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Portion control tableware differentially impacts eating behaviour in women with and without overweight

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ABSTRACT

Portion control tableware has been described as a potentially effective approach for weight management, however the mechanisms by which these tools work remain unknown. We explored the processes by which a portion control (calibrated) plate with visual stimuli for starch, protein and vegetable amounts modulates food intake, satiety and meal eating behaviour. Sixty-five women (34 with overweight/obesity) participated in a counterbalanced cross-over trial in the laboratory, where they self-served and ate a hot meal including rice, meatballs and vegetables, once with a calibrated plate and once with a conventional (control) plate. A sub-sample of 31 women provided blood samples to measure the cephalic phase response to the meal. Effects of plate type were tested through linear mixed-effect models. Meal portion sizes (mean ± SD) were smaller for the calibrated compared with the control plate (served: 296 ± 69 vs 317 ± 78 g; consumed: 287 ± 71 vs 309 ± 79 g respectively), especially consumed rice (69 ± 24 vs 88 ± 30 g) ($p < 0.05$ for all comparisons). The calibrated plate significantly reduced bite size (3.4 ± 1.0 vs 3.7 ± 1.0 g; $p < 0.01$) in all women and eating rate (32.9 ± 9.5 vs 33.7 ± 9.2 g/min; $p < 0.05$), in lean women. Despite this, some women compensated for the reduced intake over the 8 h following the meal. Pancreatic polypeptide and ghrelin levels increased post-prandially with the calibrated plate but changes were not robust. Plate type had no influence on insulin, glucose levels, or memory for portion size. Meal size was reduced by a portion control plate with visual stimuli for appropriate amounts of starch, protein and vegetables, potentially because of the reduced self-served portion size and the resulting reduced bite size. Sustained effects may require the continued use of the plate for long-term impact.

1. Introduction

Obesity is a recognised health problem for which effective interventions are needed that can be delivered at a scale to impact population health (EASO, 2015). While the food environment is known to play an important role (Cohen & Babey, 2012), individual-level solutions are still necessary (Almiron-Roig, Forde, Hollands, Vargas, & Brunstrom, 2019; Cohen & Babey, 2012; Haire & Raynor, 2014). One particular contextual factor that has a strong individual component and for which a link with obesity has been suggested, is portion size (Livingstone & Pourshahidi, 2014; Young & Nestle, 2002). Portion size is defined as the amount of a given food or drink reasonably expected to be consumed by an individual in a single occasion (Food Drink Europe, n. d.). A portion may reflect a person's own choice for example, the choice of the restaurant, that of a food producer, or a recommendation from a health professional or the government (Benton, 2015; Lewis, Ahern, & Jebb, 2012).

Exposure to large portion sizes, especially of high energy density

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food, leads to increased consumption and has the potential to induce higher energy intakes and weight gain (Diliberti, Bordi, Conklin, Roe, & Rolls, 2004; Ello-Martin, Ledikwe, & Rolls, 2005; Ledickwe, Ello-Martin, & Rolls, 2005; Rolls, Roe, Kral, Meengs, & Wall, 2004; Young & Nestle, 2002). This phenomenon is known as the portion size effect (English, Lasschuijt, & Keller, 2015). Despite the well reported effects of consuming large portion sizes, mechanisms behind the portion size effect are still unclear (Herman, Polivy, Pliner, & Vartanian, 2015).

