Appetite 99 (2016) 1–9

Contents lists available at ScienceDirect

Appetite

journal homepage: www.elsevier.com/locate/appet

What is eaten when all of the foods at a meal are served in large portions?

Liane S. Roe, Samantha M.R. Kling, Barbara J. Rolls*

Laboratory for the Study of Human Ingestive Behavior, The Pennsylvania State University, University Park, PA, USA

A R T I C L E I N F O

Article history:
Received 17 July 2015
Received in revised form
20 November 2015
Accepted 2 January 2016
Available online 5 January 2016

Keywords:
Portion size
Energy density
Palatability
Disinhibition
Food intake
Energy intake

A B S T R A C T

Portion size affects intake, but when all foods are served in large portions, it is unclear whether every food will be consumed in greater amounts. We varied the portion size (PS) of all foods at a meal to investigate the influence of food energy density (ED) on the PS effect as well as that of palatability and subject characteristics. In a crossover design, 48 women ate lunch in the laboratory on four occasions. The meal had three medium-ED foods (pasta, bread, cake) and three low-ED foods (broccoli, tomatoes, grapes), which were simultaneously varied in PS across meals (100%, 133%, 167%, or 200% of baseline amounts). The results showed that the effect of PS on the weight of food consumed did not differ between medium-ED and low-ED foods ($p < 0.0001$). Energy intake, however, was substantially affected by food ED across all portions served, with medium-ED foods contributing 86% of energy. Doubling the portions of all foods increased meal energy intake by a mean (±SEM) of 900 ± 117 kJ (215 ± 28 kcal; 34%). As portions were increased, subjects consumed a smaller proportion of the amount served; this response was characterized by a quadratic curve. The strongest predictor of the weight of food consumed was the weight of food served, both for the entire meal ($p < 0.0001$) and for individual foods ($p = 0.014$); subject characteristics explained less variability. Intake in response to larger portions was greater for foods that subjects ranked higher in taste ($p < 0.0001$); rankings were not related to food ED. This study demonstrates the complexity of the PS effect. While the response to PS can vary between individuals, the effect depends primarily on the amounts of foods offered and their palatability compared to other available foods.

1. Introduction

Increases in portion size (PS) have a substantial effect on energy intake and have been implicated as an environmental factor contributing to obesity rates (Kral & Rolls, 2011; Livingstone & Pourshahidi, 2014; Rolls, 2014). In controlled experiments, serving a larger portion of a single food increases its consumption. Although it is common in the current eating environment for all available foods to be oversized, few studies have tested the effects of simultaneously increasing the PS of multiple foods. Such investigations are needed because the portion size effect may vary for different foods at a meal. For example, intake in response to large portions may be affected by the energy density (ED) or the liking of the various foods offered; additionally, intake of one food may influence consumption of the others. Such differential changes could moderate or enhance the effect of portion size on energy intake of the entire meal. The purpose of this experiment was to investigate the effects of portion size on intake when all foods in a meal were varied simultaneously, and to explore whether the response to PS was influenced by food-related properties including ED and palatability, or by subject characteristics such as body size, age, and measures of eating behavior.

Controlled experiments in adults have shown that serving a larger portion of a single food or beverage, without changing the accompanying foods, leads to increased intake of the varied item (Diliberti, Bordi, Conklin, Roe, & Rolls, 2004; Flood, Roe, & Rolls, 2006; Kral, Roe, & Rolls, 2004; Rolls, Morris, & Roe, 2002; Rolls, Roe, & Meengs, 2010; Rolls, Roe, Kral, Meengs, & Wall, 2004; Rolls, Roe, Meengs, & Wall, 2004). The few experiments that simultaneously increased the PS of all foods at meals found that this led to increases in total intake, but effects on individual foods were

* Corresponding author. Laboratory for the Study of Human Ingestive Behavior, The Pennsylvania State University, 226 Henderson Building, University Park, PA 16802, USA.

E-mail address: bjr4@psu.edu (B.J. Rolls).

http://dx.doi.org/10.1016/j.appet.2016.01.001
0195-6663/

not systematically reported (Kelly et al., 2009; Levitsky & Youn, 2004; Rolls, Roe, & Meengs, 2006a, 2006b; Rolls, Roe, & Meengs, 2007). In two experiments that varied all foods, some data suggested that the PS effect was related to the ED of the foods. In the first study, it was observed that serving larger portions over two days led to increased intake of high-ED snacks and beverages but not the accompanying low-ED options (Rolls et al., 2006a). In an 11-day study, the magnitude of the portion size effect across 161 foods was related to the ED of the foods (Rolls et al., 2007). It is possible that this relationship between PS and ED occurred because the higher-ED foods were more palatable than those lower in ED (Drewnowski, 1998); however, the influence of palatability on the relationship was not reported. In the present study, we tested the hypotheses that serving larger portions of all foods at a meal would lead to a greater increase in consumption of higher-ED foods than lower-ED foods and that this effect would be related to the palatability of the individual foods.

Another aim was to assess the influence of subject characteristics on the PS effect. Several recent reviews have focused on identifying individual differences in response to PS, and have come to different conclusions about variability across individuals (Benton, 2015; English, Lasschuijt, & Keller, 2015; Steenhuis & Vermeer, 2009; Zlatevska, Dubelaar, & Holden, 2014). The ability to identify influential subject characteristics could be improved by better statistical modeling of the portion size effect. In our early experimental studies of portion size, we observed that the mean trajectory of intake across four or more portion sizes was curvilinear: when two smaller portions were served, intake increased steeply as subjects consumed most of the available food, but when two larger portions were served, intake increased less steeply (Rolls et al., 2002; Rolls, Roe, Kral et al., 2004; Rolls, Roe, Meengs et al., 2004). Neither we nor others, however, have previously accounted for this non-linearity in analyzing the food intake of individuals. Modeling the curvilinear relationships could help to characterize the portion size effect when all foods are available in large amounts, and thus help to determine whether it is more effective to focus interventions on all foods, foods with certain properties, or particular types of consumers.

2. Methods

2.1. Experimental design

This experiment used a crossover design with repeated measures within subjects, so that subjects served as their own controls. Once a week for four weeks, participants came to the laboratory and were served a lunch consisting of six foods: three medium in energy density and three low in energy density. Across the four meals, participants were served either baseline (100%) portions of all foods or 133%, 167%, or 200% of the baseline amounts. The order of the portion size conditions was counterbalanced across subjects using Latin squares, and subjects were randomly assigned one of the condition sequences.

