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Appetite

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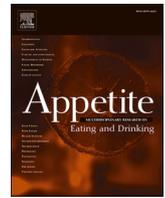
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Variety-seeking behavioral markers in an immersive virtual reality food buffet are associated with greater food and energy intake in laboratory meals

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ABSTRACT

Food variety promotes intake, and the propensity to seek a greater variety, measured by the number of unique foods selected for a meal, may predict increased food consumption. We explored whether variety-seeking in a validated immersive virtual reality (iVR) food buffet was related to measured intake in lab meals. Adults ($n = 91$; 18–71y; 64 female) were asked to select foods for a meal in an iVR buffet before consuming a standard lab meal once a week for 2 weeks. The iVR buffet contained 30 foods, 15 lower energy-dense (LED) and 15 higher energy-dense (HED), including entrees, sides, soups, and desserts. The lab meal consisted of 3 LED foods (broccoli, grapes, chicken) and 3 HED foods (pasta, rolls, cookies). Food selection in the iVR buffet was operationalized into 3 variety-seeking behavioral markers based on the unique foods selected: (1) total, (2) HED, and (3) LED. Seeking a greater total variety in iVR was a significant predictor of intake in lab meals, with each additional unique food selected in iVR relating to an additional 7.4 g of food consumed in lab meals ($p = 0.01$). These associations demonstrate specificity: (1) seeking a greater variety of HED foods in iVR was associated with increased intake of HED foods in lab meals, and (2) seeking a greater variety of LED foods in iVR was associated with increased intake of LED foods in lab meals. These preliminary findings indicate that variety-seeking behavioral markers measured in an iVR buffet are related to measured food intake.

1. Introduction

Greater food variety is associated with increased food and energy intake in both epidemiological and laboratory studies (Embling et al., 2021; Raynor & Vadielloo, 2018; Rolls et al., 1981). This ‘variety effect’ can be problematic if it leads to increased intake of higher energy-dense foods, which are abundant in our current eating environment (Raynor & Vadielloo, 2018; Rolls, 2009). This effect differs from variety-seeking behavior, which is a trait that describes an individual’s desire for a diverse range of foods, brands, categories, or products (Zhang, 2022). The measurement of food choice, indicated by the number of different

foods selected for consumption, has been considered a behavioral marker of variety-seeking (Nicklaus et al., 2005). However, conventional investigations of the variety effect serve predetermined meals in which participants do not have the opportunity to make food selections. This limits the ability to assess variety-seeking behavior, as the number and types of foods are dictated by the study design rather than individual choice. Buffet studies could address this but are challenging to conduct in controlled real-life settings (Blundell et al., 2010). Immersive virtual reality (iVR) can help overcome such challenges by providing a flexible and cost-effective tool for studying food selection behaviors in controlled settings (Long, Pritschet, et al., 2023; Martingano & Persky,

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2021). Therefore, the purpose of this study is to explore whether the variety of food selected for a meal in our iVR buffet, a behavioral marker of variety-seeking, is associated with increased food and energy consumption in laboratory meals.

The limited investigation of the relationships between variety-seeking behavior and intake can be partly attributed to the challenges of cost, feasibility, and labor associated with the measurement of food selection and consumption in controlled conditions. As a result, variety-seeking behavior is often assessed through questionnaires (Van Trijp & Steenkamp, 1992; Zhang, 2022). These behaviors are generally stable within individuals (Meiselman et al., 1998) but vary between individuals based on characteristics such as age and gender (Zhang, 2022). These individual differences in variety-seeking behavior have primarily emerged from the fields of consumer science and marketing, where the primary focus is often purchasing behavior (Zhang, 2022). Innovative methods are needed to determine whether similar patterns exist in the context of variety-seeking behaviors and food selection, as well as how these behaviors relate to measured food intake.

Advancements in technology, such as iVR, provide new approaches to understanding dietary behaviors in an array of contexts that would otherwise be difficult to measure under controlled conditions (Long, Masters, et al., 2023; Oliver & Hollis, 2021; Xu et al., 2021). Previous work has shown that food selection behaviors in iVR reflect those in the real-world and correlate to food intake in standardized laboratory meals (Cheah et al., 2020; Long, Pritschet, et al., 2023; Persky et al., 2018). The success of iVR in predicting real-world food selection and eating behaviors highlights the potential of utilizing this technology to develop measurable behavioral markers.

Energy density (kcal/gram) is a determinant of energy intake, with increased energy density leading to greater energy consumption (Rolls, 2009). The tendency of an individual to preferentially choose to eat a greater variety of either higher energy-dense or lower energy-dense foods could be a critical determinant of energy intake. For example, energy consumption was reduced at a varied meal when participants consumed a larger proportion of lower energy-dense foods rather than more higher energy-dense foods (Zuraikat et al., 2018). The effects of energy density on energy intake are observed within a meal and sustained across several days of eating (Bell & Rolls, 2001; Kral & Rolls, 2004; Rolls et al., 2006; Williams et al., 2013). Examining variety-seeking behaviors in the context of energy density selections provides unique insight into how these behaviors interact to influence consumption. For instance, greater variety-seeking for lower energy-dense foods could be associated with increased consumption of lower energy-dense foods. Understanding individual differences in variety-seeking will help identify behavioral markers that can leverage the positive effects of variety-seeking to improve diets.

Despite emerging evidence of the potential for variety-seeking behaviors to influence food selection and intake, the extent to which virtual variety-seeking behavioral markers can serve as reliable predictors of real-world consumption remains unclear. In addition, variety-seeking behavior has been shown to differ based on age and gender in other fields, but it remains unclear whether variety-seeking behavior in food selection differs based on demographic factors and eating behavior traits. Therefore, the purpose of this exploratory study is: (1) to determine whether the variety of foods selected in iVR is associated with increased laboratory food and energy consumption, (2) to explore whether the variety of higher energy-dense and lower energy-dense foods selected in iVR has differing associations with laboratory intake, and (3) to identify predictors of variety-seeking behaviors in an iVR buffet. We hypothesized that variety-seeking behavioral markers observed in our iVR buffet – measured as the number of unique total, higher energy-dense, and lower energy-dense food items selected – would be associated with food and energy consumption in laboratory meals. A greater understanding of these relationships will be instrumental in identifying markers of food selection behaviors that relate to real-world food and energy intake.

2. Methods

2.1. Experimental design

The data in this study were collected as part of an investigation into the effect of portion size on food selection in an iVR food buffet and whether this effect was similar when portion size was manipulated at laboratory meals (Long, Pritschet, et al., 2023). The original study utilized a within-subjects pseudo-randomized crossover design. Participants completed two laboratory visits one week apart but at the same time and day. Visits were scheduled between 11:00am to 2:00pm or 4:00 to 7:00pm. Prior to beginning the study, all participants provided informed consent and then completed a demographics questionnaire.

At each visit, participants first completed a food selection task within an iVR food buffet and subsequently consumed a standardized laboratory meal. Both the virtual buffet and meal varied in portion size (standard vs. large), and the portion size condition assigned to each visit was randomly determined prior to beginning the study. The portion size conditions pertained to the amount of food that would be visually presented as the default portion when selecting a food during the iVR food selection task (standard or large) and the portions of foods that were provided at the standardized laboratory meal (standard or large), as shown in Fig. 1. Participants completed their laboratory visits individually to avoid the potential influence of social facilitation on their behavior. The primary difference between the visits was that participants completed questionnaires at the end of their first visit, while they evaluated an iVR nutrition education program at the end of their second visit.