Being exposed to large portion sizes can modify eating behaviour and, in particular, make a person load more food on their fork and eat faster, an effect that is perhaps mediated by visual cues from food on the plate as the meal progresses (Almiron-Roig et al., 2015). Portion size-related stimuli could also modulate key cognitive processes such as memory and visual attention (Almiron-Roig, Majumdar, Vaughan, & Jebb, 2019; Hollands et al., 2015; Robinson et al., 2016). Visual cues generated by portion control tools such as plates and bowls including portion size demarcations, may prompt users to pay additional attention to portion size, which helps to reinforce visual memory of the distribution of various foods on the plate. Eventually, this may help to recalibrate (reduce) personal normative beliefs around what constitutes a 'normal' serving size (Almiron-Roig, Domínguez, Vaughan, Solis-Trapala, & Jebb, 2016; Robinson, Henderson, Keenan, & Kersbergen, 2019; Robinson & Kersbergen, 2018). The type of portion control tool plays a fundamental role and is a determining factor for its effectiveness (Jia et al., 2022; Vargas-Alvarez, Navas-Carretero, Palla, Martínez, & Almiron-Roig, 2021). This may be because its use encompasses a learning process (Almiron-Roig et al., 2016), which may alter perceptions about the satiating power of foods (expected satiation) (Forde, Almiron-Roig, & Brunstrom, 2015), and the ability to choose appropriate portions in future (Hollands et al., 2015). Additionally, such tools may help to decrease the energy density of a meal by shifting the relative proportion of each meal component, for example, by prompting users to self-serve larger vegetable portions, while reducing portions of starch and protein (Vargas-Alvarez et al., 2021). Though calibrated tools are inexpensive and have the potential to aid weight loss (Huber et al., 2015; Kesman, Ebbert, Harris, & Schroeder, 2011; Pedersen, Kang, & Kline, 2007), their effectiveness in the medium and long-term is less clear (Vargas-Alvarez et al., 2021). Interaction with cognitive factors at the time of eating could also modify other eating behaviours such as eating speed and bite size, plus hormonal responses, in particular those mediated by insulin, pancreatic polypeptide (PP), and ghrelin, during the very early stages of eating (cephalic-phase responses, CPRs) (Heath, Jones, Frayn, & Robertson, 2004; Yeomans, Re, Wickham, Lundholm, & Chambers, 2016).

The present study investigated the mechanisms by which exposure to predefined portion size cues, may impact portion size choice and consumption of a meal, in addition to other eating behaviors associated with overeating. Portion size cue exposure in this study was implemented by using a portion control plate (referred to here as a "calibrated plate"). This study is part of a larger (parent) study that also analysed gaze movements as a proxy for visual attention, in response to portion size cues. Here, we report results related to portion size, meal eating behaviour (i.e. eating rate), portion size norms, and memory for portion sizes previously consumed; plus, changes in the CPRs. Visual attention data will be reported separately. The working hypothesis for the present study was that in comparison with a conventional (cue-free) plate, the use of a portion control plate with visual stimuli for appropriate portions of main food groups reduces overall portion selection and improves meal eating behaviour. Our secondary hypothesis was that the presence of visual portion size cues may enhance the CPRs to a meal based on the presence of multiple sensory modalities (Dhillon, Lee, & Mattes, 2017; Teff, 2010). To diminish variability in portion size behaviour outcomes due to sex (Allison & Baskin, 2009), we focused only on women, but enrolled a sufficiently large sample to be able to investigate body mass index (BMI) effects (Rippin, Hutchinson, Jewell, Breda, & Cade, 2019).

2. Methods

Full details of the experimental design, procedures and validation of the combined methodological platform used in this study have been published previously (Vargas-Alvarez et al., 2022).

2.1. Experimental design

The study was a quasi-randomized crossover trial where participants attended two lunch sessions at the eating behaviour laboratory of the University of Navarra, using either a calibrated plate (including printed guidelines for recommended servings of starch, protein and vegetables) or a control plate (no cues) in alternated order. Treatment conditions were counterbalanced systematically to eliminate order effects; thus, women were first stratified according to BMI (lean vs. with overweight/obesity) before being assigned one of two sequences and sessions were alternated after a washout period of 7–14 days. Due to the nature of the intervention, blinding was not possible.