2.2. Subject recruitment and characteristics

Women aged 20–45 years were recruited using notices in local newspapers, in the community, and on university websites. Respondents were interviewed by telephone to determine whether they met the following initial criteria: had a reported body mass index between 18 and 40 kg/m^2, regularly ate three meals per day, and were willing to eat the foods served in the experimental meal. Potential subjects were excluded if they were dieting to gain or lose weight, had food allergies or restrictions, were taking medications known to affect appetite, were smokers or athletes in training, or were pregnant or breastfeeding.

Potential subjects who met the initial criteria came to the laboratory to complete the following questionnaires: the Zung Self-Rating Scale (Zung, 1986), which assesses symptoms of depression; the Eating Attitudes Test (Garner, Olsted, Bohr, & Garfinkel, 1982), which evaluates disordered attitudes toward food; and the Eating Inventory (Stunkard & Messick, 1985), which assesses dietary restraint, disinhibition, and tendency toward hunger. The height and weight of potential participants (without shoes and coats) was measured using a stadiometer and an electronic scale (Seca North America, Chino, CA, USA). Individuals were only eligible for study if they scored $\leq$40 on the Zung Self-Rating Scale, scored $\leq$20 on the Eating Attitudes Test, and had a measured body mass index between 18 and 40 kg/m^2. Individuals gave signed informed consent and were financially compensated for their participation in the study. The study protocol was approved by the Office for Research Protections of The Pennsylvania State University.

The sample size for the experiment was based on data from previous studies conducted in the laboratory (Kral et al., 2004; Rolls et al., 2002; Rolls, Roe, Meengs et al., 2004). Only women were included as subjects in this experiment in order to reduce the variability in intake and increase the statistical power. The minimum clinically significant difference in meal energy intake was taken to be 167 kJ (40 kcal), or about 5–10% of women's meal intakes in previous studies. A power analysis showed that a sample of 43 subjects would allow the detection of this difference with >80% power at a significance level of 0.05. Fifty-one women were enrolled in the study, but two subjects failed to attend scheduled meals and did not complete the study. The data of one additional subject was excluded for having undue influence on the results according to the procedure of Littell, Milliken, Stroup, Wolfinger, and Schabenberger (2006); at one meal this subject ate only broccoli and grapes (623 kJ; 149 kcal). Thus, the analysis included data from 48 women; 34 (71%) were normal weight, 8 (17%) were overweight, and 6 (13%) were obese. Additional subject characteristics are shown in Table 1.

2.3. Experimental meals

The experimental meal consisted of the six foods shown in Table 2, which were selected to vary in energy density (ED) and to include the components of a typical meal. The portion sizes in the baseline (100%) meal were chosen to provide generous amounts of each of the six foods, allowing for variability in preference for the different foods across subjects. The portion sizes of all foods in the other experimental conditions were simultaneously increased to 133%, 167%, and 200% of the baseline amounts. Since the amounts of the low-ED and medium-ED foods were increased proportionally,

Table 1
Characteristics of the 48 women who participated in the study.

Characteristic	Mean ± SEM	Range
Age (y)	28.6 ± 1.2	20.0–45.5
Weight (kg)	66.3 ± 2.2	49.9–117.1
Height (m)	1.65 ± 0.01	1.50–1.78
Body mass index (kg/m^2)	24.4 ± 0.7	18.6–39.3
Estimated energy expenditure (kJ/d)[a]	9321 ± 138	8050–12155
Estimated energy expenditure (kcal/d)[a]	2228 ± 33	1924–2905
Eating Attitudes Test score	4.0 ± 0.5	0–13
Restraint score[b]	8.1 ± 0.6	0–18
Disinhibition score[b]	5.4 ± 0.5	0–15
Hunger tendency score[b]	4.6 ± 0.4	0–12

[a] Energy expenditure was estimated from sex, age, height, weight, and activity level (Institute of Medicine, 2002).
[b] Scores from the Eating Inventory (Stunkard & Messick, 1985).

Table 2
Amounts of study foods served in each condition of portion size.

Study food	Food energy density		Amount served (g)			
	(kJ/g)	(kcal/g)	100% portions	133% portions	167% portions	200% portions
Low-energy-dense foods						
Cherry tomatoes	0.8	0.2	75	100	125	150
Buttered broccoli	1.9	0.4	90	120	150	180
Red grapes	2.9	0.7	100	133	167	200
Medium-energy-dense foods						
Pasta with cheese sauce[a]	8.8	2.1	300	400	500	600
Angel food cake[b]	10.5	2.5	40	53	67	80
Garlic bread[c]	15.1	3.6	55	73	92	110
Entire meal	6.7	1.6	660	880	1100	1320

[a] Stouffer's macaroni and cheese, Nestlé USA, Solon, OH, USA.
[b] Sara Lee, Downers Grove, IL, USA.
[c] Pepperidge Farm Inc., Norwalk, CT, USA.

the energy density of the meals as served did not vary across conditions. The medium-ED foods, which included the main dish, comprised 60% of the meal by weight. At each meal, an unvaried amount of water (1 l) was served as a beverage.

All foods and the beverage were consumed as desired. Food and beverage items were weighed before and after meals in order to determine the amount consumed to within 0.1 g. Energy and nutrient intakes were calculated using information from food manufacturers and a standard food composition database (USDA, 2015).

2.4. Daily procedures and assessments

Subjects were instructed to keep their evening meal and their physical activity level consistent on the day before each test day, to eat a consistent breakfast on each test day, and to refrain from drinking alcoholic beverages on the evening before and during each test day. Subjects came to the laboratory at a scheduled time on test days to eat lunch. Participants were instructed not to consume any foods or beverages, other than water, between breakfast and lunch, and not to drink any water during the hour before lunch. Prior to being served lunch, participants completed a short questionnaire that asked whether they had consumed any foods or beverages since breakfast, had taken any medications, or had felt ill. If subjects felt ill or did not comply with the study protocol, their test day was rescheduled. Participants were served their test meals in private cubicles.

Immediately before each meal was served, participants rated their hunger, prospective consumption, and fullness using visual analog scales (Hetherington & Rolls, 1987). For example, the question about prospective consumption (“How much food do you think you could eat right now?”) was answered by marking a 100-mm line that was anchored on the left with “Nothing at all” and on the right with “A large amount”. Participants also rated the taste of the six test foods before each meal; they were given a small sample of each food and used visual analog scales to rate the pleasantness of the taste (anchored by “Not at all pleasant” and “Extremely pleasant”). After subjects had finished eating the meal, they again used visual analog scales to rate their hunger, prospective consumption, and fullness.

2.5. Discharge assessments

After the final test lunch, participants completed a discharge questionnaire in which they reported their views about the purpose of the study and whether they noticed any differences between the meals. At discharge, subjects also ranked the six foods according to taste, healthfulness, and amount of energy (calories), based on their experience of the test meals.

