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Binary Components of Food Reinforcement: Amplitude and Persistence

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Abstract

Background—Demand curves provide an index of how reinforcing a food is. Research examining the latent structure of alcohol and tobacco reinforcement identified two underlying components of reinforcement, amplitude and persistence. No research has assessed latent structure of food reinforcement and how these factors are related to BMI.

Subjects and Methods—Participants were 297 adults from two studies that completed food purchasing tasks to assess the following measures of relative reinforcing efficacy (RRE) of food: intensity (Q_0): purchases made when the food was free or of very minimal price, $O_{\max}$: maximum expenditure (maximum purchases*price), $P_{\max}$: price point where maximum expenditure was observed, breakpoint: first price where 0 purchases are made, and demand elasticity (α): quantitative non-linear relationship between purchasing and price. Principal components analysis was used to examine the factor structure of RRE for food across samples and types of food.

Results—Both studies revealed two factor solutions, with $P_{\max}$, $O_{\max}$, breakpoint and α loading on factor 1 (persistence) and intensity (Q_0) loading on factor 2 (amplitude) across both high and low energy dense foods. Persistence reflects an aggregate measure of price sensitivity and amplitude reflects the preferred volume of consumption (how far vs. how much). The two factors accounted for between 91.7 to 95.4% of the variance in food reinforcement. Intensity for high energy dense foods predicted BMI for both studies ($r = 0.18$ and $r = 0.22$, p 's < 0.05).

Conclusions—The latent factor structure was similar across two significantly different independent samples and across low and high energy dense snack foods. In addition, the amplitude

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Conflict of Interest

Leonard H. Epstein is a consultant and has equity in Kurbo. Dr. Bickel is a consultant or has equity in HealthSim LLC, NotifiUs LLC, Sober Grid Inc., DxRx, Prophase LLC, Teva Branded Pharmaceuticals, General Genetic Corporation. The other authors do not declare any conflict of interest with respect to the authorship or publication of this article.

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of the demand curve, but not persistence, was related to BMI. These results suggest specific aspects of food reinforcement that can be targeted to alter food intake.

Keywords

Behavioral economics; demand curve; reinforcing value of food; exploratory factor analysis

Introduction

Behavioral economic demand curves provide a quantitative approach to measuring the reinforcing efficacy of a commodity (Hursh, Galuska, Winger, & Woods, 2005; Johnson & Bickel, 2006). A demand curve assesses the relationship between consumption of a commodity and price. As price increases, the demand for a commodity decreases, and the shape of the decelerating function is related to the reinforcing value of the commodity. This applies to food, as if the price of a food increases, someone who finds it very reinforcing will continue to purchase the food, while someone who finds it less reinforcing will look for a substitute that costs the same or less than the originally preferred item. At some point, while people may still want the good, but they do not demand any of it at that price, and they stop purchasing it. Demand curves provide a number of indices of reinforcing efficacy, including intensity, or how much people would consume if it was free (or minimally priced), breakpoint, the price at which purchases are zero, and elasticity, the quantitative relationship between price and purchasing (Bickel, Marsch, & Carroll, 2000; MacKillop et al., 2009). Two additional indices are $O_{\max}$, the maximum amount people will expend on the commodity, and $P_{\max}$, the maximal price before demand become elastic (highly price sensitive).

Demand curves have been extensively used to study reinforcing efficacy of alcohol, cigarettes and other drugs (Aston, Metrik, & MacKillop, 2015; Bickel & Madden, 1999; Bruner & Johnson, 2014; MacKillop et al., 2010; MacKillop et al., 2009; Petry & Bickel, 1998; Shahan, Bickel, Madden, & Badger, 1999). but have been used less often to study food (Epstein, Dearing, & Roba, 2010a). The various indices of reinforcing efficacy have been studied independently, but MacKillop and colleagues showed that the indices may be grouped into factors that better represent reinforcing efficacy than the five independent measures (MacKillop et al., 2016). Understanding the latent structure of demand is valuable as it provides insight into the nature of the construct at a theoretical level and permits data reduction to reduce type I error rate inflation at a practical level. In their sample of college student drinkers, two factors emerged, with factor 1, labeled as persistence, including α (elasticity) (factor loading, 0.95), breakpoint (0.88) and $P_{\max}$ (0.90), with factor two labeled as amplitude, with intensity (Q_0) as the strongest loading variable (0.99). $O_{\max}$ was more weakly related to both persistence (0.48) and amplitude (0.65). The two factors accounted for 85% of the total observed variance, and these measures were significantly related to a number of indices of alcohol consumption, with factor 1 showing weak relationships with consumption, while factor 2 was a strong predictor of alcohol consumption, with correlations between factor 2 and drinks per week or drinks per drinking day of 0.69. Subsequently, Bidwell et al (Bidwell, MacKillop, Murphy, Tidey, & Colby, 2012) replicated this factor structure for cigarette demand in a sample of adolescent smokers, also finding

evidence of amplitude and persistence factors. In this study α (elasticity) (0.62), breakpoint (0.90), $P_{\max}$ (0.92), and $O_{\max}$ (0.73) loaded on the persistence factor and only intensity (Q_0) (0.97) loaded on the amplitude factor. Both persistence and amplitude predicted number of cigarettes smoked daily (0.17, 0.24), carbon monoxide (0.31, 0.34) and cotinine (0.20, 0.21) levels. O'Connor and colleagues (O'Connor et al., 2016) also replicated a two factor solution in adult smokers. Consistent with Bidwell (Bidwell et al., 2012) breakpoint (0.90), α (elasticity) (0.81, $P_{\max}$ (0.92) and $O_{\max}$ (0.83) loaded on persistence, and intensity (Q_0) (0.98) loaded on amplitude. Persistence was related to quit intentions and restrictions on smoking at home, while amplitude was related to quit attempts, quit intentions and restrictions on smoking at home.