All participants received financial compensation for their time (\$10/visit). Study data were collected and managed using REDCap electronic data capture tools hosted at Pennsylvania State University (Harris et al., 2009, 2019). All study procedures were approved by The Pennsylvania State University Institutional Review Board (STUDY00017463).

2.2. Participant recruitment and screening

The data were collected between September 2021 and August 2022 at The Pennsylvania State University. Recruitment of adult participants was conducted through advertisements placed at The Pennsylvania State University's campus, local businesses, and on a university research website. Inclusion criteria were the following: over the age of 18, fluent in English, free of food allergies, open to eating all food items, and without prior diagnosis of cognitive or physical disabilities, dyslexia, or epilepsy. Once enrolled in the study, participants completed a demographics questionnaire and were informed that the research aimed to examine food choices in both iVR and the laboratory, without any indication that portion size would be manipulated. Participants who reported wearing glasses were asked to use contact lenses or remove their glasses if their vision was adequate for iVR.

The sample size for the primary investigation was based on providing sufficient power to detect the effect of portion size on food selection in iVR and food intake in laboratory meals (Long, Pritschet, et al., 2023). For the present secondary analysis, no formal power calculation was conducted. Overall, 101 adults were enrolled in the study but 10 were excluded from the final analysis due to violation of protocol ($n = 1$), dropout between sessions ($n = 3$), and equipment errors ($n = 6$).

2.3. Procedures

Participants visited the laboratory once a week for two weeks. At the start of the first visit only, the height (cm) and weight (kg) of the participants were measured twice by a trained research assistant using a stadiometer and digital scale (Seca North America, Chino, CA, USA). Participants were asked to remove heavy items of clothing (e.g., jackets) and footwear prior to all measurements. Participants completed a survey to assess hunger, thirst, prospective consumption, nausea, and fullness

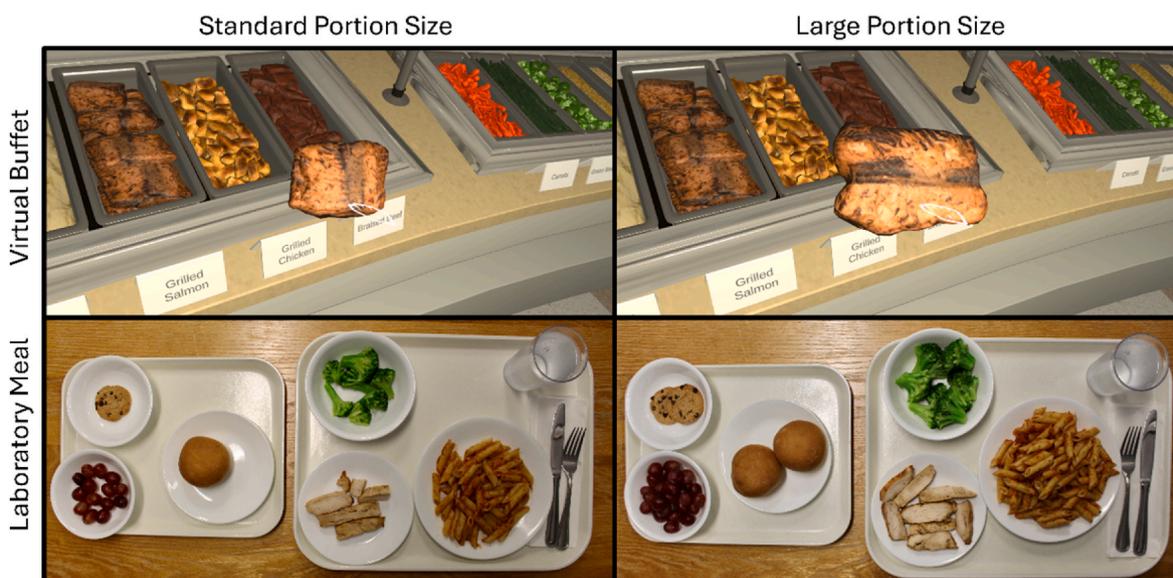


Fig. 1. The top row illustrates an iVR buffet food item (salmon) in the standard and large portion size conditions. The portion sizes in the iVR buffet only pertained to the default amount of food displayed upon selecting the food and did not affect the overall quantity of food that participants were able to select. Participants could adjust the portion sizes using their iVR remote. The bottom row contains all foods served at the standardized laboratory meals in both portion size conditions.

using a 100-mm visual analogue scale (VAS) before and after the iVR food selection task (Supplementary Fig. 1). After these initial ratings, participants were served their laboratory meal and instructed to eat as much or as little as they liked, take as much time as desired, and to notify the researcher once they were finished eating. After the meal, participants completed the post-meal VAS-ratings. At the end of visit 1, participants completed the following questionnaires: External Food Cue Responsiveness (Masterson et al., 2019), Three Factor Eating R-18 (De Lauzon et al., 2004), Adult Eating Behavior (Hunot et al., 2016), Reasons Individuals Stop Eating (Cunningham et al., 2021), and Global Physical Activity (Armstrong & Bull, 2006). At the end of visit 2, participants completed and evaluated an iVR nutrition education program (Edwards et al., 2022; Sajjadi et al., 2022).

2.4. Measures

2.4.1. Immersive virtual reality buffet food selection task

Prior to completing the iVR food selection task, participants received training on how to use the iVR equipment (e.g., controllers) and interact within the virtual environment. Participants then engaged in a tutorial program that was designed to familiarize them with the virtual buffet environment. They were provided with instructions on how to interact with food items and adjust the portion sizes.

Following the tutorial, participants completed the iVR food selection task. They were instructed to build a meal that they would typically eat for either lunch or dinner, depending on the time of their visit, and were told that they could use as many plates and bowls as desired. The task was designed to replicate a real-world buffet experience. The buffet menu consisted of a variety of main dishes, side dishes, desserts, and drinks with a total of 30 unique food items. All food items were presented in bins or on plates and were labeled with their names to aid in recognition.

The volume and portion sizes of all food items were uniformly presented throughout the buffet across both portion size conditions. The key distinction between the portion size conditions was the default portion of food that was visually presented upon selecting a food item with the iVR remote (Fig. 1). The portion size of food items defaulted to the middle portion (4 of 8) in the standard condition and to the maximum portion (8 of 8) in the large condition. Participants could adjust the portion of food at any time using their iVR remote. Once the

participant was finished building their meal, they placed their food near the register of the buffet and rang a bell to signal the completion of their selections. Upon ringing the bell, the buffet software recorded the selected weight of each chosen food. Additional details on the task design, setup, and implementation can be found in the Supplementary Materials.