2.6. Data analysis

Differences in mean outcomes across the four experimental conditions were analyzed by a mixed linear model with repeated measures. The fixed effects in the model were portion size condition (100%, 133%, 167%, or 200%) and study week. For outcomes with a significant effect of condition, the Tukey–Kramer method was used to adjust for multiple pairwise comparisons between means. The main outcomes were food intake (g) and energy intake (kJ) for the entire meal, for the combined groups of low-ED and medium-ED foods, and for each individual food. The secondary outcomes were meal energy density determined from food intake only (Ledikwe et al., 2005), ratings of hunger and satiety, and ratings of food taste. Ratings of hunger and satiety measured after the meal were adjusted by including the before-meal rating as a covariate in the model.

The design of this study, in which four portions of the foods were served on different occasions, allowed exploration of the curvilinear response that was observed in some previous studies (Rolls et al., 2002; Rolls, Roe, Kral et al., 2004; Rolls, Roe, Meengs et al., 2004). To account for this non-linearity, we used statistical methods that characterized the mathematical trajectory of intake across multiple portion sizes as well as multiple foods. This allowed investigation of the interrelated intakes that result from simultaneously varying multiple foods, as well as the influence of factors such as food properties and subject characteristics. The response to portion size was defined as the trajectory of food intake (by weight) across the various food portions served (by weight). The mean response could be characterized by either a polynomial growth curve or an exponential growth curve (Singer & Willett, 2003). Both curves characterize a theoretical pattern of intake of a single food as the portion is increased, namely: (a) intake is zero when the amount served is zero; (b) intake increases with a slope close to 1 as the amount served is increased and most of it is consumed; (c) intake continues to increase, but with decreasing curvature, as more food is served; and (d) intake approaches a maximum despite further increases in the amount served. For the current study, a polynomial equation was chosen because it allows the intake curve to peak at a maximum and then decline as larger portions are served, a pattern that might be observed for individual foods in a multi-item meal because of competition between foods.

The trajectories of intake in response to larger portions were analyzed using random coefficient models (Littell et al., 2006). Each model included two types of effects: factors affecting the mean response for the entire sample (fixed effects) and deviations from the mean for each subject (random effects); thus a separate curve for portion size response was modeled for each individual. The model was developed by sequentially adding intercept, linear, and polynomial factors of the amount served, both as fixed effects and random effects (Brown & Prescott, 2015). The significance of each added effect was assessed by the Likelihood Ratio Test (Littell, Stroup, & Freund, 2002). The curves were centered at the baseline portion size, thus the intercept of the curve represented intake of the baseline portion, the linear coefficient represented the instantaneous rate of change in intake (slope) as the portion was increased above the baseline amount, and the quadratic coefficient represented the curvature parameter, or the deceleration in the rate of intake as portions were further increased.

For the outcomes of total weight and energy consumed at meals, subject characteristics were added as covariates in the random coefficient model to investigate whether they explained any individual differences in response to meal portion size. For the outcome of intake of individual foods, a similar random coefficient model was developed that included intake of all of the foods as separate variables. Testing all of the foods in the same model allowed the intake trajectory for each food to account for the portion size and intake of the other foods in the meal. Subject characteristics were tested as covariates in the model as they were for the entire meal; in addition, food-based predictors such as food energy density and subject rankings of food taste were tested as covariates. The methods of Singer and Willett (2003) were used to calculate pseudo-R^2 values for the proportion of total outcome variation explained by each model.

Differences in the distribution of participant taste rankings across the six foods were analyzed by ordinal repeated measures logistic regression. Daily energy requirements of participants were estimated from their sex, age, height, weight, and activity level (Institute of Medicine, 2002). All analyses were performed using SAS software (SAS 9.4, SAS Institute, Inc., Cary, NC, USA). Results were considered significant at $p < 0.05$ and are reported as mean ± SEM.

3. Results

3.1. Effects of meal portion size on food intake by weight

Increasing the portion size of all foods led to significant increases in the mean weight consumed of the entire meal ($p < 0.0001$) as well as of each food (Fig. 1A; all $p < 0.003$). Increasing all baseline portions by 33% increased meal intake by 25%; increasing the portions by 67% or 100% increased intake by 34%. Serving larger portions significantly increased intake of the three medium-ED foods considered together and of the three low-ED foods together (both $p < 0.0001$). There was no difference in consumption of the medium-ED and low-ED foods in response to larger portions ($p = 0.58$ for interaction); doubling the portions increased intake of the medium-ED foods by 68 ± 11 g and the low-ED foods by 73 ± 12 g. The medium-ED foods accounted for 56 ± 1% of meal intake by weight, and as portion sizes were increased this proportion did not vary ($p = 0.64$) nor did the overall ED of food consumed at the meal (6.61 ± 0.84 kJ/g [1.58 ± 0.02 kcal/g]; $p = 0.83$). Subjects consumed the entire amount of available food at 3 of the 192 meals (1.6%); excluding these meals from the analysis did not change the significance of the effect of portion size on intake.

Individual foods differed in their portion size effect; doubling the portions led to increases in intake that ranged from 22% for pasta to 60% for broccoli. The magnitude of change also varied across portions; as an example, broccoli intake increased 28% between the two smallest portions but a non-significant 6% between the two largest portions (Fig. 1A). Subject ratings of hunger, prospective consumption, and fullness after meals (adjusted for before-meal ratings) did not differ significantly as food portion sizes were increased, despite the substantial increase in intake. For example, ratings of fullness after the baseline (100%-portion) meal were 82.8 ± 1.9 mm and after the 200%-portion meal were 85.2 ± 1.9 mm ($p = 0.61$).

At discharge, 39 of the 48 subjects (81%) reported that they noticed differences between meals in the amount of food served, and 15 (31%) guessed that the purpose of the study related to changes in portion size. The effects of portion size on food intake were significant whether or not subjects noticed changes in portion size or guessed the purpose of the study.