Behavioral demand curves have been used infrequently to assess relative reinforcing efficacy of food (Epstein et al., 2010a). The goal of this study is to assess whether the same factors are observed for food as for alcohol and cigarette demand, and how these factors relate to BMI. Studying food reinforcement differs from alcohol or tobacco reinforcement given the diversity of food types, ranging from healthy, nutrient dense, low energy dense foods to less nutrient dense, less healthy, high energy dense foods. Since people generally find higher energy dense foods more palatable than lower energy dense foods (Drewnowski, 1998), features of the demand curve may be different for low energy dense than high energy dense foods. The reinforcing value of the food would also be expected to be related to BMI, as has been observed in both children (Epstein et al., 2015; Hill, Saxton, Webber, Blundell, & Wardle, 2009; Kong, Feda, Eiden, & Epstein, 2015; Temple, Legierski, Giacomelli, Salvy, & Epstein, 2008a) and adults (Carr, Lin, Fletcher, & Epstein, 2014; Epstein, Carr, Lin, Fletcher, & Roemmich, 2012; Giesen, Havermans, Douven, Tekelenburg, & Jansen, 2010; Saelens & Epstein, 1996). However, reinforcing efficacy of food may not be as strong a predictor as reinforcing efficacy for alcohol or cigarette consumption. Obesity is a disorder of energy balance, which includes energy expenditure as well as energy intake. A complete picture of obesity development or maintenance is best acquired using both sides of the energy balance equation. Food is also necessary for life, while alcohol or nicotine is not.

Previous results (Bidwell et al., 2012; MacKillop et al., 2009; O'Connor et al., 2016) suggest that intensity is the major contributor to the amplitude factor. The amplitude factor was the strongest predictor of alcohol consumption (MacKillop et al., 2009), but amplitude and persistence were equal predictors of tobacco consumption (Bidwell et al., 2012), and both predicted quit intentions and quit attempts (O'Connor et al., 2016). In sum, across several studies, research shows that both amplitude and persistence can predict different aspects of consumption of different commodities. Persistence relates to different components of the demand curve that model how consumption is related to changes in price. It could be predicted that obese people are less price sensitive than leaner people. Amplitude refers to how much a person would consume if the price was free, this setting the y-axis of the demand curve. It could also be predicted that obese people would show stronger intensity for food than leaner peers.

The utility of factor scores to predict consumption is based on the notion that the factor scores are superior to individual components of reinforcing efficacy. Thus, we will be comparing prediction of BMI for individual as well as factor scores.

Method

Participants

Data were used from two separate studies that had participants complete purchasing tasks to measure indices of demand and reinforcing efficacy and BMI was measured. The Grocery Store study consisted of 217 participants participating in an online grocery store to examine the effects of taxes and subsidies on purchasing (Epstein, Dearing, Roba, & Finkelstein, 2010b). Reinforcing efficacy of food data was collected as part of a battery of screening measures. The Multisite Intervention Neuroimaging Delay Discounting (MINDD) study consisted of 111 participants recruited for a study on medical adherence and delay discounting in pre-diabetic adults in a multi-site study at two study sites Buffalo, NY and Roanoke, VA.

Measures

Demographics—Information about age, race/ethnicity, income, and educational level were obtained using a standardized questionnaire adapted from MacArthur's network for studies on socio-economic status and health (Adler, Epel, Castellazzo, & Ickovics, 2000).

Anthropomorphic measurement—For the Grocery store study, height was measured three times with a digital stadiometer (Measurement Concepts & Quick Medical, North Bend, WA). The median height was used for data analysis. Weight was assessed using a Tanita digital scale (Arlington Heights, IL). For the MINDD study height was measured in centimeters to the nearest millimeter using a SECA stadiometer (Seca Corp., Chino, CA) and weight was measured using a Tanita digital scale. Measurements were used to calculate BMI (kg/m^2).

Purchasing Task—In the grocery store study, participants completed two food purchase tasks, one task for a low energy dense snack food (LED), and one for a high energy dense snack food (HED). Participants first chose the most preferred food from a list of foods (LED): apples, bananas, mandarin oranges, low-fat strawberry yogurt, celery with dip, carrots with dip, applesauce, red seedless grapes, or pineapple chunks; (HED): nacho cheese Doritos®, milk chocolate M&M's®, Chips Ahoy! cookies, Reese's® peanut butter cups, Hershey's® chocolate, mini Oreos®, Original Pringles® Chips, or Little Debbie® zebra cakes) and proceeded to make hypothetical purchases of their chosen food over 19 increasing price points. Prices used were \$0(free), \$0.01, \$0.05, \$0.13, \$0.25, \$0.50, \$1, \$2, \$3, \$4, \$5, \$6, \$11, \$35, \$70, \$140, \$280, \$560, and \$1120. Each price referred to the cost to purchase 30g serving of food.

