001; Figure 5B). A similar effect was observed in extrastriate cortex ([–20 – 98 02], z = 3.84, p < 0.0001). To determine if there was differential connectivity with these visual sensory regions and areas of the meso-striato-prefrontal regions when estimating energy density for fat versus carbohydrate or fat + carbohydrate, we ran a PPI with the extracted time series from a 5 mm sphere around the fusiform gyrus peak ([–26 – 72 – 8]). This showed that estimated energy density increased fusiform connectivity with the vmPFC ([-10 38 – 11], z = 3.02, p < 0.00001; Figure 5C), anterior cingulate gyrus ([-10 44 8], z = 4.217; Figure 5C), and cerebellum ([26 – 68 – 17], z = 4.17; Figure 5D) when estimating the energy density of fat compared with the energy density of carbohydrate or fat + carbohydrate. This suggests that accurate estimates of energy density are associated with greater coupling of activity between the fusiform gyrus and the vmPFC, cingulate, and cerebellum.

**DISCUSSION**

Our study produced two novel findings that are relevant for understanding food choice. First, we demonstrate for the first time that foods containing both fat and carbohydrate are more rewarding, calorie for calorie, than those containing only fat or only carbohydrate, and we further describe a network of brain regions (caudate, putamen, and mediodorsal thalamus) underlying this effect. Second, we discovered, unexpectedly, that individuals are better able to estimate the energy density of fat compared with carbohydrate and fat + carbohydrate foods, with accurate estimations of energy density depicted in pictures of fatty foods associated with increased coupling of visual sensory areas with the vmPFC and cerebellum. Both findings support and extend work from animal models indicating that these two energy sources have distinct pathways for conveying nutritive value to the CNS to ultimately guide food choice and highlight the need to further understand the mechanisms driving the interaction of macronutrients on circuits regulating ingestive behavior.

Studies in mice show that the ability of ingested nutrients to produce dopamine release to drive reward depends critically upon their utilization as a cellular fuel (Tellez et al., 2013b, 2013c). Vagotomy blocks the orexigenic effects of the fatty acid oxidation blocker mercaptoacetate, but not of the orexigenic effects of the glucose utilization blocker 2-deoxy-D-glucose (Ritter and Taylor, 1990). This suggests that the gut-brain pathways driving fat and carbohydrate reward differ. Several observations from the current study support this contention.

First, our data suggest that the association between reward and energy density differs for fat and carbohydrate (Figure 2). For fatty foods, willingness to pay (our measure of reward) is tightly coupled to energy density and self-reported food liking. Although both food liking and energy density are associated with willingness to pay, mediation analyses indicate that these factors contribute independently to reward value. In contrast, for carbohydrate-containing foods, willingness to pay is positively related to self-reported food liking, but not energy density. Moreover, although individuals are very accurate at estimating the energy density of fatty foods, they are poor at estimating the energy density of carbohydrate-containing foods, which our fMRI data suggest results from differential engagement of the fusiform gyrus.

The fusiform gyrus is critical for encoding features of the visual world to enable object and place recognition. Our findings add to a growing literature suggesting it also contributes to the recognition and valuation of visual features of foods that convey information about energy density. There are numerous references to fusiform responses to food-related visual cues in the neuroimaging literature. Such responses are sensitive to the caloric value of the depicted food and to the internal state of the individual (Frank et al., 2010; Kilkore and Yurgelun-Todd, 2005; Siep et al., 2009). Typically, they have been interpreted as part of a network of regions coding visual attention and/or food cue saliency. Accordingly, fusiform responses to high-calorie-food images predict inability to maintain weight loss following a similar pattern as midbrain and striatum; Murdaugh et al., 2012), spontaneous fluctuations in the fusiform gyrus correlate...
with self-reported craving (Chen et al., 2017), and responses to food cues are greater in obese compared with healthy-weight youth (Allen et al., 2016; Janowitz et al., 2015) as well as in healthy weight individuals that carry the obesity predisposing variant of the FTO gene (Kuhn et al., 2016). Fusiform gyrus response to food pictures also covaries with degree of parental dietary restriction on children (Allen et al., 2016), as well as personal dietary restraint (Zhao et al., 2017), indicating that the fusiform gyrus is sensitive not only to the energetic properties and value of food pictures but also to the experience of food decisions where taste and energy density must be considered.