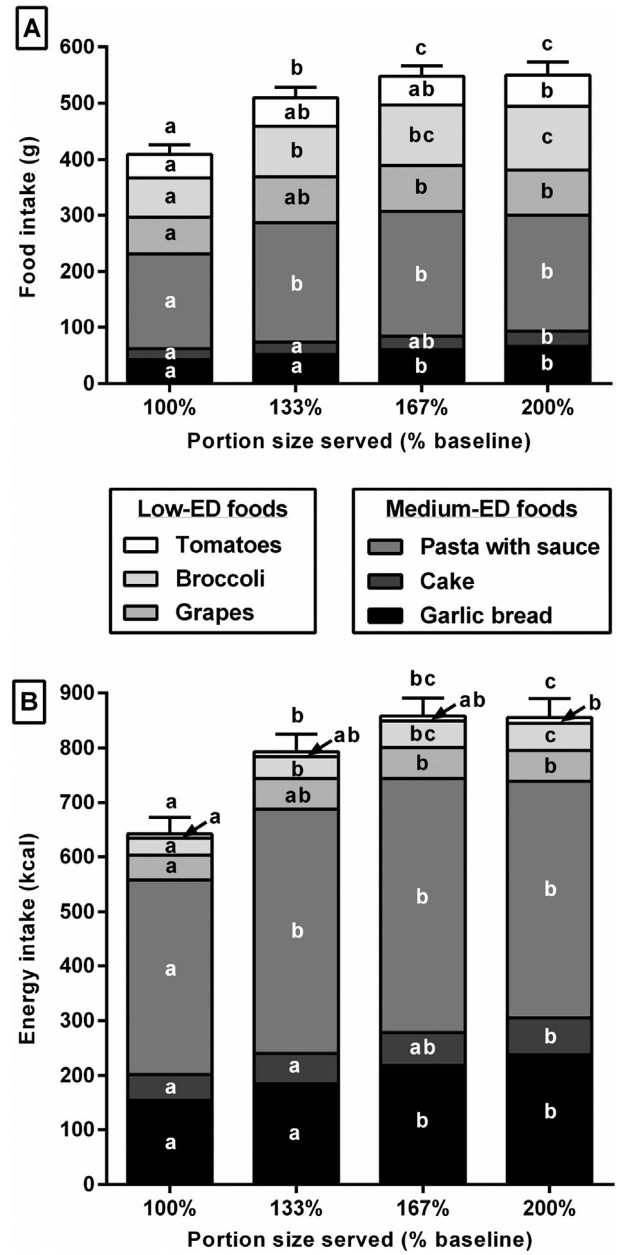

Fig. 1. Mean (±SEM) food intake (A) and energy intake (B) of 48 women who were served a meal of six foods that were varied in portion size. Three of the foods were low in energy density (ED) and three were medium in ED. Means for the same outcome marked with different letters are significantly different according to a mixed linear model with repeated measures ($p < 0.02$).

3.2. Effects of meal portion size on energy intake

Increasing the portion size of all foods also significantly increased mean energy intake of the entire meal ($p < 0.0001$) and of each food (Fig. 1B; all $p < 0.003$). Increasing the portions of all foods by 33% increased energy intake at the meal by 24%; increasing portions by 67% or 100% increased energy intake by 34% (900 ± 117 kJ; 215 ± 28 kcal). For both the three medium-ED foods considered together and the three low-ED foods together, energy intake increased significantly as larger portions were served (both $p < 0.0001$). The medium-ED foods accounted for 86 ± 1% of meal energy intake, and this proportion did not differ as portions were increased ($p = 0.80$). Because of the difference in energy density of the foods, energy intake in response to larger portions was greater for the medium-ED foods than for the low-ED foods ($p < 0.0001$ for interaction). Doubling the portions of the medium-ED foods increased their intake by 761 ± 113 kJ (182 ± 27 kcal) and doubling portions of the low-ED foods increased their intake by 138 ± 25 kJ (33 ± 6 kcal). Thus, although the effect of portion size on the weight of food consumed did not differ for low-ED and medium-ED foods, the effect on energy intake did differ, since the medium-ED foods provided a more concentrated source of energy per weight.

3.3. Characterization of meal intake curves in response to meal portion size

Intake by weight: Results from the random coefficient analysis showed that mean intake of the entire meal in response to portion size was characterized by a quadratic curve (Fig. 2). The curvilinear relationship fit the data significantly better than a linear relationship, as indicated by a Likelihood Ratio Test ($p < 0.0001$). The mean curve had a positive linear coefficient (instantaneous slope) of 0.55 ($p < 0.0001$) and a small negative quadratic coefficient of −0.00051 ($p < 0.0001$). The linear coefficient indicated that as meal portion size was increased beyond the baseline amount, subjects ate a mean of 55% of the additional food; this rate of intake, however, was rapidly reduced by the quadratic coefficient as meal size was further increased. The maximal mean intake (vertex of the curve) was at a meal portion size of 1196 ± 13 g, between the amounts served in the 167% and 200% portion size conditions. The pseudo-R^2 value showed that the weight of food served at meals explained 16% of the variability in the weight of food consumed across meals.

The contribution of the random subject effects to the response curve was significant for the intercept ($p < 0.0001$) and the linear coefficient ($p = 0.012$), indicating that there was variation between individuals in both baseline meal intake and in the proportion of additional food consumed as portions were increased. Across subjects, intake of the baseline meal ranged from 198 to 659 g and the instantaneous slope ranged from 0.38 to 0.82 of food eaten per additional weight of food served. The maximal meal intake ranged across subjects from 284 g to 950 g at meal portion sizes ranging from 1035 g to 1467 g.

Energy intake: In response to increased portion size, energy intake showed a curvilinear relationship similar to that for food intake by weight. The mean curve had a positive linear coefficient of 3.6 kJ/g [0.85 kcal/g] ($p < 0.0001$) and a negative quadratic coefficient of −0.0033 kJ/g [-0.00080 kcal/g] ($p < 0.0001$). The mean maximal energy intake (vertex of the curve) was 3640 ± 111 kJ (870 ± 26 kcal) at a meal portion size of 1190 ± 7 g. The pseudo-R^2 value indicated that the meal weight served explained 13% of the variability in energy intake across meals.

3.4. Influence of subject characteristics on intake curves for the entire meal

Intake by weight: Testing subject characteristics for influence on the intake response curve for the entire meal showed that two measures had a significant effect: the disinhibition score on the Eating Inventory and the pre-meal ratings of prospective consumption. The disinhibition score influenced both the intercept ($p = 0.006$) and the linear coefficient ($p = 0.005$) of the response curve. Compared to subjects with lower disinhibition, subjects with higher disinhibition consumed a smaller weight of food at the baseline meal but had greater intake as portions were increased above baseline; thus, subjects with higher disinhibition showed a stronger response to large portions. Pre-meal ratings of prospective consumption affected the magnitude of baseline meal intake ($p < 0.0001$), in that subjects with higher values consumed a greater weight of food at the baseline meal; these ratings, however, did not significantly affect the curvature of intake as portions were