Participants were instructed to “*Imagine a TYPICAL DAY during which you could eat your preferred (low calorie/snack) foods. The following questions ask how many portions of your preferred (low calorie/snack) food you would consume if they cost various amounts of money. Assume you have the same income/savings that you have now and NO ACCESS to any other low calorie food other than the (low calorie/snack) food offered at these prices. In addition, assume that you would consume the food that you request on that day; that is you*

cannot save or stockpile the food for a later date.” Participants experienced all price points even after choosing to abstain from purchasing any food at a particular price point.

In the MINDD study, participants completed a single food purchase task after choosing their “favorite” food from a list of ten HED snack foods (Cheetos®, Cheez-Its®, Chips Ahoy!®, cookies, nacho cheese Doritos®, Fritos®, M&M’s®, Oreos, Lay’s® potato chips, Reese’s® peanut butter cups, or Swedish fish candy). Prices used were \$0.01, \$0.05, \$0.10, \$0.25, \$0.50, \$1, \$2, \$5, \$10, \$20, \$40, \$80. Prices referred to the cost to purchase 20g serving of food.

Participants were instructed *“In the following questions, servings of [chosen food] will be available for purchase at various prices. At each price, please use the keyboard to enter the number of 20-gram servings that you would like to purchase [show them the 20-gram picture of chosen food]. You may purchase as much food at each price as you would like. However, the amount that you purchase can only be eaten during a single, 30-minute sitting. Also assume that you cannot save this food for a later time or give it away, and that you have no other access to this food. Each time a new price is presented, decide again as though you hadn’t purchased any food at previous prices. After you have entered an amount, the program will ask you to either confirm this amount or give you a chance to re-enter the amount. These are hypothetical questions, but please answer as if all purchases are real and that you are spending your own money with the same income/savings as you have now. There are no right or wrong answers in this task. Please take your time and answer thoughtfully.”*

Data for both studies were processed with the same procedures. Participants’ hypothetical purchases over the all price points resulted in the following facets of reinforcing efficacy shown in Table 1.

Demand elasticity is calculated with the following equation (Koffarnus, Franck, Stein, & Bickel, 2015; Yu, Liu, Collins, Vincent, & Epstein, 2014):

$$Q = Q_0 * 10^{k \left(e^{-\alpha Q_0^P} - 1 \right)}$$

This equation was modified from the exponential demand equation introduced by Hursh and Silberberg (Hursh & Silberberg, 2008) to allow analysis of zero values in consumption. Here, Q is consumption, P is price, k is a constant of span of minimum to maximum consumption in log10 units, and Q₀ and α served as dependent measures of demand intensity and elasticity, respectively. Measures were natural log-transformed and standardized prior to analysis to normalize skewed distributions and aid comparisons of factor coefficients. This equation is different from the standard measure of price elasticity which is generally defined as the percentchange in consumption to a given percent-change in the price of the good (Andreyeva, Long, & Brownell, 2010). The demand elasticity equation takes into account the empirical observation that consumption is inelastic to price changes

over a wide variety of prices before consumption decreases as price increases, rather than being linearly related to price changes.

Analytic Plan

Data were screened for non-systematic responding (Stein, Koffarnus, Snider, Quisenberry, & Bickel, 2015) with non-systematic trend (i.e., invariant purchasing across price), as well as bounce and reversal (i.e., inconsistent purchasing across price) criteria flagged. Demand z-scores were then assessed for outliers by excluding scores beyond ± 3.29 . Factor analyses were carried out using principal components analysis (PCA) with oblique rotation ($\gamma=0$), for observed and derived demand variables separately. Each factor analysis included observed intensity, $O_{\max}$, $P_{\max}$, and breakpoint, and derived α . The number of factors was determined using eigenvalues >0.80 and by examination of a scree plot of eigenvalues to see if any other factors beyond the elbow of the plot were suggested. Based on the pattern of results, variables that loaded at least 0.80 on a factor were considered to load on that factor, and allowed a variable to load on only one factor.

Factor scores were created using component loadings to weight them, only using variables that loaded on that factor. Pearson product-moment correlations for both individual demand variables and the factor scores on participant weight and body mass index (BMI) to examine the strength of individual and factor associations with weight and BMI. All analyses were carried out in Systat 11.

Results

Sample and demand curve characteristics

Characteristics of both samples are shown in Table 2. Several differences were observed between the samples, including sex distribution, age, and BMI (p 's < 0.001). This facilitates the study of factor structure across samples of different types of individuals. The sample for Study 1 were the primary food purchasers for their family, which trended towards women. In Study 1 2.8% (6/217) participants' low energy density food purchases were flagged as non-systematic purchasing due to violating trend criteria, with 2.3% (5/217) exceeding outlier cutoffs. For high energy density purchases, 1.8% (4/217) were flagged as non-systematic, with 3.7% (8/217) exceeding outlier cutoffs. This reduced the sample to 205 for all factor analyses. For Study 2, 12.6% (14/111) of high energy dense food purchases were flagged as non-systematic with 4.5% (5/111) exceeding outlier cutoffs for one or more standardized scores. The final sample for factor analysis was reduced to 92.