Sample size was estimated using an on-line sample size calculator (http://powerandsamplesize.com/). Sample size for the parent study was based on expected differences in visual attention and verified against minimal requirements for eating behaviour outcomes. Thus, for a desired power of 80%, with alpha 0.05, a minimum of 30 women of the same BMI group were required to detect a minimal significant difference in fixation (dwell) time of 325 ms per area of interest (AOI) between plates, assuming a SD of 445 ms, based on a previous study in lean women (van der Laan, Papies, Hooge, & Smeets, 2017). To account for potential variability in visual attention measures across BMI groups, sample size was increased to 60 women (including 50% with overweight/obesity). This sample size covered the requirements for detecting differences in meal micro-structural parameters ($n = 60$) (Laessle, Lehrke, & Dückers, 2007) and gut hormones ($n = 30$) (Bowen, Noakes, Trenerry, & Clifton, 2006; Yeomans et al., 2016), plus plate effects on portion size choice and intake ($n = 30$) (Almiron-Roig et al., 2016; Hollands et al., 2015). Assuming an expected 12% drop-out rate (Almiron-Roig et al., 2015), the required sample size was 68 women. The study had to be terminated in March 2020 due to the COVID-19 pandemic with 65 women enrolled. All participants gave informed consent before taking part. The study was approved by the University of Navarra Research Ethics Committee (registration number 2017.031mod1) and the trial was registered at Clinical Trials.Gov (NCT03610776).

2.2. Subjects

Potential participants were recruited by newsletters, flyers, and an internal database of preexisting volunteers, between September 2018 and February 2020. The study was advertised as "a study to validate a new plate for healthy eating" in order to avoid conditioning participants' eating behaviour (Robinson et al., 2014). Interested candidates were first interviewed by telephone and then invited to a laboratory screening session to confirm their eligibility. The inclusion and exclusion criteria were: age between 18 and 60 years, BMI between 18.5 and 35 kg/m^2, normal gastro-intestinal function and visual health; consuming breakfast at least 5 days per week, liking the study foods, able to consume food without the need for prescription glasses (contact lenses were allowed), not taking any medication that may affect sight, body weight, gastro-intestinal function or appetite, nonsmoker; performing <10 h of intense physical activity per week, consuming <14 units of alcohol per week, able to understand and be willing to sign the informed consent form, and to follow the study procedures. Pregnant and lactating women, those with relevant food allergies and restrictions, a history of epilepsy or having an implanted medical device, plus those scoring ≥ 19 on the Eating Attitudes Test-26 (EAT-26) (potential presence of eating disorders) were excluded (Garner & Garfinkel, 1979; Rivas, Bersabé, Jiménez, & Berrocal, 2010).

After the initial telephone interview, candidates attended a screening session in the lab where their height and weight were measured, they completed the EAT-26, a tasting test plus an equipment familiarization test. In the tasting test participants tasted and rated, through electronic 100 mm visual analogue scales (VAS) (Hill & Blundell, 1982), the boiled rice, peas and carrots, plus the meatballs. To be eligible, participants had to assign a score of 40 mm or more for the rice, meatballs and, at least one of the vegetables. Participants also consumed 125 g of sweetened yogurt while seated at the Universal Eating Monitor (UEM) and practiced using electronic VAS. Those meeting the inclusion criteria were enrolled in the study.

2.3. *Study procedures*

On each study day, participants arrived at the laboratory between 11:30 and 14:30 after a 3 h fast. Starting time was kept constant across both sessions and protocol compliance was verified through a short questionnaire. Participants were asked to consume 200 ml of still water to standardized thirst levels. Following this, baseline appetite ratings were measured with electronic VAS, after which, participants were accompanied to the kitchen where they were asked to self-serve lunch from a hot meal buffet (Fig. 1).

Participants were instructed to self-serve as much as they desired from the buffet in just one helping, using either the calibrated or the control plate (Fig. 2) and selecting at least one of the vegetables. Brief instructions on how to read the demarcations were also provided with the calibrated plate for guidance.

Participants were left alone to self-serve and later consume the meal. All selected and consumed foods were covertly weighed. After self-serving the meal, participants were accompanied back to the UEM, located in a separate room, and filled in an electronic expected satiety VAS. The researcher then brought the meal and participants started eating. Participants alerted the investigator when finished, at which point the researcher removed any leftovers and offered the participant complimentary water and any pre-selected fruit. Immediately after the meal, participants completed another set of subjective satiety and liking questionnaires (electronic VAS), plus paper questionnaires on portion size norms, portion tool acceptance and portion control self-efficacy (described below). Participants were then allowed to leave the laboratory temporarily but were asked not to consume any food or liquid (except for non-carbonated water); and to keep their physical activity and routines constant during this period. Participants returned to the laboratory 3 h after the meal to complete a short memory reconstruction task. Following this, the researcher gave instructions on how to fill in an 8 h estimated food record, to be returned on the next session. On the last session participants completed the Three Factor Eating Questionnaire (TFEQ), were debriefed, and received a crockery portion control plate plus advice on how to use it, in compensation for their time and effort.