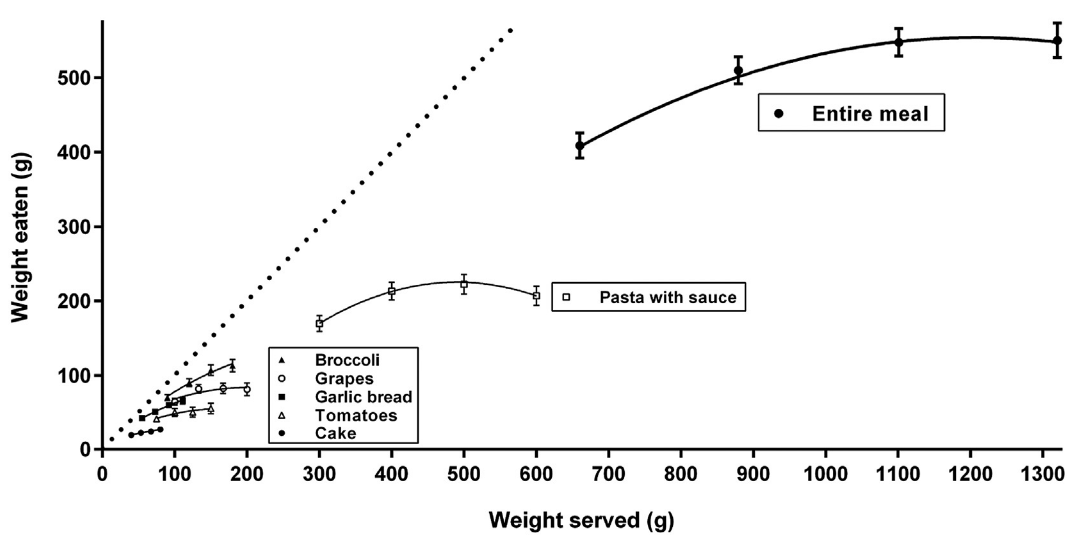

Fig. 2. Mean intakes by weight (±SEM) for individual foods and for the entire meal served to 48 women. The mean curves of food intake in response to increases in the portion served were modeled by a random coefficient analysis, in which individual trajectories were allowed to vary across subjects. The weight consumed of the entire meal and of each food was significantly influenced by the weight served ($p < 0.0001$). Intake curves for each food also differed significantly from each other ($p < 0.014$). The dotted line shows the potential maximum intake (consumption of the entire amount served).

increased. Together, disinhibition score and prospective consumption ratings explained a further 7% of total variability in the weight of food consumed at meals, beyond that explained by the weight served. Subject age, body mass index, restraint score, and estimated daily energy expenditure had no significant influence on meal intake in response to increased portion size.

Energy intake: The subject characteristics of disinhibition score ($p < 0.05$) and prospective consumption ratings ($p < 0.0001$) had a similar effect on the response curve for energy intake as they did for meal intake by weight. In addition, subjects' estimated energy expenditure had a positive effect on the linear coefficient of the trajectory and a negative effect on the quadratic coefficient (both $p < 0.03$). Subjects with higher energy needs had portion response curves with greater slope and less deceleration as portions were increased, whereas subjects with lower energy needs had response curves that were flatter across the portions served. Thus, the differences in the magnitude and trajectory of subjects' meal energy intakes was partially explained by differences in their energy requirements. Together, subject disinhibition scores, prospective consumption ratings, and estimated energy expenditure explained a further 15% of the variability in meal energy intake in addition to that explained by the weight served.

Energy density: There was no difference in mean ED across portion sizes, and none of the subject characteristics influenced this relationship. The mean ED of meals across all portion size conditions was 6.61 kJ/g (1.58 ± 0.02 kcal/g). Regardless of portion size, however, participants with higher body mass index (BMI) consumed meals with significantly higher meal ED (0.016 ± 0.007 ED units per BMI unit; $p = 0.039$). For example, participants below the median BMI (23 kg/m^2) had a meal ED of 6.23 kJ/g (1.49 kcal/g) and those above the median BMI had a meal ED of 6.99 kJ/g (1.67 kcal/g).

3.5. Subject rankings of properties of individual foods

Subject rankings of food qualities, which were completed at discharge, differed for the six foods in the meal. For the property of healthfulness, the rankings across all subjects varied according to food ED ($p < 0.0001$): tomatoes and broccoli were ranked higher in healthfulness than grapes, which were ranked higher than the three medium-ED foods. The three low-ED foods were chosen as the top three for healthfulness by 45 of the 46 subjects who completed the rankings. For the property of the amount of energy in each food, subject rankings were independently affected by both food ED and baseline portion size, and thus were also related to the energy served of each item (all $p < 0.0001$). The distribution of rankings of energy across all subjects was parallel to the relative energy content of the portions served: pasta > garlic bread > cake > grapes, broccoli > tomatoes. These rankings indicated that the subjects were aware of the health and nutritional properties of the foods served at the meal; this awareness, however, did not affect intake of the individual foods in response to larger portions (see next section).

Subject rankings of taste differed across the six foods served at the meal ($p = 0.0003$) but did not differ according to the ED of the foods ($p = 0.26$). Across all subjects, the foods ranked highest for taste were garlic bread, broccoli, and pasta, and those ranked lowest were tomatoes and angel food cake; grapes were ranked intermediate in taste. The rankings of relative taste had a significant effect on intake in response to the portion size of the foods (see next section). Subject ratings of food taste, which were made using visual analog scales at the start of each meal, showed similar results to the rankings made at discharge: the highest-rated food was garlic bread (79.9 ± 1.2 mm; $p < 0.004$) and the lowest-rated foods were cake (66.8 ± 1.9 mm) and tomatoes (62.9 ± 2.0 mm).

3.6. Influences on intake curves of individual foods

The combined analysis of the six foods in the meal found that for the individual items, as for the total meal, the magnitudes and trajectories of intake were significantly affected by the portions that were served ($p < 0.0001$). In addition, food intake curves in response to portion size were significantly influenced by characteristics related to both the foods and the subjects.

The intake response curves had significant differences across the individual foods ($p = 0.014$; Fig. 2). The linear coefficients of the intake response curves were greater for broccoli (mean 0.62) and pasta (mean 0.58) than for grapes (mean 0.30) and tomatoes (mean 0.28; all $p < 0.004$). In addition, the curves for pasta and grapes reached a point of maximal intake and then decreased as portions were further increased, in contrast to the continued increase in intake of the other foods. For example, the calculated maximal intake (vertex of the curve) for broccoli was 115 g at a portion size of 197 g, which was greater than the largest portion served. Increases in portion size and differences in response between foods explained a majority of the variation in the food weights consumed (Pseudo-$R^2 = 60\%$). For the outcome of energy intake, the linear coefficients of the curves also differed by food ($p < 0.0001$). The instantaneous slopes were greatest for garlic bread and least for broccoli, grapes, and tomatoes, reflecting the differences between the foods in both energy density and intake by weight. Thus, serving larger portion sizes led to increased intake of all foods, but the trajectories of intake in response to portion size differed across the foods.