2.4.2. Operationalization of variety-seeking behavioral markers

The trait of variety-seeking describes an individual's desire for variety (Van Trijp & Steenkamp, 1992). The measurement of food choice, indicated by the number of different foods selected for consumption, has been considered a behavioral marker of variety-seeking (Nicklaus et al., 2005). Therefore, we considered the variety of foods selected in the iVR buffet as a behavioral marker of variety-seeking and a potential predictor of food consumption. We operationalized variety-seeking behavior as the number of unique food items that a participant selected to build their meal in the iVR buffet. The 'Total Variety Selected' was calculated as the overall count of unique foods selected, irrespective of the amount of each food. For example, a meal composed of chicken, broccoli, and one cookie would yield the same Total Variety Selected as a meal composed of chicken, broccoli, and three cookies, since both meals consisted of three distinct food items.

Furthermore, to explore whether the energy density of foods selected differentially affected the associations between variety-seeking and intake, the Total Variety Selected was further delineated by categorizing all food items into higher energy-dense and lower energy-dense groups. All foods ($n = 15$) with an energy density above the median of 1.50 kcal/g were categorized as higher energy-dense, and all foods ($n = 15$) with an energy density below the median were categorized as lower energy-dense. The 'Higher Energy-Dense Variety Selected' was calculated as the count of unique higher energy-dense food items (>1.50 kcal/g) that a participant selected to build their meal. The 'Lower Energy-Dense Variety Selected' was calculated as the count of unique lower energy-dense food items (<1.50 kcal/g) that a participant selected to build their meal. This categorization is consistent with our previously published iVR buffet work and similar to other studies (Cheah et al., 2020; Drewnowski, 1998). A comparative illustration of lower variety-seeking behavior and higher variety-seeking behavior is shown in Fig. 2.

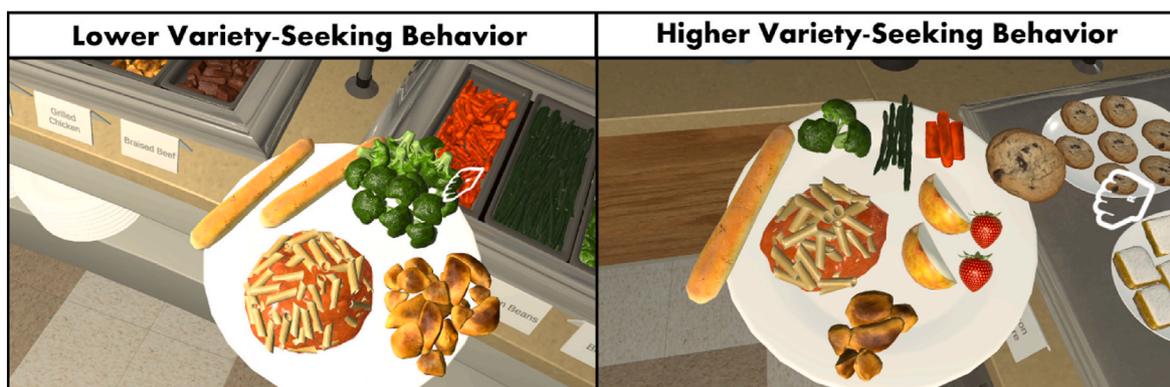


Fig. 2. Comparative illustration of lower variety-seeking behavior and higher variety-seeking behavior based on the number of unique food items selected in an iVR buffet meal.

2.4.3. Food intake

Following the iVR buffet selection task, participants were seated at individual booths in the laboratory and served a standardized meal. The meal consisted of a pasta dish, grilled chicken strips, rolls, broccoli, grapes, and cookie(s) with water as a beverage (Fig. 1). The food items and portion sizes were selected based on a previous study investigating the effect of portion size on food intake (Zuraikat et al., 2018). The standard portion of the meal was 515 g (747 kcal) and the large portion of the meal was 917 g (1361 kcal). All meals were served with a fixed amount of 300 g of water, but participants were allowed additional water upon request. All food items were ranked by their energy density and the top three food items were categorized as higher energy-dense food items (all >1.50 kcal/g) and the bottom three were categorized as lower energy-dense food items (all <1.50 kcal/g). This categorized broccoli, grapes, and grilled chicken as lower energy-dense food items and the pasta dish, rolls, and cookie(s) as higher energy-dense food items. The specific energy density, macronutrient distribution, weight, and kcal for each food item in both portion size conditions can be found in Supplementary Table 1. Participants were instructed to eat as much or as little as they liked, take as much time as they needed, and to notify the researcher when they were done eating. Intake was measured by weighing the food and water before and after the meal to the nearest ± 0.1 g on a digital scale (Mettler-Toledo XS6001S; Mettler-Toledo, Columbus, OH, USA).

2.5. Data analysis

The sample demographic characteristics were assessed via descriptive statistics such as means, medians, standard deviations, and percentages. Intraclass correlation coefficients were calculated to assess the consistency of the variety-seeking behavioral markers (Total Variety Selected, Higher Energy-Dense Variety Selected, and Lower Energy-Dense Variety Selected) across portion size conditions in the iVR buffet. The intraclass correlation coefficients and their 95 % confidence intervals were calculated based on a single measurement, consistency, two-way mixed-effects model (ICC[3,1]).

Linear mixed-effects models were used to address the three main research objectives: (1) to determine whether the variety of foods selected, a behavioral marker of variety-seeking, is associated with increased real-world food and energy consumption, (2) to explore whether the energy density of the selected foods affects this relationship, and (3) to identify predictors of variety-seeking behaviors in an iVR buffet. Normality model assumptions were confirmed using Q-Q plots of the residuals for all models.

For the first and second objectives, our focus was examining the association between the variety-seeking behavioral markers and measured intake in laboratory meals. This was accomplished through two distinct sets of linear mixed-effects models. The first set of models

included Total Variety Selected as a predictor and examined its association with overall gram intake, higher energy-dense gram intake, and lower energy-dense gram intake in the laboratory meals. The second set of models included both the Higher Energy-Dense Variety Selected and Lower Energy-Dense Variety Selected as predictors and assessed their association with overall gram intake, higher energy-dense gram intake, and lower energy-dense gram intake in laboratory meals. These two sets of models were utilized separately to avoid issues of multicollinearity as the sum of Higher Energy-Dense Variety Selected and Lower Energy-Dense Variety Selected equates to the Total Variety Selected. All models controlled for participant sex, portion size, and visit week as covariates. A random intercept was included for participants to account for the inherent variability between individuals and the correlation of repeated measures within individuals. Models with overall kcal intake, higher energy-dense kcal intake, and lower energy-dense kcal intake as the outcomes showed similar findings and are detailed in Supplementary Table 2 and Supplementary Figs. 2 and 3.

For the third objective, our focus was identifying predictors of variety-seeking behaviors in the iVR buffet. Separate linear random intercept models, grouped by participant, were employed for each variety-seeking behavioral marker (Total Variety Selected, Higher Energy-Dense Variety Selected, and Lower Energy-Dense Variety Selected) as the primary outcome. The fixed effects in the models included participant demographics (age, sex, race, income, and education), experimental variables (portion size and visit week), and subscales of questionnaires (TFEQ-R18, AEBQ, RISE-Q). Variance inflation factors showed low multicollinearity (<5.00), except for the subscales of emotional eating and emotional overeating, which exceeded this threshold (Cohen et al., 2013). Emotional overeating had the highest variance inflation factor in all models (>5.00) and was highly correlated with emotional eating ($r = 0.88$). Therefore, emotional overeating was removed from all models. After removing emotional overeating from the models, all remaining variables showed variance inflation factors under 5.00, indicating that multicollinearity was not an issue in our final models. Cognitive restraint was a strong predictor of all variety-seeking behaviors, and sex differences were also observed in variety-seeking behaviors. To further explore this pattern, a *t*-test was conducted to assess potential sex differences in cognitive restraint, as this could help contextualize the observed sex differences in variety-seeking behaviors.