The mechanism by which striatal dopamine influences fusiform activity is unclear; however, a striatum to vmPFC to fusiform circuit is possible. Accordingly, we observe preferential connectivity between the fusiform gyrus and vmPFC when bidding for fat versus carbohydrate or fat + carbohydrate foods. The vmPFC plays a critical role in determining food choices based on comparing taste and health information (Hare et al., 2009) and the fusiform gyrus to vmPFC neural circuit is thought to integrate visual features of objects with the generation of value signals to drive choice (Lim et al., 2013). In a prior study, vmPFC response correlated with bid amount and actual, but not estimated, energy density (Tang et al., 2014). The pattern of activations we observe suggests that the fusiform gyrus-vmPFC circuit plays an important role in accurately estimating energy density from visual information. More specifically, estimates are accurate when there is a negative association between energy density and fusiform response (lower responses for higher energy density; Figure 5) coupled with increased functional connectivity with the vmPFC (and cerebellum). Collectively, these data suggest that the fusiform has access to the value of the nutritional properties of foods conveyed by visual information and that interactions between the fusiform and vmPFC are important in enabling more accurate estimates of energy density for fat compared with

### Table 2. ANOVA and t Test Results from Extracted PE Values for Bid Amount, Bid PPI, Estimated Energy Density, and Estimated Energy Density PPI

<table>
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<th>Analysis</th>
<th>Peak Voxels</th>
<th>Z Value</th>
<th>Area</th>
<th>Contrast</th>
<th>Test Value</th>
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<td>14 - 4 20</td>
<td>3.82</td>
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<td></td>
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<td>FC &gt; F</td>
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<tr>
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<td>-28 - 2 - 2</td>
<td>3.37</td>
<td>putamen</td>
<td>FC &gt; F and C</td>
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<td>-10 - 12 18</td>
<td>3.87</td>
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<td>FC &gt; F and C</td>
<td>F$_{p,57}$ = 116.2</td>
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All p values are Bonferroni corrected.

Hipp/amyg, anterior temporal lobe, including the hippocampus and amygdala; extrastriate, extrastriate cortex; Ant Cing, anterior cingulate; Est. ED, estimated energy density.
carbohydrate-containing foods. One possibility is that the post-ingestive signal conveying information about the nutritive value of fat is successfully integrated with visual information about foods to determine value, whereas the value of carbohydrates may derive primarily from other features, such as flavor or visual presentation; however, further research is needed to confirm this hypothesis. An alternative possibility is that the ubiquity of artificial sweeteners in modern diets degrades the association between carbohydrate-containing foods and energy density, resulting in an impaired ability to estimate calories (Davidson and Swithers, 2004). For example, in the gustatory modality, intensity ratings of sweetness are positively related to sugar content, but...
the association is significantly stronger for raw and moderately processed foods compared with highly processed foods (van Dongen et al., 2012).

We also show, for the first time, that fat and carbohydrate interact to potentiate reward, by demonstrating greater brain response to, and increased willingness to pay for, equally caloric foods containing fat and carbohydrate compared with fat or carbohydrate alone. We further show that these effects are not accounted for by differences in food liking or energy density since the interactive effects of fat and carbohydrate survive the inclusion of these factors as covariates in statistical models. Finally, we rule out portion size as a contributing factor because portion size is unrelated to willingness to pay, which is consistent with a recent report showing different patterns of evoked brain response to food portion size and energy density (English et al., 2016).