Testing subject covariates in the model of the six foods showed that three characteristics had significant effects on the intake curves in response to portion size. First, subject rankings of food taste, which were completed at discharge, significantly affected intake of the foods as portion sizes were increased (Fig. 3; $p < 0.0001$). For the foods ranked higher in taste by each subject, both the linear coefficients (instantaneous slopes) and the intercepts (baseline intakes) of the curves were greater than for lower-ranked foods. Thus, both at baseline meals and as portions were increased, subjects consumed more of the foods that they ranked higher in taste than those they ranked lower. Including subject taste rankings in the model explained an additional 12% of the variability in consumption of individual foods as portions were increased.

Secondly, subject age significantly influenced the intake response curves for the foods ($p < 0.009$); the instantaneous slopes of the curves were larger for younger subjects than for older subjects. Finally, subject disinhibition scores also influenced the portion size response for individual foods as they did for total meal intake ($p < 0.023$). Including these two subject characteristics explained an additional 3% of the variability in individual food intakes beyond that explained by the taste rankings. Several other subject characteristics had effects on the amounts consumed at baseline, but did not affect the curvature of the portion size response, namely: rankings of food healthfulness, pre-meal ratings of prospective consumption and food taste (assessed by visual analog scales), the restraint score on the Eating Inventory, and the score on the Eating Attitudes Test.

4. Discussion

This study demonstrated that serving larger portions of all foods at a meal led to increased intake of the entire meal and of each food. The energy density of the foods did not influence the weight consumed, so that serving larger portions promoted intake of both low-ED and medium-ED items. Energy intake of the meal was substantially affected by food ED across all of the portions served.

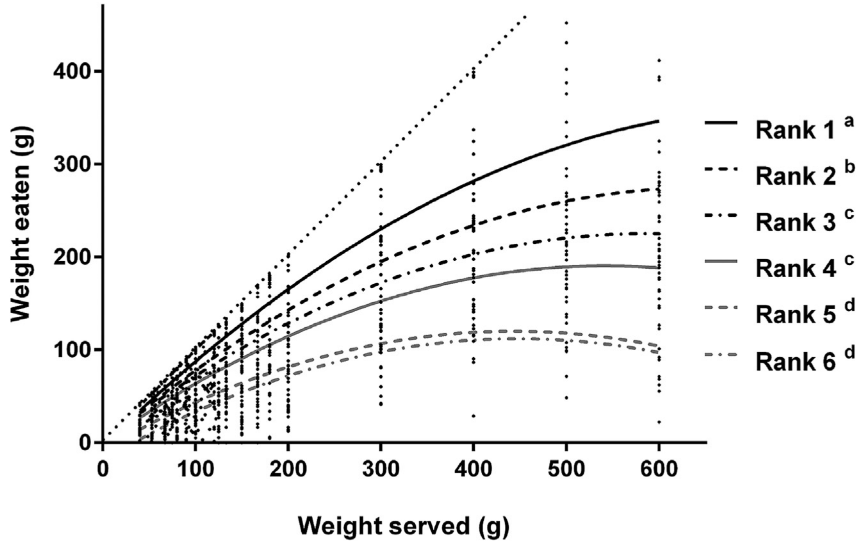

Fig. 3. Mean food intake curves for six foods according to their taste ranking at discharge, along with scatterplots of individual food intakes for 46 women. The mean curves of food intake in response to increases in the portion served were modeled by a random coefficient analysis, in which trajectories were allowed to vary across subjects. Subject rankings of food taste significantly affected intake of the foods as portion sizes were increased ($p < 0.0001$). Taste rankings with different superscripts differ significantly in the linear coefficient of the intake curve ($p < 0.03$). The curve for Rank 1 shows the mean intake of the food ranked as best-tasting, which differed across individuals. The dotted line shows the line of potential maximum intake (consumption of the entire amount served).

As portions got larger, subjects consumed an increasingly smaller proportion of the amount served; this response was characterized by a quadratic curve, and the strongest predictor of food intake was the portion size of the foods. Intake was also influenced by the ranking of taste of the foods; as portions increased, the best-liked foods at the meal showed the greatest increase in consumption. This study demonstrates the complexity of the PS effect. While the response to PS can vary between individuals, the effect depends primarily on the amounts of foods offered and their palatability compared to other available foods.

Effects on meal intake: Serving larger portions of all items led to increased food and energy intake at the meal; these findings are consistent with several previous controlled experiments in adults that increased the portion size of all foods at a meal or over several days (Kelly et al., 2009; Levitsky & Youn, 2004; Rolls et al., 2006a, 2006b, 2007). Despite substantial increases in intake, we found no differences in ratings of fullness after the meals, a result that has been previously noted (Herman, Polivy, Pliner, & Vartanian, 2015; Rolls et al., 2002). The present experiment is the first to systematically compare portion size effects across the various foods that were served. At a meal with multiple options, individuals have the opportunity to adjust their intake of foods varying in ED, either in response to food preferences or in order to moderate their energy intake when large portions are offered. The results, however, showed no evidence of such adjustment; as portions were increased, there were no differences in the proportions of low-ED and medium-ED foods that were consumed or in overall meal ED. Thus, although these subjects were aware of the health and nutritional properties of the foods, there was no indication that they responded to larger portions by adjusting their intake of low-ED and medium-ED foods in order to control their energy intake.

Effects on intake of individual foods: Including the individual foods together in the same statistical model explained substantially more of the variability than evaluating intake of the entire meal. Although the foods differed in ED and their role in the meal, serving larger portions led to increased intake of all items. This result is in contrast to two previous studies in adults, which reported that some meal components were not affected by increases in portion size. In a two-day study, serving larger portions increased intake of high-ED snacks and energy-containing beverages, but not the accompanying low-ED snacks and water (Rolls et al., 2006a). In an 11-day study, there was no effect of larger portions on intake of either low-ED vegetable side dishes at meals or of fruit served as a snack along with a higher-ED item (Rolls et al., 2007). The current study found portion size effects for all foods served at the meal, but the foods varied in their intake trajectories; consumption was influenced by rankings of food taste, which in these participants were not related to the ED of the available foods. When larger portions were served, the increase in intake was greater for the foods that subjects considered to taste better. Thus, in previous studies the disparities in PS effects between foods may be partly explained by lower palatability of low-ED items; when ED and palatability vary together, as is often the case (Drewnowski, 1998), their influence cannot be distinguished. The present results suggest that serving larger portions can increase intake of all foods in a meal, whether lower or higher in ED, but the effect is likely to be influenced by the availability and relative palatability of other foods at the meal.