We also analyzed the associations between variety-seeking markers and laboratory meal intake excluding participants who consumed nearly all of their laboratory meal (<20.00 g uneaten) as a sensitivity analysis intended to assess the influence of “plate cleaners” and to ensure the associations were not driven by ceiling effects. We also assessed the effect of participant characteristics and pre-meal ratings on model outcomes by controlling for age, BMI, race, education, income, hunger, thirst, prospective consumption, nausea, and fullness; none changed the general magnitude or general pattern of significance. Lastly, we

examined the number of unique foods participants tried in the laboratory meal, defining a food as ‘tried’ if at least 2 g was consumed. This analysis was conducted to ensure that meal intake was not overly restricted to a small subset of food items.

All data analyses were conducted using R (version 4.3.2) (RStudio: Integrated Development Environment for R., 2023). The data and code used to analyze and visualize the data are available via Open Science Framework at <https://osf.io/7nstp/>. Our hypothesis that the Total Variety Selected would be associated with laboratory intake was specified prior to data analyses. However, we conducted post-hoc analyses to determine whether this association was driven by the energy density categorization of food items selected. Statistical significance was defined as $\alpha < 0.05$ for all models.

3. Results

3.1. Participant characteristics

Ninety-one adults (64 females), between the ages of 18–71 ($M = 29$, $SD = 14$) completed both visits of the study. The mean BMI of the sample was 25.3 ($SD = 5.7$) with 22 participants (24 %) with overweight and 17 participants (18 %) with obesity. The race of the sample was predominately White (56 %), followed by Asian (31 %), and Mixed or Other (13 %). The specific characteristics of the sample are reported in Table 1.

3.2. Descriptives of variety-seeking behavioral markers

The average and median number of total unique food items selected per iVR meal was 9 ($SD = 3$), comprising an average of 4 higher energy-dense ($SD = 2$) and 5 lower energy-dense ($SD = 2$) items. Fig. 3 presents histograms that visualize the distribution of these variety-seeking behavioral markers.

3.3. Reliability of variety-seeking behavioral markers

The ICCs were calculated to assess the consistency of Total Variety Selected, Higher Energy-Dense Variety Selected, and Lower Energy-Dense Variety Selected in the iVR buffet across portion size conditions. The ICC for Total Variety Selected was 0.77 (95 % CI: 0.67 to 0.84, $p < 0.0001$), for Higher Energy-Dense Variety Selected was 0.68 (95 % CI: 0.55 to 0.78, $p < 0.0001$), and for the Lower Energy-Dense Variety Selected was 0.75 (95 % CI: 0.64 to 0.83, $p < 0.0001$). These results indicate a moderate-to-good level of consistency in participants’ selection behaviors according to the criteria specified in (Koo & Li, 2016). Thus, these variety-seeking behavioral markers were stable within participants and across portion size conditions.

3.4. Food intake in the laboratory meals (grams)

Table 2 reports the mean overall food intake, higher energy-dense food intake, and lower energy-dense food intake. The summary outputs of the linear mixed-effect models predicting overall food intake, higher energy-dense food intake, and lower energy-dense food intake in the laboratory meals are reported in Table 3 and the data are visualized in Figs. 4 and 5. In brief, there was a statistically significant association between Total Variety Selected and Higher Energy-Dense Variety Selected with overall food intake in the laboratory meals, controlling for portion size, sex, and the visit number. Additionally, the associations highlighted specificity in relation to the energy density of food items consumed in the laboratory meals; Higher Energy-Dense Variety Selected was associated with intake of higher energy-dense food items and Lower Energy-Dense Variety Selected was associated with intake of lower energy-dense food items.

Table 1
Participant characteristics.

	Total (n = 91)		
	Mean	SD	Range
Age (year)	29	14	18–71
Height (cm)	167.2	9.1	148.8–192.0
Weight (kg)	71.2	17.5	43.8–130.3
Body Mass Index (kg/m ²)	25.3	5.7	17.8–50.9
Three Factor Eating Questionnaire R-18			
Cognitive Restraint	42.43	19.25	0.00–83.33
Uncontrolled Eating	39.03	16.96	0.00–88.89
Emotional Eating	40.66	31.48	0.00–100.00
Adult Eating Behavior Questionnaire			
Enjoyment of Food	4.38	0.65	2.00–5.00
Emotional Overeating	2.64	1.00	1.00–4.80
Emotional Undereating	3.04	0.94	1.00–5.00
Food Fussiness	1.92	0.84	1.00–5.00
Slowness in Eating	2.74	1.10	1.00–5.00
Hunger	3.11	0.79	1.00–4.80
Satiety Responsiveness	2.73	0.78	1.25–4.75
Food Responsiveness	3.23	0.74	1.50–5.00
Reasons Individuals Stop Eating Questionnaire			
Decreased Food Appeal	2.84	1.13	1.11–6.78
Physical Satisfaction	5.29	0.86	3.14–7.00
Planned Amount	4.52	1.14	1.67–7.00
Self-Consciousness	2.52	1.27	1.00–6.60
Decreased Priority of Eating	2.87	1.24	1.00–6.50
	Total (n)		
Sex			
Female	64		
Male	27		
Race/Ethnicity			
White or Caucasian	51		
All other races	40		
Education			
No Degree	46		
Degree	45		
Income			
<20k	50		
>20k	41		
Previously Used iVR			
Yes	57		
No	34		

The Three-Factor Eating Questionnaire R-18 measures cognitive restraint, uncontrolled eating, and emotional eating. The subscales are calculated as the mean of item responses that range from 1 to 4 and are reported as adjusted scores.

The Adult Eating Behavior Questionnaire measures food approach and food avoidance traits. The subscales are calculated as the mean of item responses that range from 1 to 5.

The Reasons Individuals Stop Eating Questionnaire measures reasons for meal termination. The subscales are calculated as the mean of item responses that range from 1 to 7.

3.4.1. Overall food intake: Associations Between the Variety-Seeking Behavioral Markers and Intake in the laboratory meals

The average overall food intake was 467.8 g ($SD = 161.3$). Total Variety Selected was a statistically significant predictor of food intake ($p = 0.01$) in the laboratory meals. Each additional unique food item selected in iVR was associated with an additional 7.4 g ($SE = 3.1$) consumed in the laboratory meals. Similarly, the Higher Energy-Dense Variety Selected was a statistically significant predictor of food intake ($p = 0.01$) in the laboratory meals. Each additional unique Higher Energy-Dense food item selected in iVR was associated with an additional 12.0 g ($SE = 5.1$) consumed in the laboratory meals. Lower Energy-Dense Variety Selected was not a statistically significant predictor of food intake in the laboratory meals ($p = 0.45$).