Replicating prior work (Tang et al., 2014), irrespective of macronutrient category bid amount was associated with BOLD response in the anterior cingulate cortex and orbitofrontal cortex, which has also been shown to code food attributes (Suzuki et al., 2017). However, Tang et al. (2014) also reported associations between bid amount and energy density in the vmPFC and striatum, which we did not observe when considering all food items. Rather, we found that striatum (caudate and putamen/globus pallidus) was selectively engaged when bidding for foods that contain fat and carbohydrate, compared with fat or carbohydrate alone. This is of note because this area is thought to play an important role in the shift from goal-directed to habitual control over behavior, which is a fundamental characteristic of addiction (Belin et al., 2009).

Relatively, dopamine release in the dorsal striatum is sensitive primarily to the nutritional, rather than the hedonic, properties of foods (Tellez et al., 2016), with evidence for caudate dopamine release in humans upon food consumption (Small et al., 2003) and aberrant caudate BOLD responses to fat/sugar foods associated with increased risk for weight gain (Stice et al., 2008; Sun et al., 2015). Moreover, using an operant task in which fractal cues are rewarded with snacks containing fat and carbohydrate, Tricomi et al. (2009) show that increasing response in the putamen/globus pallidus (overlapping with the putamen peak isolated here) is associated with the development of habitual responding. It is therefore possible that simultaneous striatal dopa-
and engagement of neural circuits involved in habit formation and reward value. They also suggest that the association between energy density and reward is distinct for fat and carbohydrate, with energy density better appreciated at a cognitive level for fatty foods and acting with fatty food liking to determine reward. In contrast, liking, and not energy density, influences the value of carbohydrate-containing and fat + carbohydrate-containing foods. Portion size and estimated energy density, whether accurate or not, played little role in reward in our healthy-weight sample. However, individuals were better able to estimate the energy density of fatty foods compared with carbohydrate-containing and fat + carbohydrate-containing foods, an ability that depends on connectivity between the fusiform gyrus and the vmPFC. Overall, these results indicate that combining fat and sugar increases the reward value of foods independently of caloric load, liking, and portion size and disrupts the ability to accurately estimate the energy density of fatty foods.

These results imply that a potentiated reward signal generated by foods high in both fat and carbohydrate may be one mechanism by which a food environment rife with processed foods high in fat and carbohydrate leads to overeating.

**STAR METHODS**

Detailed methods are provided in the online version of this paper and include the following:

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**SUPPLEMENTAL INFORMATION**

Supplemental Information includes two figures and can be found with this article online at https://doi.org/10.1016/j.cmet.2018.05.018.

**ACKNOWLEDGMENTS**

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**AUTHOR CONTRIBUTIONS**


**DECLARATION OF INTERESTS**

The authors declare no competing interests.

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**REFERENCES**


STAR★METHODS

KEY RESOURCES TABLE

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CONTACT FOR REAGENT AND RESOURCE SHARING

For further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Dana M. Small (dana.small@yale.edu).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

All procedures were approved by the ethics committee at the University of Cologne. Participants were recruited via flyers from the local community and university population. All participants reported having no known metabolic, neurologic, and psychiatric disorders. Fifty-six participants rated stimuli in a pre-testing session to validate the stimuli used. They had an average age of 25 (SEM ± 0.39) and an average BMI of 22.6 (SEM ± 0.2). They were Caucasian and 30 were male. For the fMRI portion of the study, 24 participants were recruited, but due to a technical error during scanning, data were discarded from 4. The resulting 20 participants were Caucasian with an average age of 27.5 (SEM ±0.98), and an average BMI of 23.29 (SEM ±0.56). Twelve were female.

METHOD DETAILS

Pre-testing, Stimuli Selection, and Scales

A selection of photographs was created in house to ensure stimuli would be familiar to the local population, others were drawn from an existing database (Blechert et al., 2014a). As described in the results section, stimuli were chosen to depict equi-caloric portions, be similarly liked, and familiar. Liking was rated on a vertical scale, translated to German from English (Lim et al., 2009). Familiarity, estimated energy density, and estimated portion calories were rated on horizontal scales.