Characterizing the PS response: This experiment revealed aspects of the PS response within individuals that have not been previously demonstrated, which were found by modeling trajectories of intake. Food intake across portion sizes was shown to approach a maximal value following a quadratic curve, and the change in the amount served was the main determinant of this response. This trajectory reflects a theoretical pattern of intake that combines the effects of increasing food availability with a diminishing propensity to consume. Other outcomes related to portion size have been described by curved relationships, notably intake across portion size experiments with different designs, foods, and populations (Zlatevska et al., 2014), and eating rates of individuals in response to compulsory portions (Almiron-Roig et al., 2015). The varying trajectory of the PS response has implications for research methods, particularly regarding the number of portions to be served. In experiments with the primary purpose of investigating PS effects on intake, it is recommended that more than three portions be tested in order to characterize the trajectory of the response.

The curvilinear nature of the intake response also has implications for choosing the sizes of portions to be tested in experiments. In this study, for example, the intake curve for the main dish was relatively flat across portion sizes; consumption reached a maximum and then decreased for the largest portion. The amounts of pasta served were apparently large for this population or in relation to the number of competing side dishes; the decline in intake with increasing portion size may be attributable to competition from accompanying foods or to sensory-specific satiety from the large amounts consumed (Rolls, Rolls, Rowe, & Sweeney, 1981). Moreover, if the experiment had included only the three largest portions of the main dish, the portion size effect would have appeared to be negligible for this food. In contrast, the broccoli portions fell on the steeper part of the response curve, and it appears that even larger portions could have been consumed by this population. Thus, the selection of amounts to serve in PS studies can have a substantial influence on the results, and researchers should be aware of this when comparing PS effects across foods, even within the same subjects.

In addition, the varying curvature of the PS effect hinders attempts to describe its magnitude and to compare results across different experiments and populations. In controlled studies of portion size, the magnitude of increased intake is often reported as a percentage of the baseline portion intake. This measure is convenient and allows comparison across experiments; it has consequently been used to summarize the PS effect, which has been reported to average about 30% across studies when portions are doubled (Livingstone & Pourshahidi, 2014; Steenhuis & Vermeer, 2009; Zlatevska et al., 2014). The apparent magnitude of the portion size response, however, is highly dependent on the portions that researchers choose to serve. For example in the current study, if only the two smallest portions of broccoli had been served, a 30-g increase in portion size would have led to a 28% increase in broccoli intake; in contrast, if only the two largest portions had been served, the effect of the same increase in serving weight would have been 6% and not significantly different from zero. Comparison of portion size effects on a percentage basis (whether across studies, foods, or populations) offers a convenient measure, but its limitations should be acknowledged.

Individual responsiveness to PS: This study found variation between individuals in their response to larger portions, in that serving the same series of portion sizes to all subjects resulted in different trajectories of intake. It is unclear, however, whether this finding should necessarily be regarded as evidence of a differential response to portion size. Analysis of energy intake of the entire meal showed that differences in the portion size effect were partly related to individual energy needs. Thus, apparent differences in responsiveness to larger portions may be due to variations between subjects in their intake trajectories, which in turn depend on energy requirements. For example, different portion size effects have been reported for women and men, as well as variable responses due to age and body size (Kelly et al., 2009; Steenhuis & Vermeer, 2009; Zlatevska et al., 2014). In contrast, in the two studies that served larger amounts of all foods but adjusted the portions for usual intakes, there was no difference in the magnitude of the response between women and men (Levitsky & Youn, 2004; Rolls et al., 2007). These findings suggest that if the experimental portions were adjusted to individual energy needs, the average portion size response would be similar for women and men; this might also be the case for subjects of different body size and age.

In the present study, the only individual characteristic that influenced the PS effect, after accounting for food taste and factors related to energy needs, was the disinhibition score. This score assesses responsiveness to stimulation to eat, whether external or internal, and has been repeatedly associated with increased energy intake and obesity (French, Epstein, Jeffery, Blundell, & Wardle, 2012). This concept is consistent with the finding that larger portions increased intake to a greater extent in individuals with higher disinhibition scores. Subject ratings of prospective consumption, an indication of hunger, also influenced the magnitude of intake but not the trajectory across portion sizes. These subject characteristics considered together, however, explained only a small amount of intake variability in the study population, compared to the effect of serving larger portions. In this experiment, only women were studied, and this may have limited the predictive ability of the subject characteristics. The rankings of food healthfulness and energy content showed that the subjects were knowledgeable about food, which may also have affected the results, although these factors were not found to influence the portion size effect. Differences in individual characteristics are likely to have some effect on the portion size response, but their magnitude may be modest compared to food-related characteristics such as the portions served and the relative liking for the foods.

Conclusion: The effect of portion size on intake depended primarily on the amounts of foods served at the meal and was greatest for the foods that were liked the best. The influence of subject characteristics on intake was modest compared to these food-related factors, and the portion size effect was robust across individuals. This finding suggests that interventions to moderate the effect of portion size on energy intake should focus primarily on changes in the composition of meals, for example, by moderating portions of higher-ED foods in order to reduce meal energy density.

Acknowledgments

The authors thank the study participants and staff of the Laboratory for the Study of Human Ingestive Behavior at The Pennsylvania State University. This work was supported by the National Institute of Diabetes and Digestive and Kidney Diseases (grant R01-DK059853) and is registered at clinicaltrials.gov (NCT02369588).

References

Almiron-Roig, E., Tsiountsioura, M., Lewis, H. B., Wu, J., Solis-Trapala, I., & Jebb, S. A. (2015). Large portion sizes increase bite size and eating rate in overweight women. *Physiology and Behavior, 139*, 297–302. http://dx.doi.org/10.1016/j.physbeh.2014.11.041.

Benton, D. (2015). Portion size: what we know and what we need to know. *Critical Reviews in Food Science and Nutrition, 55*, 988–1004. http://dx.doi.org/10.1080/10408398.2012.679980.

Brown, H., & Prescott, R. (2015). *Applied mixed models in medicine* (3rd ed.). Chichester, West Sussex: John Wiley and Sons.

Diliberti, N., Bordi, P. L., Conklin, M. T., Roe, L. S., & Rolls, B. J. (2004). Increased portion size leads to increased energy intake in a restaurant meal. *Obesity Research, 12*, 562–568.

Drewnowski, A. (1998). Energy density, palatability, and satiety: implications for weight control. *Nutrition Reviews, 56*, 347–353.