Characteristics of the demand curves are presented in Table 3. The only significant difference between measures for HED foods was for intensity ($p < 0.001$), as people would consume more of the HED foods in Study 2 when they were purchasing it for a 30-minute period than when purchasing HED foods in Study 1 over a day. There were reliable differences in characteristics of the demand curves for HED versus LED foods in Study 1 for each of the measures of demand. It is interesting that in each case, the measure of demand was greater for LED than HED foods, and the elasticity measure suggested that people were more price sensitive for HED than LED foods.

Demand curves of purchases and expenditures for low and high energy density foods in Study 1 and high energy density foods in Study 2 are illustrated in the graphs in Figure 1. The graphs on the left side of Figure 1 (1a, 1c, 2a) show that purchases generally decrease as prices increase, but there is a range of prices in which purchases are inelastic, and then purchases decrease in an exponential function as prices increase until purchases stop. While there are differences in the characteristics of the curve, the general pattern and the fit of the data to the model are similar across types of foods and studies. The right hand graphs (1b, 1d, 2b) show that expenditure increases as prices increase up to a point, at which expenditure reduce as prices further increase until expenditures stop. Once again, the general shape of the curves are similar across graphs, though as shown in Table 3, the specific measures of the demand curves differ as a function of study and type of food.

Factor analyses

Using the criteria adopted by MacKillop (MacKillop et al., 2009), scree plots of eigenvalues from PCA revealed a flattened elbow beyond two factors for each of the dependent variables. Factor loadings for each factor, the percent variance accounted for by that factor, and the total eigenvalues for that factor are shown in Table 4. Factor 1 included four variables, $P_{\max}$, $O_{\max}$, breakpoint and α . These factors accounted for $\approx 70\%$ of the variance for HED and LED foods across both studies. The only variable that loaded on Factor 2 in both studies for both types of food was intensity, accounting for between 21.9 to 23.5% of the variance. The two factors accounted for between 91.7 to 95.4% of the variance in food reinforcement across the studies and types of food.

Relationship with BMI

Pearson r 's for individual variables and factors are shown in Table 5. Intensity or Factor 2 for HED foods were related to BMI in both studies ($p < 0.05$). None of the observed or derived individual or factor scores for LED foods were significant predictors of BMI.

Discussion

A consistent pattern of variables loaded on Factors 1 and 2 across the two studies, and for both low and high energy density foods. The first factor labeled persistence included measures of α , breakpoint, $P_{\max}$ and $O_{\max}$. The variables are related to how much people are willing to pay for that food, and the overall relationship between price and purchases. The second factor, amplitude, included intensity (Q_0), which assesses the amount a person wanted to eat if it was free or very inexpensive. The consistency in the factor structure is impressive given that the data were observed across two very different samples in terms of sex distribution, age and BMI, and across different types of foods, and across different instructions in terms of how long to consider purchasing foods for (30 min versus one day). In addition, these two factors accounted for over 90 percent of the variance in food reinforcement, suggesting that they represent the primary components of food reinforcement.

The only variables or factors that were related to BMI were intensity (Q_0) for HED foods, or factor 2 that was based on intensity. The relationships were similar for Studies 1 ($r = 0.18$)

and 2 ($r = 0.22$). The consistency of the effect sizes across studies with very different samples suggests that intensity is the aspect of the demand curves that is most related to BMI. If the goal is to predict BMI, the data suggest that not much is gained by the factor analysis beyond knowledge of intensity, as the effect sizes are not greater when factor scores rather than the individual intensity score was used.

Reinforcing efficacy of alcohol is a stronger predictor of alcohol intake (MacKillop et al., 2009) than reinforcing value of food predicts BMI or the reinforcing value of smoking predicts smoking (Bidwell et al., 2012). The reinforcing efficacy of alcohol or cigarettes are logically related to alcohol or cigarette consumption, while in the case of BMI, the reinforcing value of food is only part of the energy balance equation. Other factors that may contribute to the positive energy balance associated with obesity are activity expenditure and the calorie and macronutrient content of the food. We have preliminary data on the relationship between the reinforcing value of food and energy intake by examining participants in Study 2 who provided biologically plausible energy intake (did not underreport) (Lam et al., 2014) collected using repeated 24 hour recalls. These data showed stronger relationships between factors 1 and 2 of the RRE and energy intake ($n = 27$, r 's = 0.40, $p < 0.05$, -0.32 , $p = 0.10$, respectively) than for BMI (r 's = -0.13 , 0.19 , p 's > 0.30). It is logical that both factors were stronger predictors of energy intake than BMI, as food reinforcement should be more directly related to energy intake than BMI, which has other determinants. Future studies should obtain laboratory measures of eating behavior as well as additional intake in the natural environment, correcting for under reporting (Lam et al., 2014), to refine the relationship between demand for food based on these behavioral economic demand curves and eating behavior.