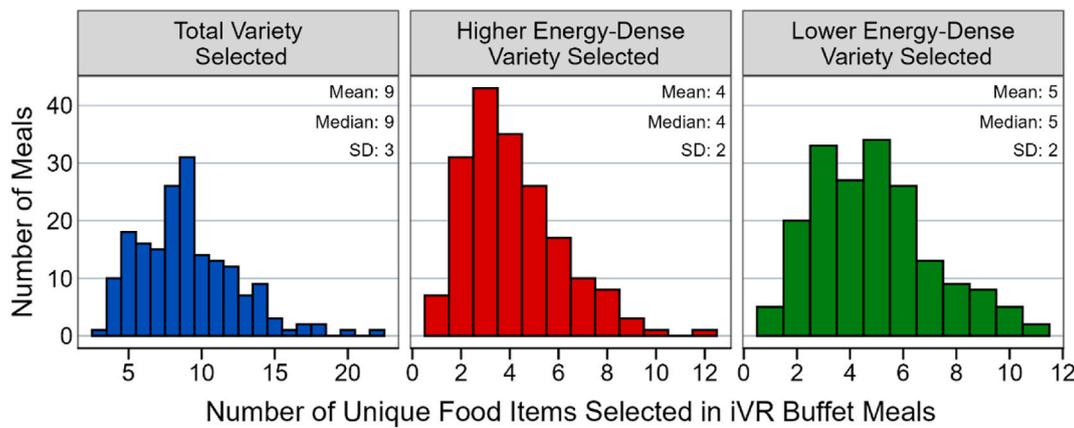


Fig. 3. Distributions of the unique total, higher energy-dense, and lower energy-dense food items selected in an iVR buffet meal. The average and median values are indicated within each panel.

Table 2

The mean overall intake of higher energy-dense and lower energy-dense foods in the laboratory meal.

	Overall Intake	Higher Energy-Dense Intake	Lower Energy-Dense Intake
Food Intake (g)	467.8 ± 161.3	233.2 ± 112.1	234.6 ± 85.8
Energy Intake (kcal)	659.6 ± 260.2	479.8 ± 226.7	179.8 ± 72.4

Data are presented as mean ± SD. There were 3 higher energy-dense food items (all >1.50 kcal/g) and 3 lower energy-dense food items (all <1.50 kcal/g).

3.4.2. Higher energy-dense food intake

Associations Between the Variety-Seeking Behavioral Markers and Intake of the Higher Energy-Dense Food Items in the Laboratory Meals.

The average overall higher energy-dense food intake was 233.2 g (SD = 112.1). The Higher Energy-Dense Variety Selected was a statistically significant predictor of higher energy-dense food intake ($p = 0.007$) in the laboratory meals. Each additional unique higher energy-dense food item selected in iVR was associated with an additional 10.6 g ($SE = 3.9$) of higher energy-dense food consumed in the laboratory meals. In contrast, neither Total Variety Selected ($p = 0.10$), nor Lower Energy-Dense Variety Selected ($p = 0.58$) predicted intake of the higher energy dense foods in the laboratory meals.

3.4.3. Lower energy-dense food intake

Associations Between the Variety-Seeking Behavioral Markers and Intake of the Lower Energy-Dense Food Items in the Laboratory Meals.

The average overall lower energy-dense food intake was 234.6 g (SD = 85.8). Lower Energy-Dense Variety Selected was a statistically significant predictor of lower energy-dense food intake ($p = 0.02$) in the laboratory meals. Each additional unique lower energy-dense food item selected in iVR was associated with an additional 5.8 g ($SE = 2.6$) of lower energy-dense food consumed in the laboratory meals. Similarly, Total Variety Selected was a statistically significant predictor of lower energy-dense food intake ($p = 0.02$) in the laboratory meals. Each additional unique food item selected in iVR was associated with an additional 3.8 g ($SE = 1.7$) of lower energy-dense food consumed in the laboratory meals. In contrast, Higher Energy-Dense Variety Selected did not predict intake of the lower energy-dense foods ($p = 0.61$) in the laboratory meals.

3.5. Sensitivity analysis

All participants (100 %) tried at least three foods, 98.35 % tried at least four foods, 84.62 % tried at least five foods, and 58.79 % tried all six foods. The average number of foods tried was 5.42 (SD = 0.79), suggesting that meal intake was not overly restricted to a small subset of food items in the laboratory meal.

3.6. Predictors of variety-seeking behavioral markers in iVR

The summary outputs of the linear mixed-effect models predicting the variety-seeking behavior markers in iVR are depicted in Fig. 6. All variables were standardized to illustrate the effect sizes on a uniform scale. The results reported in the text of this section use standardized predictors for continuous variables such as cognitive restraint and non-standardized predictors for binary variables such as sex, where changes in standard deviation are not applicable. Detailed summary outputs from all variables in the models are reported in Supplementary Figs. 4, 5, and 6.

Cognitive restraint was the strongest predictor associated with all variety-seeking behavioral markers. Participants chose an additional 1.2 unique food items, comprised of 0.6 unique higher energy-dense and 0.6 unique lower energy-dense, for each standard deviation decrease in cognitive restraint ($p < 0.01$ for all). Additionally, there were sex differences in the behavioral markers, with females exhibiting lower variety-seeking behavior. Male participants selected an additional 2.0 unique food items ($p = 0.008$), comprised of 0.8 unique higher energy-dense items ($p = 0.057$) and 1.2 unique lower energy-dense items ($p = 0.03$), compared to female participants. However, there were no significant sex differences in cognitive restraint ($p = 0.38$), suggesting that the observed sex differences in variety-seeking behaviors were not driven by differences in cognitive restraint. Other participant demographics and specific questionnaire subscales were significantly associated with various variety-seeking behavioral markers. For detailed findings, please refer to Fig. 6 and the supplementary material.

4. Discussion

Our study presents novel findings that variety-seeking behaviors observed in our iVR food buffet are related to measured intake in standardized laboratory meals. Seeking an overall greater variety of food items in iVR was related to increased intake, with a notably stronger effect for seeking a variety of higher energy-dense food items. These associations demonstrated specificity in the relation to the energy density of food items consumed in the laboratory meals as: (1) seeking a greater variety of higher energy-dense food items in iVR was associated

Table 3
Linear mixed-effect models for the associations between variety-seeking behavioral markers in the iVR buffet and measured intake in the laboratory meals.