In a sub-sample of 31 participants, serial blood samples were extracted before and at 5, 10, 30, 60 and 90 min after the meal. These participants remained in the laboratory until the memory test but were allowed to use the bathroom and to stretch their legs if necessary.

2.4. *Intervention plates*

The calibrated plate was specifically designed for this study by Precise Portions NLS (Virginia, US) by adapting existing versions of tableware to achieve reasonable fitting with a Mediterranean diet lifestyle, plus further improved based on previous research (Almiron-Roig et al., 2016; Almiron-Roig, Majumdar, et al., 2019). For example, all written instructions were removed to eliminate language barriers. The final prototype plate featured printed food illustrations and demarcations for recommended amounts of protein foods, starchy foods and vegetables based on US Department of Agriculture guidelines (MyPlate/MiPlato | *Center for Nutrition Policy and Promotion*, n.d.). The control plate was a white dish of the same size and depth but slightly lighter in weight; it was purchased from Group Carrefour, France. Both were ceramic plates, microwave and dishwasher safe, with an enamel finish (Fig. 2). Both plates measured 25 cm in diameter including a 3.5 cm rim.

2.5. *Study foods*

The laboratory hot meal buffet included foods normally consumed by the Spanish population as part of the main meal. It consisted of precooked, ready to eat, seasoned white rice (Brillante, Sevilla, Spain), boiled peas and boiled carrots (brand Carrefour, France), home-style meatballs in sauce (brand Carrefour), olive oil (Capricho Andaluz, Córdoba, Spain), whole meal bread, salt and pepper (brand Carrefour).