These behavioral economic demand curves are based on hypothetical purchases at different prices. While hypothetical and real purchase tasks have shown correspondence between demand measures (Amlung, Acker, Stojek, Murphy, & MacKillop, 2012; Wilson, Franck, Koffarnus, & Bickel, 2016), these are not veridical to operant tasks in which people actually work for access to food, which are related to obesity, and energy intake (Epstein et al., 2010a).

Behavioral economic demand curves also do not assess reinforcing value using a choice paradigm. Each commodity is studied separately, rather than people having to make a choice between allocating money for purchasing one commodity versus a different commodity. In other words, they assess "own-price sensitivity" not "cross-price sensitivity." This may be relevant, as in the case of food (or alcohol), people have to make the choice between eating versus engaging in a different behavior, or eating a different type of food. This may be particularly relevant for food, as research has shown that food is more reinforcing than alternative behaviors for obese youth, while alternatives to food are more reinforcing than food (Temple, Legierski, Giacomelli, Salvy, & Epstein, 2008b). The reinforcing value of alcohol likely depends on what other behaviors are available as alternatives to drinking (Vuchinich & Tucker, 1988). Research strongly suggests that absence of alternatives to smoking are related to development of regular smoking behavior (Audrain-McGovern et al., 2009; Audrain-McGovern et al., 2004; Bickel, DeGrandpre, Higgins, Hughes, & Badger, 1995; Leventhal et al., In press) suggesting that a

complementary and perhaps more incisive estimate of reinforcing efficacy might require people to allocate resources to concurrent choices. The ability of demand for food to predict BMI could be improved by knowledge of alternative behaviors and concurrent activity patterns.

It is interesting that the strongest predictor of BMI was intensity, or how much would you eat if the product was free or very inexpensive, rather than other aspects of food reinforcement that relate to the relationship between price and consumption. This may have implications for how to approach interventions to reduce eating. Intensity may be related to craving or incentive salience (Berridge, 1996; Robinson & Berridge, 2000), or the attraction to the food independent of cost. Modifying the attraction to a specific food would reduce the motivation to consume that food, and potentially reduce food intake. The challenge remains of how to reduce craving or incentive salience of powerful reinforcers such as food. One approach to reducing the incentive salience value of food is to provide an enriched array of alternatives to food that can compete with food reinforcement (Goldfield & Epstein, 2002). Providing reinforcing alternatives to food would reduce the desire to consume the food, and attempts to reduce access to food, either by environmental control or by increasing pricing, could increase the probability of people making the choice of not eating that snack food. Research suggests that cognitive and social activities can reduce food reinforcement (Carr & Epstein, In press), and weight control participants with greater access to strong alternative to food do better in weight control programs (Buscemi, Murphy, Berlin, & Raynor, 2014). The simplicity of measuring reinforcing efficacy of alternatives using the reinforcing efficacy questionnaire suggests this may be a reasonable approach to identifying alternatives to food reinforcers in the future. An alternative approach is to use episodic future thinking, which is designed to target problems with discounting the future that obese persons experience (Amlung, Petker, Jackson, Balodis, & MacKillop, 2016) that also has the benefit of reducing the demand for food and modifying the intensity aspect of the food demand curve (Sze, Stein, Bickel, Paluch, & Epstein, 2017).

Price dependent measures, including O_{max} , P_{max} , breakpoint or demand elasticity, were not as strongly related to BMI as intensity. A small previous study showed that O_{max} derived from demand curves was related to BMI (Epstein et al., 2010a), but this was not replicated in our study. This suggests that an understanding of individual differences in price dependent aspects of demand curves would not be useful to predicting who might be responsive to price changes. On the other hand, persistence was related to energy intake in this study, consistent with previous research that showed demand elasticity was related to laboratory energy intake BMI (Epstein et al., 2010a). Additional research is needed to confirm that demand elasticity has a stronger relationship with the energy intake side of the energy balance equation than BMI, which integrates energy intake and energy expenditure.

Of particular interest is the observation that the same general factors are observed for alcohol, tobacco, and food purchasing. While alcohol is a drug, and the focus is often on the pharmacological properties of alcohol, alcohol is also a food product that has calories and that people consume for both its gustatory and pharmacological properties. Thus, it would be interesting to compare different aspects of reinforcing efficacy for alcohol and food product matched for nutrient composition to assess the unique role of the psychoactive compound of

ethanol on reinforcing efficacy (i.e., ethanol demand = beverage alcohol demand – calorically/nutritionally matched beverage demand). Furthermore, alcohol is also a complement to food for some people and behavioral economic methods may illuminate the complementarities and substitutability of alcohol. Developing a better understanding of this relationship may be useful in developing unique interventions that reduce intake of foods that are strong complements to alcohol intake with the goal of reducing alcohol intake. Although the current data cannot directly speak to these possibilities, they are clear priorities for the future.