Predictors	Overall Gram Intake				Higher Energy-Dense Gram Intake				Lower Energy-Dense Gram Intake						
	β	SE	95 % CI	p-value	R ²	β	SE	95 % CI	p-value	R ²	β	SE	95 % CI	p-value	R ²
Intercept	414.4	37.9	339.4–489.4	0.016	0.40 0.75	218.3	29.8	159.5–277.2	0.102	0.23 0.73	193.6	21.1	151.8–235.4	0.028	0.34 0.72
Total Variety Selected	7.4	3.1	1.4–13.5	<0.001		3.9	2.4	-0.8–8.6	<0.001		3.8	1.7	0.4–7.1	<0.001	
Large Portion Size	156.0	12.1	131.9–180.1	<0.001		70.2	8.8	52.8–87.7	<0.001		85.9	6.8	72.4–99.3	<0.001	
Female Participant	-133.8	25.8	-185.0–-82.6	<0.001		-84.2	20.8	-125.6–-42.8	<0.001		-49.3	14.4	-77.9–-20.8	<0.001	
Second Visit	5.2	12.1	-18.8–29.3	0.666		7.7	8.8	-9.7–25.1	0.381		-2.4	6.7	-15.8–11.0	0.719	
Intercept	412.7	38.0	337.6–487.7	0.019	0.41 0.75	216.5	29.4	158.5–274.6	0.007	0.25 0.73	194.3	21.1	152.6–236.0	0.034	0.34 0.72
Higher Energy-Dense Variety Selected	12.0	5.1	2.0–22.1	0.459		10.6	3.9	2.9–18.2	0.580		1.4	2.8	-4.2–7.1	0.611	
Lower Energy-Dense Variety Selected	3.5	4.7	-5.7–12.7	<0.001		-2.0	3.6	-9.0–5.1	<0.001		5.8	2.6	0.7–10.9	0.026	
Large Portion Size	157.7	12.2	133.4–182.0	<0.001		72.7	8.8	55.1–90.2	<0.001		85.0	6.9	71.4–98.6	<0.001	
Female Participant	-131.2	25.9	-182.6–-79.8	<0.001		-80.5	20.5	-121.4–-39.7	<0.001		-50.6	14.3	-79.1–-22.2	<0.001	
Second Visit	3.8	12.1	-20.3–28.0	0.754		5.6	8.8	-11.8–23.0	0.524		-1.7	6.8	-15.2–11.8	0.804	

R² is reported as Marginal R² | Conditional R², where Marginal R² represents the variance explained by the fixed effects and the Conditional R² represents the variance explained by both fixed and random effects. The intercept represents the prediction for a standard portion size laboratory meal presented to a male participant at the first visit. Each outcome was analyzed using two separate linear mixed-effects models: one with Total Variety Selected as the predictor, and another with both Higher Energy-Dense Variety Selected and Lower Energy-Dense Variety Selected as predictors. The two sets of models were utilized separately to avoid issues of multicollinearity as the sum of Higher Energy-Dense Variety Selected and Lower Energy-Dense Variety Selected equates to the Total Variety Selected. All models controlled for portion size, participant sex, and visit number.

with increased intake of higher energy-dense food items, and (2) seeking a greater variety of lower energy-dense food items in iVR was associated with increased intake of lower energy-dense food items. Additionally, the consistency of variety-seeking behaviors across portion size conditions suggests that these are stable behavioral markers within the context of this laboratory study. These findings highlight the utility of behavioral data captured in iVR as predictors of real-world food and energy intake.

A possible application for variety-seeking behavioral data captured in our food selection task is to use iVR as a screening tool to characterize an individual's intake in response to a variety of energy-dense foods. We found that Higher Energy-Dense Variety Selected in iVR was the strongest predictor of overall intake and intake of higher energy-dense foods in the laboratory. This is consistent with the well-established relationship between the intake of higher energy-dense foods and greater energy intake (Rolls, 2017). In contrast, seeking a greater variety of lower energy-dense foods was associated with greater intake of lower energy-dense foods in laboratory meals but was not associated with overall intake nor intake of higher energy-dense foods. These positive outcomes align with the goal of encouraging the selection and intake of lower energy-dense foods, such as fruits and vegetables, which are associated with reduced energy intake (Rolls, 2017; Wallace et al., 2020). Together, these findings strengthen the support for using iVR as a screening tool to identify an individual's propensity for over-consumption and facilitate targeted interventions to promote healthier eating behaviors.

In addition to the associations between variety-seeking behaviors in iVR and intake in the laboratory meals, we also found sex differences in variety-seeking behaviors, independent of cognitive restraint. Compared to female participants, male participants exhibited greater overall variety-seeking and lower energy-dense variety-seeking, selecting an average of 2 additional unique food items and 1.2 more unique lower energy-dense food items. These findings suggest that female participants may exhibit greater dietary restraint in the context of food selections, potentially due to stronger societal pressure for weight management, leading to their reduced selection of foods. While we expected these differences to be driven by cognitive restraint, males and females did not significantly differ in their ratings of cognitive restraint, measured by the Three Factor Eating Questionnaire R-18, in our sample. These observed sex differences may also be influenced by our sample, which was skewed toward female participants (70 %). Future research is needed to confirm these findings. Sex differences in variety-seeking behavior have also been found in other fields, where the primary focus is often on purchasing behavior rather than food selection (Chen et al., 2016; Zhang, 2022). Our findings are consistent with this, showing that males tend to seek a greater variety compared to females in the context of this laboratory meal. These results highlight the importance of sex differences in dietary behaviors and warrant further exploration of the factors contributing to these differences.

The number of unique foods selected by participants was consistent across different portion size conditions. The observed consistency of variety-seeking behaviors across portion size conditions suggests that these behaviors are relatively stable within individuals, reinforcing their potential as reliable behavioral markers of food selection and intake. Participants selected a mean of nine food items, with roughly half being higher energy-dense foods and the other half being lower energy-dense foods for their meal. Although these numbers are derived from our novel iVR food selection task and not from conventional 24-h dietary recalls, they are consistent with other findings reported in the literature (Drewnowski et al., 1997; Raynor et al., 2012; Vadiveloo et al., 2018). For example, an 18-month weight loss trial found that participants reported consuming, on average, nearly half of their foods as higher energy-dense and the other half as lower energy-dense per day throughout the trial (Vadiveloo et al., 2018). Other epidemiological work found an average of 16 total foods consumed per day (Vadiveloo et al., 2016). This discrepancy in the number of foods may be attributed

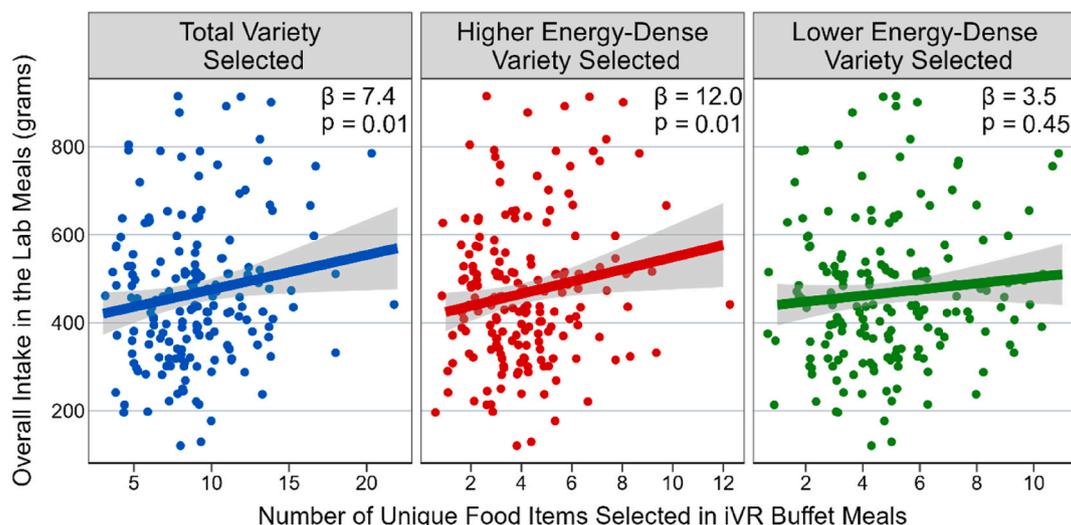


Fig. 4. Variety-Seeking Behavioral Markers are Associated with Measured Intake in Laboratory Meals. Each panel illustrates the association between the unique number of food items selected in iVR buffet meals and overall gram intake in laboratory meals, categorized by variety-seeking behavioral markers: Total Variety Selected, Higher Energy-Dense Variety Selected, and Lower Energy-Dense Variety Selected. The associations are visualized with individual data points, accompanied by a linear trend line and its 95 % confidence interval.

to the greater variety of food items available in our buffet environment compared to other eating contexts. Despite the general stability of variety-seeking behaviors, these behaviors likely vary across different contexts, over time, and within individuals. Future research can utilize iVR as a cost-effective tool to assess these behaviors with repeated measures across various settings and time periods.