Liking was rated on a vertical scale with “Staerkste Vorliebe, die vorstellbar ist” (most liked sensation imaginable) at the upper anchor point and “Staerkste Abneigung, die vorstellbar ist” (most disliked sensation imaginable) at the lower anchor point (Lim et al., 2009). Familiarity was rated on a horizontal scale with the prompt “Wie gut kennen Sie das Essen?” (How well do you know this food), “gar nicht gut” (not well at all) at the left anchor point and “sehr gut” (very well) at the right anchor point. Participants were asked calories per portion with the prompt “Wie viele Kalorien denken Sie hat hie hier abgebildete Portion?” (How many calories do you think are in the pictured portion?). The scale was bounded on the left by “wenige Kalorien” (few calories) and the right by “viele Kalorien” (many calories). Energy density of each item was assed by asking participants “Wie kalorienhaltig denken Sie das Essen generell?” (How caloric do you think the food is, in general). This scale was bounded on the left by “niedrig kalorisch” (low caloric) and “hoch kalorisch” (high caloric).
fMRI Session
Subjects entered the laboratory after an overnight fast. Blood was drawn to measure fasting insulin and glucose. Brain response was assessed 3 hours after a standard breakfast containing 426 kcals, designed to have low glycemic index and low protein content (Tang et al., 2014) on a 3T Siemens Prisma scanner while subjects performed the auction task. The auction task was presented using Presentation software (Neurobehavioral Systems, Berkeley, CA, USA, RRID: SCR_002521). In this version of the Becker-de Groot-Marschak task subjects are told they can bid between 0 and 5 euros for a displayed food item. At the end of the experiment, one food item will be chosen at random, if they bid more than the computer, they will receive that food item, but the bid will come out of their remuneration. Four 8-minute runs were performed on each participant. Over all runs, participants saw each of the 39 (13 from each category) snack items 3 times. They were presented in a random order for 5 seconds, participants were then given 5 seconds to respond. Four 8-minute runs were performed on each participant. Over all runs, participants saw each of the 39 (13 from each category) snack items 3 times. They were presented in a random order for 5 seconds, participants were then given 5 seconds to bid. The ITI was 9 seconds (Figure 1H). Acquisition parameters for the echo planar images (EPI) were: TE=30ms, echo spacing=0.7ms, TR=2s, flip angle= 90°, voxel size= 2.8 mm x 2.8 mm x 2.8 mm, number of slices=33. Sets of identical images, but with opposite (posterior to anterior) phase encoding were collected to perform geometric distortion correction. A previously collected high quality T1 weighted anatomical image (TE=2.23ms, TR=2.3s, flip angle=8° voxel size= 0.9x0.9) was used for registration of functional images.

QUANTIFICATION AND STATISTICAL ANALYSIS
Behavioral Analysis
Linear regressions were performed on behavioral data using GraphPad Prism version 7.0.1, (GraphPad Software, La Jolla, California, USA, RRID: SCR_002798) and MATLAB 2014b (MathWorks, Natick, Massachusetts, USA, RRID: SCR_001622). All behavioral data were plotted using GraphPad Prism. Linear mixed effects models (LME) were performed using MATLAB 2014b. In Figures 1, 2, S1, and S2, the n=39 (the number of pictures rated), rather than the sample size. In all other figures n=20 (the number of participants). A description of the regression or GLM for each result can be found in the appropriate location in the results section. All data were treated as if they met parametric assumptions except for an ANOVA ran on beta weights from subject-wise regressions, as they were not normally distributed tested by the D’Agostino and Pearson test of normality (K2=12.11, p=0.0023).

fMRI Analysis
Preprocessing
First, the susceptibility-induced off-resonance field was estimated using the opposite phase encoded images and a correction applied using TOPUP (Andersson et al., 2003) implemented with FSL (Smith et al., 2004) (RRID: SCR_002823). Functional EPI images were analyzed using FSL-FEAT (fMRI Expert Analysis Tool 6.0) part of FMRIB’s Software Library (FSL) (Smith et al., 2004). Using FSL-FEAT, images were brain extracted, slice-time corrected, motion corrected, high-passed filtered, smoothed (8 mm FWHM), and FILM pre-whitened. Images were registered to standard MNI space by first registering the EPI then to the T1-weighted anatomical, then finally to standard space.