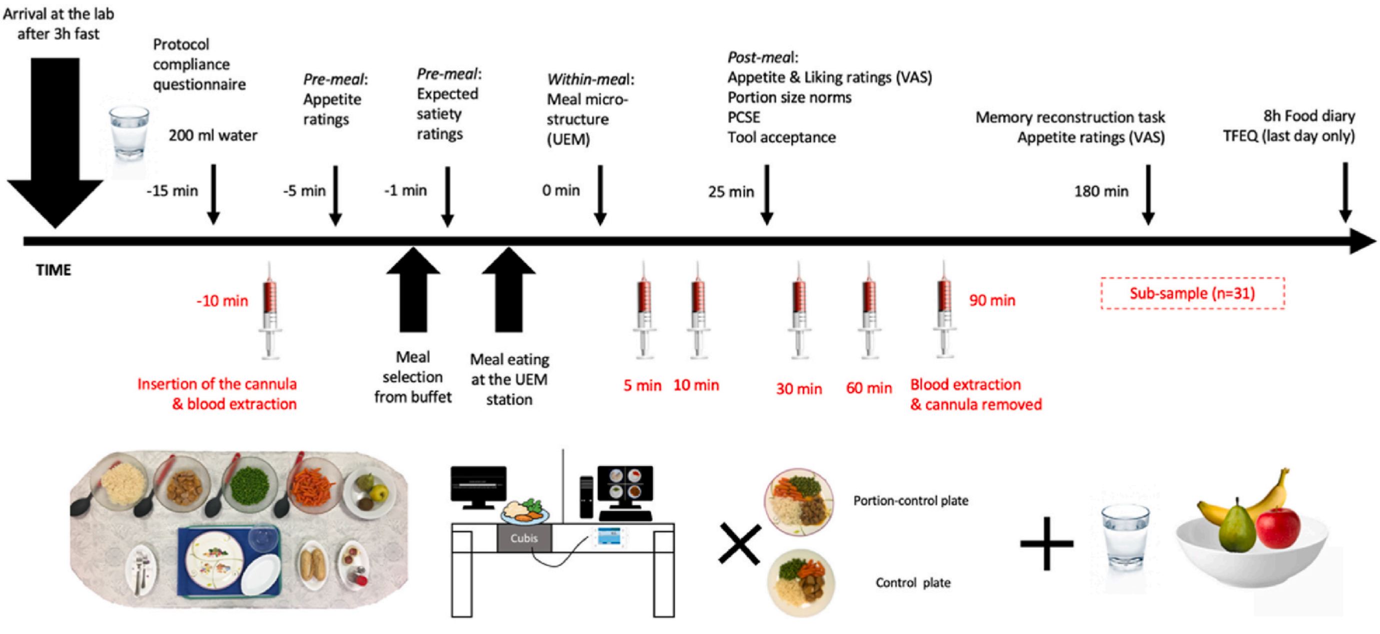


Fig. 1. Daily procedure for participants. *Abbreviations*: PCSE, portion control self-efficacy scale; TFEQ, three factor eating questionnaire; UEM, Universal Eating Monitor; VAS, visual analogue scale questionnaire. Participants were required to select rice, meatballs and at least one of the vegetables, as part of the meal. The water, bread, condiments and fruit were optional.

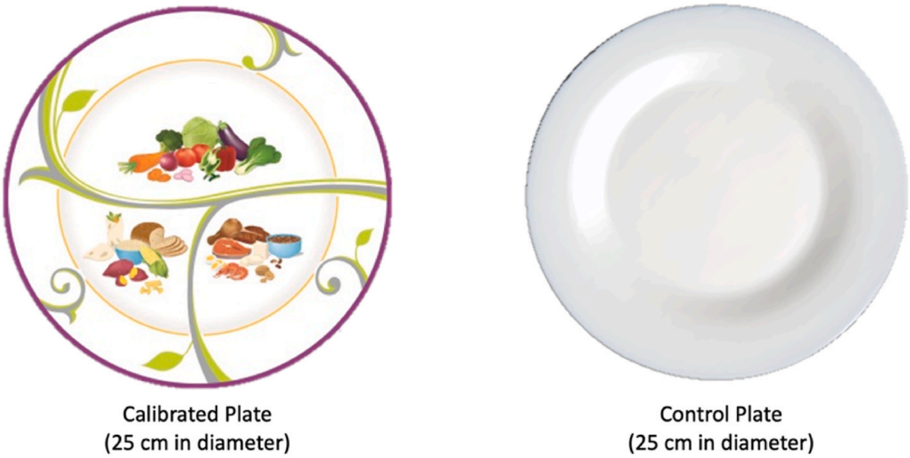


Fig. 2. Intervention plates. Calibrated plate picture courtesy of Precise Portions LLC, Virginia, USA. Control plate purchased from Group Carrefour, France.

The rice, vegetables and meatballs were presented hot (66 °C) in transparent serving bowls (2 L capacity; 400 g portions each food), accompanied by identical serving spoons. Fresh bread was obtained from a local bakery (presented as two 50–60 g portion rolls). The oil was presented in two individual servings of 10 g each. Participants could also select seasonal fresh fruit (up to 3 medium size pieces), and still water, if they wished (to be consumed only after the plated meal). The four main foods (rice, meatballs, peas and carrots) were chosen as they matched the nutritional/food group composition for the calibrated plate. In addition, these foods did not require cutting or applying any pressure in order to be consumed therefore avoiding erroneous scale readings on the UEM. Due to their large size, the meatballs were presented halved.

2.6. *Equipment and software*

2.6.1. *Universal Eating Monitor (UEM)*

An optimised version based on the original UEM by Kissileff et al. (Kissileff, Klingsberg, & Van Itallie, 1980) was designed and built in-house, plus its performance verified for this study (Vargas-Alvarez et al., 2022). The optimised UEM was constructed on a bespoke anti-vibratory table (Borda Laboratorios, Madrid), containing a concealed precision scale (Sartorius Model MSA5201S-1CE-D0) placed under a hole. The hole and the scale were covered with a secured place mat to allow positioning of the plate. The scale was connected to a PC hosting the Sussex Ingestive Pattern Monitor software (SIPM) (Yeomans, 2000), programmed to record weight readings from the scale at 2 s intervals (precision 0.1 g). The scale readings were used to calculate average bite size (the difference between each two consecutive weight records), eating rate (grams eaten per minute) and deceleration rate (milligrams eaten per squared second).