Variety-seeking behavior and the variety effect are distinct yet interconnected in the context of food selection and intake. Variety-seeking is a trait that can be measured through questionnaires or through observable behaviors, such as the number of different foods selected to consume at a meal (Nicklaus et al., 2005; Van Trijp & Steenkamp, 1992). The well-studied variety effect is seen when the presence of a greater number of distinct food items at an eating occasion increases food and energy intake of the available foods or drinks (Embling et al., 2021). While this variety effect directly influences consumption, variety-seeking may theoretically amplify this response. A recent study found that participants with higher variety-seeking, as measured by the VARSEEK questionnaire, were more responsive to the effects of meal variety (Cunningham et al., 2023b; Van Trijp & Steenkamp, 1992). Participants with higher variety-seeking consumed more food when served a greater variety of food compared to participants with lower variety-seeking. Thus, both theoretical mechanisms and empirical data support that the distinct, yet interrelated constructs of food variety and variety-seeking can drive greater food selection and intake. A greater understanding of how these constructs interact will aid in utilizing the iVR variety-seeking behavioral markers as predictors of intake. Our findings suggest that variety-seeking behavior in iVR may provide insight into how individuals respond to the availability of food variety, particularly in relation to energy density of foods. For example, greater variety-seeking behavior for lower energy-dense foods may be associated with a higher variety effect for the intake of lower energy-dense foods, which has positive implications for dietary quality and energy balance. Further research is needed to explore how these constructs interact and their implications for dietary behaviors.

Food switching is another relevant mechanism to consider in the context of food selection, intake, and variety-seeking. Switching refers to behavior within an eating occasion in which an individual takes a bite of one food followed by a bite of a different food, or takes a bite of food followed by a sip of a beverage, and vice versa (Cunningham et al., 2023a; Neuwald et al., 2024). While greater switching has been associated with increased food intake in both children and adults (Cunningham et al., 2023a; Neuwald et al., 2023, 2024), more frequent

switching may be driven by variety-seeking behavior. This may occur because switching affects orosensory exposures, which in turn may delay sensory-specific satiety and prolong eating (Neuwald et al., 2023). While this mechanism has been proposed in previous literature (Neuwald et al., 2023), it currently remains theoretical. Further research is needed to directly examine how variety-seeking behavior and food switching interact to influence sensory-specific satiety and food intake.

There are several limitations of the present study that provide opportunities for future work. While it is possible that the portion size intervention affected our results, it is unlikely, as the variety-seeking behaviors were consistent across portion sizes. Although these behaviors were stable within our iVR food buffet, these measures have not been compared to real-world buffet settings. Additionally, our variety-seeking behaviors were related to intake in laboratory meals with only six unique food items. It remains unclear how these findings extend to other real-world meal contexts. Future work should also explore whether variety-seeking behaviors in an iVR buffet relate to self-reported variety-seeking, such as assessed by the VARSEEK questionnaire (Van Trijp & Steenkamp, 1992). Given the exploratory nature of this study, multiple comparisons were conducted, increasing the probability of Type I errors. While several associations were statistically significant, some effect sizes were small, and findings should be considered preliminary until further validation. Future research should aim to replicate these results in larger samples with pre-registered analyses to confirm the findings.

Food selection behaviors are fundamental to meal creation but have remained a relatively unexplored area in relation to actual dietary intake. We present initial evidence that variety-seeking behaviors in an iVR food selection task are associated with measured intake in laboratory meals. These behavioral markers exhibit specificity with the energy density of consumed foods: variety-seeking higher energy-dense foods is related to increased higher energy-dense food intake and variety-seeking lower energy-dense foods is related to increased lower energy-dense food intake. By utilizing iVR technology to expand the scope of traditional dietary variety measures, our study enriches our understanding of the dynamics between food selection and consumption. Our study also highlights the potential for employing technological innovations to unravel the complexities between food selection behaviors and actual intake. These insights can be used to inform personalized dietary interventions and public health strategies aimed at promoting healthier eating habits.