A major advantage of these demand curves is that they are easily measured, multiple commodities can be measured in the same session, and they do not pose a burden on subjects. Developing a better understanding of which facets of food reinforcement are most related to eating and body composition may provide ideas about which aspects of food reinforcement should be addressed in treatment. This could allow investigators and clinicians to go beyond the idea that obese people find food reinforcing to what aspects of food reinforcement are susceptible to change and can influence the biggest effect on obesity.

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References

- Adler NE, Epel ES, Castellazzo G, & Ickovics JR (2000). Relationship of subjective and objective social status with psychological and physiological functioning: Preliminary data in healthy white women. *Health Psychology*, 19, 586–592. [PubMed: 11129362]
- Amlung M, Petker T, Jackson J, Balodis I, & MacKillop J (2016). Steep discounting of delayed monetary and food rewards in obesity: a meta-analysis. *Psychological Medicine*, 46, 2423–2434. [PubMed: 27299672]
- Amlung MT, Acker J, Stojek MK, Murphy JG, & MacKillop J (2012). Is talk “Cheap”? An initial investigation of the equivalence of alcohol purchase task performance for hypothetical and actual rewards. *Alcoholism-Clinical and Experimental Research*, 36, 716–724.
- Andreyeva T, Long MW, & Brownell KD (2010). The impact of food prices on consumption: a systematic review of research on the price elasticity of demand for food. *American Journal of Public Health*, 100, 216–222. [PubMed: 20019319]
- Aston ER, Metrik J, & MacKillop J (2015). Further validation of a marijuana purchase task. *Drug and Alcohol Dependence*, 152, 32–38. [PubMed: 26002377]
- Audrain-McGovern J, Rodriguez D, Epstein LH, Rodgers K, Cuevas J, & Wileyto EP (2009). Young adult smoking: what factors differentiate ex-smokers, smoking cessation treatment seekers and nontreatment seekers? *Addictive Behaviors*, 34, 1036–1041. [PubMed: 19619948]
- Audrain-McGovern J, Rodriguez D, Tercyak KP, Epstein LH, Goldman P, & Wileyto EP (2004). Applying a behavioral economic framework to understanding adolescent smoking. *Psychology of Addictive Behaviors*, 18, 64–73.
- Berridge KC (1996). Food reward: brain substrates of wanting and liking. *Neuroscience and Biobehavioral Reviews*, 20, 1–25.

- Bickel WK, DeGrandpre RJ, Higgins ST, Hughes JR, & Badger GJ (1995). Effects of simulated employment and recreation on drug taking: A behavioral economic analysis. *Experimental and Clinical Psychopharmacology*, 3, 467–476.
- Bickel WK, & Madden GJ (1999). A comparison of measures of relative reinforcing efficacy and behavioral economics: cigarettes and money in smokers. *Behavioral Pharmacology*, 10, 627–637.
- Bickel WK, Marsch LA, & Carroll ME (2000). Deconstructing relative reinforcing efficacy and situating the measures of pharmacological reinforcement with behavioral economics: a theoretical proposal. *Psychopharmacology (Berl)*, 153, 44–56. [PubMed: 11255928]
- Bidwell LC, MacKillop J, Murphy JG, Tidey JW, & Colby SM (2012). Latent factor structure of a behavioral economic cigarette demand curve in adolescent smokers. *Addictive Behaviors*, 37, 1257–1263. [PubMed: 22727784]
- Bruner NR, & Johnson MW (2014). Demand curves for hypothetical cocaine in cocaine-dependent individuals. *Psychopharmacology*, 231, 889–897. [PubMed: 24217899]
- Buscemi J, Murphy JG, Berlin KS, & Raynor HA (2014). A behavioral economic analysis of changes in food-related and food-free reinforcement during weight loss treatment. *Journal of Consulting and Clinical Psychology*, 82, 659–669. [PubMed: 24660672]
- Carr KA, & Epstein LH (In press) Influence of sedentary, social and physical alternatives on food reinforcement *Health Psychology*.
- Carr KA, Lin H, Fletcher KD, & Epstein LH (2014). Food reinforcement, dietary disinhibition and weight gain in nonobese adults. *Obesity (Silver Spring)*, 22, 254–259. [PubMed: 23512958]
- Drewnowski A (1998). Energy density, palatability, and satiety: implications for weight control. *Nutrition Reviews*, 56, 347–353. [PubMed: 9884582]
- Epstein LH, Carr KA, Lin H, Fletcher KD, & Roemmich JN (2012). Usual energy intake mediates the relationship between food reinforcement and BMI. *Obesity (Silver Spring)*, 20, 1815–1819. [PubMed: 22245983]
- Epstein LH, Carr KA, Scheid JL, Gebre E, O'Brien A, Paluch RA, & Temple JL (2015). Taste and food reinforcement in non-overweight youth. *Appetite*, 91, 226–232. [PubMed: 25891040]
- Epstein LH, Dearing KK, & Roba LG (2010a). A questionnaire approach to measuring the relative reinforcing efficacy of snack foods. *Eat Behav*, 11, 67–73. [PubMed: 20188288]
- Epstein LH, Dearing KK, Roba LG, & Finkelstein E (2010b). The influence of taxes and subsidies on energy purchased in an experimental purchasing study. *Psychological Science*, 21, 406–414. [PubMed: 20424078]
- Giesen JCAH, Havermans RC, Douven A, Tekelenburg M, & Jansen A (2010). Will work for snack food: The association of BMI and snack reinforcement. *Obesity (Silver Spring)*, 18, 966–970. [PubMed: 20150901]
- Goldfield GS, & Epstein LH (2002). Can fruits and vegetables and activities substitute for snack foods? *Health Psychology*, 21, 299–303. [PubMed: 12027037]
- Hill C, Saxton J, Webber L, Blundell J, & Wardle J (2009). The relative reinforcing value of food predicts weight gain in a longitudinal study of 7–10-y-old children. *The American Journal of Clinical Nutrition*, 90, 276–281. [PubMed: 19535428]
- Hursh SR, Galuska CM, Winger G, & Woods JH (2005). Addictive drugs, effective therapies: It's all about the economy! *Molecular Interventions*, 5, 20–28. [PubMed: 15731502]
- Hursh SR, & Silberberg A (2008). Economic demand and essential value. *Psychological Review* 115, 186–198. [PubMed: 18211190]
- Johnson MW, & Bickel WK (2006). Replacing relative reinforcing efficacy with behavioral economic demand curves. *Journal of the Experimental Analysis of Behavior*, 85, 73–93. [PubMed: 16602377]
- Koffarnus MN, Franck CT, Stein JS, & Bickel WK (2015). A Modified Exponential Behavioral Economic Demand Model to Better Describe Consumption Data. *Experimental and Clinical Psychopharmacology*, 23, 504–512. [PubMed: 26280591]
- Kong KL, Feda DM, Eiden RD, & Epstein LH (2015). Origins of food reinforcement in infants. *The American Journal of Clinical Nutrition*, 101, 515–522. [PubMed: 25733636]
- Lam YY, Redman LM, Smith SR, Bray GA, Greenway FL, Johannsen D, & Ravussin E (2014). Determinants of sedentary 24-h energy expenditure: equations for energy prescription and