2.6.2. *Memory reconstruction software*

To measure episodic memory for the portion sizes chosen at the meal, customised software was designed and programmed by the Nutrition and Behaviour Unit at the University of Bristol (U.K.). The software allows the user to select adjustable portions of different foods, based on the method of adjustment (Brunstrom, 2014). From the selected image data, it is possible to calculate the relative (%) accuracy in recalled portion sizes vs actual amounts served on the plate. Details of the software development and piloting for this study have been published elsewhere (Vargas-Alvarez et al., 2022).

2.7. *Questionnaires*

2.7.1. *Electronic questionnaires*

Subjective satiety was measured through validated, electronic 100 mm VAS (Flint, Raben, Blundell, & Astrup, 2000; Hill & Blundell, 1982) programmed in the SIPM software on the UEM, for hunger, fullness, nausea, thirst and expected satiation, plus liking of the meal. The questions were: *How hungry do you feel right now?; How full do you feel right now?; How thirsty do you feel right now?; How nauseous do you feel right now?; How much do you think the food that you have self-served will satiate you?; How much did you like the meal?*, with anchors *Not at all* to *Extremely*. A Spanish-language version of these measures was adapted from their implementation in a previous study (Vargas-Alvarez et al., 2022).

2.7.2. *Paper questionnaires*

Portion size norms were measured using published 100 mm VAS (Robinson et al., 2016). Portion control self-efficacy was assessed through the validated PCSE scale (range 1–40 points) (Fast, Harman, Maertens, Burnette, & Dreith, 2015). Portion tool acceptance was measured with a shortened version of a 5-pt Likert scale previously piloted questionnaire (Almiron-Roig et al., 2016). All three instruments were translated into Spanish and back-translated by a professional translator, plus verified with the authors. Eating traits (restraint, disinhibition and hunger) were evaluated only once at the end of the study using the Spanish validated version of the TFEQ (Sánchez-Carracedo, Raich I Escursell, Figureas Piqueras, Torras Clarasó, & Mora Giral, 1999). Further details can be found in the accompanying validation paper (Vargas-Alvarez et al., 2022).

2.8. *Dietary assessment*

Mean energy and macronutrient intake (carbohydrates, protein and fat) from the consecutive 8 h period after each study visit was calculated through a written journal (estimated food diary). Participants filled in the hour, place, cooking method, description and amount of the food consumed using household measures and food packaging information. The investigators reviewed the food diary from both visits and checked any points needing clarification with the participants before carrying out the nutritional analysis (see Data processing).

2.9. *Blood sampling and processing*

To minimize the potential for blood drawing to impact eating behaviour and other variables, the feasibility of the blood extraction protocol was pre-piloted in the first 10 volunteers and adjustments were applied, as necessary (Vargas-Alvarez et al., 2022). All blood samples were drawn from the antecubital vein while participants were seated. To avoid multiple venepuncture, a cannula was used. Participants were instructed to stop eating and to look away from the plate while the nurse carried out the drawings and the blood extraction time was excluded from the meal micro-structural analyses.

Basal samples were taken before food exposure (10 min before the meal) and then at 5, 10, 30, 60 and 90 min after meal consumption to examine cephalic phase response markers (Yeomans et al., 2016). Serum samples for glucose and insulin were collected in 5 ml Vacutainer Gel serum tubes mixed by inversion and let to clot at room temperature for 30–60 min, after which they were centrifuged at 1500 G for 15 min at 4 °C. Plasma samples for ghrelin and pancreatic polypeptide (PP) were collected in 4 ml Vacuette K_2EDTA and K_3EDTA tubes, respectively. Immediately after each draw, a protease inhibitor (Pefabloc, Sigma-Aldrich), was added to the K_2EDTA tube (ghrelin analyses) and mixed by inversion before processing the samples to reach a final concentration of 1 mg/ml. Both tubes were left at 4 °C after which they were centrifuged within 1 h of collection at 1500 G for 15 min at 4 °C. Once centrifuged, hydrochloric acid (final concentration 0.05 N) was added to the plasma extracted from the K_2EDTA tube. All blood samples were stored at –80 °C until analysis.