English, L., Lasschuijt, M., & Keller, K. L. (2015). Mechanisms of the portion size effect. What is known and where do we go from here? *Appetite, 88*, 39–49. http://dx.doi.org/10.1016/j.appet.2014.11.004.

Flood, J. E., Roe, L. S., & Rolls, B. J. (2006). The effect of increased beverage portion size on energy intake at a meal. *Journal of the American Dietetic Association, 106*, 1984–1990.

French, S. A., Epstein, L. H., Jeffery, R. W., Blundell, J. E., & Wardle, J. (2012). Eating behavior dimensions. Associations with energy intake and body weight. A review. *Appetite, 59*, 541–549. http://dx.doi.org/10.1016/j.appet.2012.07.001.

Garner, D. M., Olsted, M. P., Bohr, Y., & Garfinkel, P. E. (1982). The eating attitudes test. Psychometric features and clinical correlates. *Psychological Medicine, 12*, 871–878.

Herman, C. P., Polivy, J., Pliner, P., & Vartanian, L. R. (2015). Mechanisms underlying the portion-size effect. *Physiology and Behavior, 44*, 129–136. http://dx.doi.org/10.1016/j.physbeh.2015.03.025.

Hetherington, M., & Rolls, B. J. (1987). Methods of investigating human eating behavior. In F. M. Toates, & N. E. Rowland (Eds.), *Feeding and drinking* (pp. 77–109). Amsterdam: Elsevier.

Institute of Medicine, Food and Nutrition Board. (2002). *Dietary reference intakes for energy, carbohydrates, fiber, fat, fatty acids, cholesterol, protein, and amino acids*. Washington, DC: The National Academies Press.

Kelly, M. T., Wallace, J. M., Robson, P. J., Rennie, K. L., Welch, R. W., Hannon-Fletcher, M. P., et al. (2009). Increased portion size leads to a sustained increase in energy intake over 4 d in normal-weight and overweight men and women. *British Journal of Nutrition, 102*, 470–477. http://dx.doi.org/10.1017/S0007114508201960.
Kral, T. V. E., Roe, L. S., & Rolls, B. J. (2004). Combined effects of energy density and portion size on energy intake in women. *American Journal of Clinical Nutrition, 79*, 962–968.
Kral, T. V. E., & Rolls, B. J. (2011). Portion size and the obesity epidemic. In J. Cawley (Ed.), *The Oxford handbook of the social science of obesity – the causes and correlates of diet, physical activity, and obesity* (pp. 367–384). Oxford, England: Oxford University Press.
Ledikwe, J. H., Blanck, H. M., Khan, L. K., Serdula, M. K., Seymour, J. D., Tohill, B. C., et al. (2005). Dietary energy density determined by eight calculation methods in a nationally representative United States population. *Journal of Nutrition, 135*, 273–278.
Levitsky, D. A., & Youn, T. (2004). The more food young adults are served, the more they overeat. *Journal of Nutrition, 134*, 2546–2549.
Littell, R. C., Milliken, G. A., Stroup, W. W., Wolfinger, R. D., & Schabenberger, O. (2006). *SAS for mixed models* (2nd ed.). Cary, NC: SAS Institute Inc.
Littell, R. C., Stroup, W. W., & Freund, R. J. (2002). *SAS for linear models* (4th ed.). Cary, NC: SAS Institute Inc.
Livingstone, M. B., & Pourshahidi, L. K. (2014). Portion size and obesity. *Advances in Nutrition, 5*, 829–834. http://dx.doi.org/10.3945/an.114.007104.
Rolls, B. J. (2014). What is the role of portion control in weight management? *International Journal of Obesity, 38*, S1–S8. http://dx.doi.org/10.1038/ijo.2014.82.
Rolls, B. J., Morris, E. L., & Roe, L. S. (2002). Portion size of a food affects energy intake in normal-weight and overweight men and women. *American Journal of Clinical Nutrition, 76*, 1207–1213.
Rolls, B. J., Roe, L. S., Kral, T. V. E., Meengs, J. S., & Wall, D. E. (2004a). Increasing the portion size of a packaged snack increases energy intake in men and women. *Appetite, 42*, 63–69.
Rolls, B. J., Roe, L. S., & Meengs, J. S. (2006a). Larger portion sizes lead to sustained increase in energy intake over 2 days. *Journal of the American Dietetic Association, 106*, 543–549.
Rolls, B. J., Roe, L. S., & Meengs, J. S. (2006b). Reductions in portion size and energy density of foods are additive and lead to sustained decreases in energy intake. *American Journal of Clinical Nutrition, 83*, 11–17.
Rolls, B. J., Roe, L. S., & Meengs, J. S. (2007). The effect of large portion sizes on energy intake is sustained for 11 days. *Obesity, 15*, 1535–1543.
Rolls, B. J., Roe, L. S., & Meengs, J. S. (2010). Portion size can be used strategically to increase vegetable consumption in adults. *American Journal of Clinical Nutrition, 91*, 913–922.
Rolls, B. J., Roe, L. S., Meengs, J. S., & Wall, D. E. (2004b). Increasing the portion size of a sandwich increases energy intake. *Journal of the American Dietetic Association, 104*, 367–372.
Rolls, B. J., Rolls, E. T., Rowe, E. A., & Sweeney, K. (1981). Sensory specific satiety in man. *Physiology and Behavior, 27*, 137–142.
Singer, J. D., & Willett, J. B. (2003). *Applied longitudinal data analysis: Modelling change and event occurrence*. New York: Oxford University Press.
Steenhuis, I. H., & Vermeer, W. M. (2009). Portion size: review and framework for interventions. *International Journal of Behavioral Nutrition and Physical Activity, 6*, 58. http://dx.doi.org/10.1186/1479-5868-6-58.
Stunkard, A. J., & Messick, S. (1985). The three-factor eating questionnaire to measure dietary restraint, disinhibition, and hunger. *Journal of Psychosomatic Research, 29*, 71–83.
US Department of Agriculture. (May 2015). *Agricultural research service, nutrient data laboratory*. Version current. USDA National Nutrient Database for Standard Reference, release 27. Internet http://www.ars.usda.gov/ba/bhnrc/ndl (Accessed 10.07.15).
Zlatevska, N., Dubelaar, C., & Holden, S. S. (2014). Sizing up the effect of portion size on consumption: a meta-analytic review. *Journal of Marketing, 78*, 140–154. http://dx.doi.org/10.1509/jm.12.0303.
Zung, W. W. K. (1986). Zung self-rating depression scale and depression status inventory. In N. Sartorius, & T. A. Ban (Eds.), *Assessment of depression* (pp. 221–231). Berlin, Germany: Springer-Verlag.