adjustment in a respiratory chamber. *American Journal of Clinical Nutrition*, 99, 834–842. [PubMed: 24500151]

- Leventhal AM, Bello MS, Unger JB, Strong DR, Kirkpatrick MG, & Audrain- McGovern J (In press). Diminished alternative reinforcement as a mechanism underlying socioeconomic disparities in adolescent substance use. *Preventive Medicine*.
- MacKillop J, Miranda R, Monti PM, Ray LA, Murphy JG, Rohsenow DJ, ... Gwaltney CJ (2010). Alcohol demand, delayed reward discounting, and craving in relation to drinking and alcohol use disorders. *Journal of Abnormal Psychology*, 119, 106–114. [PubMed: 20141247]
- MacKillop J, Murphy JG, Tidey JW, Kahler CW, Ray LA, & Bickel WK (2009). Latent structure of facets of alcohol reinforcement from a behavioral economic demand curve. *Psychopharmacology*, 203, 33–40. [PubMed: 18925387]
- MacKillop J, Weafer J, Gray JC, Oshri A, Palmer A, & de Wit H (2016). The latent structure of impulsivity: impulsive choice, impulsive action, and impulsive personality traits. *Psychopharmacology*, 233, 3361–3370. [PubMed: 27449350]
- O'Connor RJ, Heckman BW, Adkison SE, Rees VW, Hatsukami DK, Bickel WK, & Cummings KM (2016). Persistence and amplitude of cigarette demand in relation to quit intentions and attempts. *Psychopharmacology*, 233, 2365–2371. [PubMed: 27048156]
- Petry NM, & Bickel WK (1998). Polydrug abuse in heroin addicts: a behavioral economic analysis. *Addiction*, 93, 321–335. [PubMed: 10328041]
- Robinson TE, & Berridge KC (2000). The psychology and neurobiology of addiction: an incentive-sensitization view. *Addiction*, 95, S91–117. [PubMed: 11002906]
- Saelens BE, & Epstein LH (1996). Reinforcing value of food in obese and non-obese women. *Appetite*, 27, 41–50. [PubMed: 8879418]
- Shahan TA, Bickel WK, Madden GJ, & Badger GJ (1999). Comparing the reinforcing efficacy of nicotine containing and de-nicotinized cigarettes: a behavioral economic analysis. *Psychopharmacology (Berl)*, 147, 210–216. [PubMed: 10591889]
- Stein JS, Koffarnus MN, Snider SE, Quisenberry AJ, & Bickel WK (2015). Identification and management of nonsystematic purchase task data: Toward best practice. *Experimental and Clinical Psychopharmacology*, 23, 377–386. [PubMed: 26147181]
- Sze YY, Stein JS, Bickel WK, Paluch RA, & Epstein LH (2017). Bleak present, bright future: Online episodic future thinking, scarcity, delay discounting and food demand. *Clinical Psychological Science*, 5, 683–697. [PubMed: 28966885]
- Temple JL, Legierski CM, Giacomelli AM, Salvy S-J, & Epstein LH (2008a). Overweight children find food more reinforcing and consume more energy than do nonoverweight children. *The American Journal of Clinical Nutrition*, 87, 1121–1127. [PubMed: 18469229]
- Temple JL, Legierski CM, Giacomelli AM, Salvy SJ, & Epstein LH (2008b). Overweight children find food more reinforcing and consume more energy than do nonoverweight children. *American Journal of Clinical Nutrition*, 87, 1121–1127. [PubMed: 18469229]
- Vuchinich RE, & Tucker JA (1988). Contributions from behavioral theories of choice to an analysis of alcohol abuse. *Journal of Abnormal Psychology*, 97, 181–195. [PubMed: 3133403]
- Wilson AG, Franck CT, Koffarnus MN, & Bickel WK (2016). Behavioral economics of cigarette purchase tasks: Within-subject comparison of real, potentially real, and hypothetical cigarettes. *Nicotine & Tobacco Research*, 18, 524–530. [PubMed: 26187389]
- Yu J, Liu L, Collins RL, Vincent PC, & Epstein LH (2014). Analytical problems and suggestions in the analysis of behavioral economic demand curves. *Multivariate Behavioral Research*, 49, 178–192. [PubMed: 26741176]