Glucose concentrations were determined by the hexokinase test (Horiba ABX, Montpellier, France). Enzyme-linked immunoassay kits were used to determine insulin concentrations (Mercodia, Uppsala, Sweden). Human Ghrelin ELISA (Merck KGaA, Darmstadt, Germany) and Human PP ELISA (Millipore, Missouri, USA) were performed to determine total ghrelin and PP concentrations respectively, following the manufacturer's instructions.

2.10. Data processing and statistical analyses

Data cleaning was performed on the raw UEM outputs as follows. Bite size records of <1 g or >23 g were excluded on the basis that they represented scale background noise or the result of the participant unknowingly applying weight or movement while sitting at the UEM (Almiron-Roig et al., 2015). After data cleaning, meal micro-structure parameters were calculated for the plated meal components (rice, meatballs, vegetables) plus accompanying foods (bread and condiments) but excluding the fruit and water. Meal eating rate was defined as the total consumed amount in grams per minute (with meal duration being defined as the duration of the meal in minutes, extracted from the UEM outputs). Meal bite size was calculated as the average of the cumulative weight changes (difference between each two consecutive weight records) and deceleration rate was defined as milligrams consumed per squared second. For the sub-sample of participants providing blood samples, the extraction time employed by the nurse at each session was subtracted from the meal duration.

The calibrated plate was judged effective in cases where it delivered a reduction of at least 1 tablespoon (30 g) relative to the control plate, or by at least a 10% reduction in terms of energy. The 10% kcal-reduction threshold was chosen based on the assumption that the meal could potentially contribute a maximum of half of a total daily reduction of 20%, based on the UK Government's calorie reduction plan at population level (Public Health England, 2018).

Percentage error in recalled portion size (memory test), was calculated as follows:

$$Memory\ error\ rate = \left(\frac{Eaten\ portion\ size\ (g) - Recalled\ portion\ size\ (g)}{Eaten\ portion\ size\ (g)}\right) * 100$$

Energy and macronutrients consumed at the laboratory meal plus for the following 8 h after each lab session were calculated from the food diary data with the EvalFINUT® software (https://www.finut.org/evalfinut/) which employs the USDA (United States Department of Agriculture) and BEDCA (Spanish Food Composition Database) databases (https://www.bedca.net/). Whenever participants provided the specific brand or package label for eaten products, the available nutrient data for such products were used over default values.

Energy compensation (%) over the 8 h period following the intervention was calculated using the following published algorithm (Almiron-Roig, Palla, et al., 2013):

$$\%EC = [\ (EI_{\text{Intervention Plate}} - EI_{\text{Control Plate}})/EP]*100$$

Where EI represents the cumulative energy intake at the end of the day under the intervention or control plate conditions, excluding the energy of the test lunch; and EP represents the difference in energy intake at lunch between the 2 conditions (control and intervention lunch). EC values of 100% or close indicate sustained energy adjustment during the intervention plate day vs the control plate day. EC values $>$ 100% indicate over-adjustment (i.e. reduced energy intake at dinner beyond the reduced intake at lunch). Values $<$ 100% indicate partial adjustment, of which values $<$ 0% indicate overeating (i.e. eating additional energy at dinner beyond the difference in lunch energy content). Energy compensation was calculated only for participants who handed-in the 8 h food diary for both visits, and who consumed at least 10 kcal (around 1 teaspoon of boiled rice) fewer with the calibrated plate vs the control, that is, those who showed a measurable response to the intervention tool ($n = 20$ out of 37 women handing two valid food diaries).

Blood parameters were analysed as raw values, changes from baseline (CFB) and incremental area under the curve (iAUC), the last one calculated with the trapezoid method (Wolever, Jenkins, Jenkins, & Josse, 1991).

Statistical analyses were carried out using the R-language free software, version April 1, 1106 (R Project for Statistical Computing, www.r-project.org) and STATA v.12 (StataCorp LLC, Texas, USA). Participant baseline characteristics across BMI groups were compared using independent samples *t*-tests or Mann-Whitney U tests (continuous variables); and Fisher's tests (categorical variables). BMI groups were defined as per WHO conventions (Regional office for Europe, 2021). Thus, normal weight was defined as a BMI between 18.5 and 24.5 kg/m^2; overweight and obesity was defined as a BMI of 25 kg/m^2 and over. In this study the groups with overweight and obesity are referred to collectively as 'overweight.'