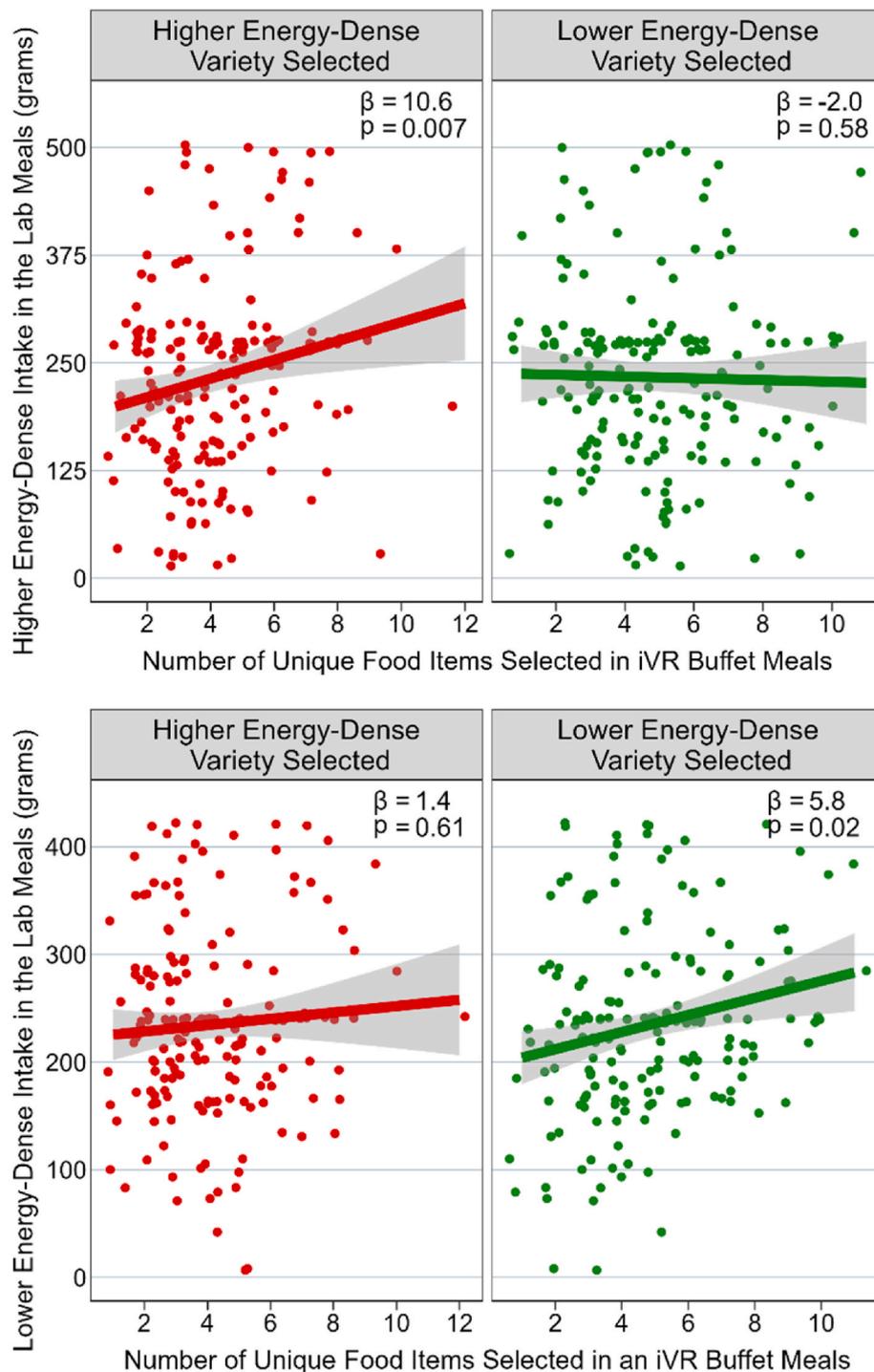


Fig. 5. Specificity in Variety-Seeking Behavioral Markers: Energy Density Choices Reflect Corresponding Energy Density Intake in Laboratory Meals. The associations between the unique number of food items selected in iVR buffet meals and specific intake in the laboratory meals. The top plot depicts higher energy-dense intake in laboratory meals and the bottom plot depicts lower energy-dense intake in laboratory meals. Within each plot, the left panel presents Higher Energy-Dense Variety Selected, while the right panel presents Lower Energy-Dense Variety Selected, illustrating how each variety-seeking behavioral marker relates to higher energy-dense and lower energy-dense intake in laboratory meals. The data are visualized with individual data points, accompanied by a linear trend line and its 95 % confidence interval.

CRedit authorship contribution statement

John W. Long: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Paige M. Cunningham:** Writing – review & editing, Writing – original draft, Conceptualization. **Sara J. Maksi:** Project administration, Investigation. **Kathleen L. Keller:** Writing – review & editing,

Conceptualization. **Charissa S.L. Cheah:** Software, Resources, Funding acquisition, Conceptualization. **Lee Boot:** Software, Resources. **Alexander Klippel:** Writing – review & editing, Software, Funding acquisition, Conceptualization. **Timothy R. Brick:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Caitlyn G. Edwards:** Project administration, Investigation, Conceptualization. **Janelle Kort:** Investigation. **Paige Grabusky:** Investigation. **Barbara J.**

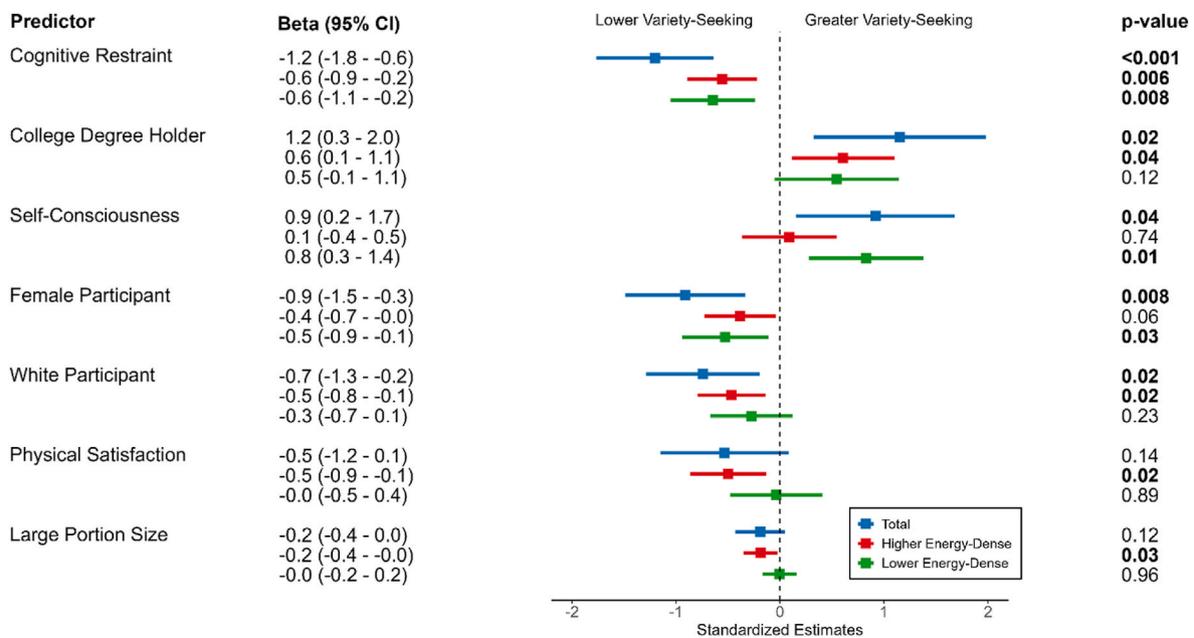


Fig. 6. Predictors of Variety-Seeking Behavioral Markers. Standardized effect sizes (beta estimates) from linear mixed-effect models demonstrating the associations between individual participant characteristics and Variety-Seeking behavior markers in the iVR buffet. Significant predictors for any of the three Variety-Seeking behaviors are included. All variables are standardized for uniform effect size comparison. For binary variables (college degree holder, female participant, white participant, and portion size), the standardized estimates represent differences relative to the reference group (non-degree holders, male participants, non-white participants, and standard portion size, respectively). For example, the negative beta coefficient for female participants indicates that females exhibit reduced variety-seeking behavior compared to males. Self-Consciousness and Physical Satisfaction, in this context, refer to cues for meal termination and are measured by the Reasons Individuals Stop Eating Questionnaire. Marginal R^2 represents the variance explained by the fixed effects and the Conditional R^2 represents the variance explained by both fixed and random effects. For the Total model: $R^2_m = 0.37$, $R^2_c = 0.80$; Higher Energy-Dense model: $R^2_m = 0.32$, $R^2_c = 0.72$; Higher Energy-Dense model: $R^2_m = 0.28$, $R^2_c = 0.79$.

Rolls: Writing – review & editing, Funding acquisition, Conceptualization. **Travis D. Masterson:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Ethical statement

All participants provided informed consent and received financial compensation for their time. All study procedures were approved by The Pennsylvania State University Institutional Review Board (STUDY00017463).

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Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.appet.2025.107988>.

Data availability

The data and code used to analyze and visualize all of the data are available via Open Science Framework at <https://osf.io/7nstp/>.

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