Figure 1. Demand and expenditure curves for high (1a-b) and low (1c-d) energy density foods for Study 1 and high energy density foods (2a-b) for Study 2. Data are scaled in natural log units.

Table 1.

Measures of reinforcing efficacy

Measure	Definition
Intensity	Number of purchases made when food was free or minimal price (e.g.
	\$0.01)
Pmax	Price point for maximal expenditure
Omax	Maximal expenditure (maximum purchases * price)
Breakpoint	First price where no purchases were made
Demand Elasticity	Quantitative non-linear relationship (decaying slope) between purchasing and price

Table 2.

Participant characteristics (mean $\pm$ standard deviation) in the two studies.

Study	Study 1 (n =205)	Study 2 (n = 92)	p
Sex (male/female)	7/198	41/51	< 0.001
Minority (minority/non-minority)	44/161	21/71	0.793
Age	42.53 $\pm$ 7.36	56.07 $\pm$ 11.36	< 0.001
Height (cm)	164.84 $\pm$ 6.85	169.13 $\pm$ 9.54	< 0.001
Weight (kg)	74.79 $\pm$ 20.83	90.70 $\pm$ 25.66	< 0.001
Body Mass Index (BMI)	27.47 $\pm$ 7.15	31.62 $\pm$ 8.10	< 0.001

Table 3.

Demand characteristics (mean $\pm$ standard deviation) in the two studies. HED refers to high energy dense snack foods, and LED refers to low energy dense foods. Contrasts of log transformed demand characteristics differences by study tested using between subjects ANOVA and contrast of HED vs. LED differences in Study 1 tested with repeated measure ANOVA.

	HED		LED	HED only	Study 1 only
Measure	Study 1	Study 2	Study 1	p	p
				Study 1 vs 2	HED vs. LED
Intensity H (Q_0)	2.71 $\pm$ 2.74	3.82 $\pm$ 3.36	3.56 $\pm$ 2.50	< 0.001	< 0.001
O _{max} H	1.76 $\pm$ 2.55	1.70 $\pm$ 1.73	3.13 $\pm$ 9.95	0.649	< 0.001
P _{max} H	1.28 $\pm$ 1.34	1.34 $\pm$ 1.44	1.72 $\pm$ 2.77	0.885	< 0.001
Breakpoint H	2.35 $\pm$ 2.91	3.06 $\pm$ 3.10	3.46 $\pm$ 6.69	0.265	< 0.001
Elasticity H	0.17 $\pm$ 0.23	0.27 $\pm$ 0.62	0.11 $\pm$ 0.11	0.070	< 0.001

Table 4.

Factor Analysis pattern matrices for observed and derived demand variables.

Factor	Factor 1			Factor 2		
Study	Study 1		Study 2	Study 1		Study 2
Food	HED	LED	HED	HED	LED	HED
Observed Demand Curve						
$P_{\max}$	0.978	0.981	1.016	0.223	0.222	0.1731
Breakpoint	0.995	0.973	0.968	0.103	0.079	0.020
$O_{\max}$	0.928	0.904	0.915	-0.186	-0.187	-0.124
Elasticity	-0.871	-0.809	-0.824	0.297	0.312	0.209
Intensity (Q_0)	0.013	0.015	0.030	-0.985	-0.976	-0.979
% variance	71.82	68.25	70.63	23.53	23.46	21.89
Total eigenvalue	3.69	3.57	3.81	1.05	1.02	0.81

Note – HED = High Energy Dense, LED = Low Energy Dense, % variance = percent variance accounted for.

Table 5.

Relationship (pearson r coefficients) between individual variables and factor scores with BMI and weight.

Type of food	HED		LED
	1	2	1
Study			
Intensity (Q_0)	0.18 *	0.22 *	-0.09
$O_{\max}$	0.06	0.11	0.02
$P_{\max}$	-0.03	-0.003	0.03
Breakpoint	-0.02	0.02	0.03
Elasticity	-0.10	-0.17	0.03
Factor 1	0.02	0.05	0.04
Factor 2	0.18 *	0.22 *	0.01

Note –

*
p < 0.05

**
p < 0.01