First and Second Level Models
To replicate Tang et al. (2014), two GLMs with distinct parametric modulators were created. In GLM1 willingness to pay for each trial was entered as a parametric modulator orthogonalized with true energy density and in a second model, alone. They modulated the picture viewing period which was modeled as a 4 second box-car. Bidding period and head movement were also included as regressors of no interest.

To test our unique hypothesis, an additional GLM was created. This model contained estimated calories, true energy density, hedonic value, and bid amount for each item broken out by macronutrient group, resulting in 3 main onsets with 4 parametric modulators each. Picture viewing and bidding period were also included, as in the previous model. The contrast of combination greater than either macronutrient alone was modeled on the first level to account for within subject variance. Six head motion regressors were included as regressors of no interest.

To test brain correlates of energy density in fat versus carbohydrate groups, we created a final GLM containing energy density for all three groups and nuisance regressors. The other regressors were left out of the model as they did not differ between the fat and carbohydrate groups.

After first level modeling for all GLMs, the four runs were then combined for each participant using a fixed effects model. The resulting contrast maps were analyzed on a third level using Flame1 (Smith et al., 2004) variance estimation and whole brain cluster corrected at p<0.001, a significance threshold selected to reduce the risk of type I error (Eklund et al., 2016). Statistical maps are presented as z-scores of the t-statistic and are overlaid on the MNI template and displayed using MRicroN (Rorden and Brett, 2000). Finally, analyses of variance (ANOVA) and Student’s t-tests, where appropriate, were run on extracted parameter estimates using GraphPad Prism, post-hoc differences between groups were tested and the resulting p-values were Bonferroni corrected and reported.
**Influence of Gender on Primary Findings**

To test the role of gender in our main effect of macronutrient content on bid amount, we added gender as a covariate to our linear mixed effects model. There was no main effect of gender in the model $F(1,772)=0.22, p=0.6364$ and the main effect of macronutrient was still significant ($p<0.000001$). Gender, however, did not improve model fit and appeared to decrease model fit (as indicated by AIC).

For our main neuroimaging findings of interest, we used a similar approach and entered gender as a covariate on the group level. Adding gender as a covariate does not alter the main effects.

**DATA AND SOFTWARE AVAILABILITY**

This accession number for the statistical maps of the human brain is NeuroVault: HYELUVKG.
Supplemental Information

Supra-Additive Effects of Combining Fat and Carbohydrate on Food Reward

Alexandra G. DiFeliceantonio, Géraldine Coppin, Lionel Rigoux, Sharmili Edwin Thanarajah, Alain Dagher, Marc Tittgemeyer, and Dana M. Small
Figure S1. Related to Figure 2. Additional relationships between snack characteristics and participant ratings. All three macro nutrient groups are shown combined on the right and separated on the left. Willingness to pay is not associated with portion size (A). Participants could not estimate the true portion calories (B). Liking was associated with both willingness to pay (C) and true caloric density (D). However, there was not relationship between liking and estimated calories (E). All tests are Bonferroni corrected for the total number of tests performed in this series (32). * p>0.05 ** p>0.001
Figure S2. Related to Figure 4. The subgroup of images was similar to the whole in that equal calories were shown (A), they were equally familiar (B), and equally liked (C). Like the whole group, in the subset, FC images were estimated to be more energy dense (D) and were actually more energy dense (E). Reaction time did not differ across groups (F). Participants were willing to pay more for FC items in the subgroup (G). Data are represented as mean ± SEM. * p<0.05