The impact of plate type on main outcome variables was explored with linear mixed effects models. The main models considered were those examining portion size intake for the whole meal, bite size, hunger, memory for portion size (% error in recalling previously served amounts), insulin and pancreatic polypeptide levels. Additional exploratory models were run including some sensitivity analyses for other meal microstructural parameters (eating rate, deceleration rate, and meal duration); other measures of food portion size (served grams for the whole meal and each meal component; consumed grams of each individual meal component; meal energy; meal energy density); subjective appetite and meal liking (VAS ratings for, fullness, thirst and nausea; liking and expected satiety); portion size perceptions (portion norms, tool acceptance, PCSE); and additional biochemical parameters (glucose, ghrelin).

Models were built following the backwards elimination method, according to their group/cluster nature, with a random intercept to account for the repeated observations for each individual, and fitted using maximum likelihood estimation, likelihood ratio tests (REML). Participant characteristics (age, BMI, TFEQ restraint, disinhibition and susceptibility to hunger scores), order of exposure (plate sequence), total amount of served food, and pre-meal fullness and hunger levels were used as adjusting variables in order to fit all models. To evaluate the independent effect of plate type, univariate models were first created for each outcome variable. Subsequently, multivariate models were fitted using ANOVA and R^2 values for model selection and any relevant interactions explored. Models where BMI had a significant impact on at least one of the outcome variables, were fitted again for each specific BMI category.

Results are reported as means ± SD or SEM. Data on served and consumed meal components are presented separately, according to the order in which they were offered and chosen by participants (foods exclusively served on the plate i.e. rice, meat, vegetables; optionally eaten with the plate food, i.e. bread, oil; optionally eaten after the plate had been removed i.e. water and fruit).

Statistical significance was set at the $p < 0.05$ level.

3. Results

3.1. Participants

Over 200 women were telephone-interviewed to participate in this trial, of which 105 were screened in the laboratory. Of these, 65 met the eligibility criteria and were enrolled. Of the 31 women with normal weight and the 34 women with overweight starting the study, 61 completed both visits (Fig. 3). Clinical visits took part between Oct-2018 and Feb-2020. Three participants did not complete the study due to failure to attend the second visit but results from the first visit were included in the analyses. One participant deviated from the protocol on one visit and those data were excluded. Blood samples were collected from 31 women (of which 17 with overweight) for both visits, except for two participants who attended only the first visit, and less 3% of samples which were lost due to hemolysis. The rate of non-useable UEM outputs due to technical issues or protocol deviations was 13% (19/149) (for full details see Vargas-Alvarez et al., 2022). Finally, twenty-four women failed to return the second food diary after visit 2. No adverse events were recorded.

Participant characteristics are shown in Table 1. All had fasting blood levels for glucose and insulin within the normal range except for eight participants who had at least one of the fasting glucose values between 100 and 110 mg/dL (impaired glucose tolerance). Fasting ghrelin levels were significantly lower and disinhibition scores significantly higher in the group with overweight, who were slightly older, compared with the lean group. Most volunteers had never experienced a portion control tool before and consumed most of their meals at home. Most lived with children or other adults, and most prepared meals for others beyond themselves.

3.2. Impact of plate type on portion size selection and intake

Overall participants self-served and consumed significantly smaller portions using the calibrated plate compared with the control plate (Table 2). Consumed amounts for the food on the plate exclusively were 287 ± 71 vs 309 ± 79 g ($p < 0.05$) for the calibrated and the control plate, respectively while consumed amounts including complimentary bread and oil were also smaller (316 ± 78 g vs 336 ± 85 g, $p < 0.05$). This effect was driven by changes in the portion size of rice (multivariate adjusted model $B = 18.55$; 95%CI: 12.13, 24.92; $p < 0.001$). Portion size differences translated into an average difference of 43 kcal less eaten from the plated meal on the calibrated plate (32 kcal less when including bread, oil, and fruit), of which 37 kcal were from rice. Differences for all other meal components were <8 kcal (and non-significant). Overall, out of the 61 women completing both visits, 27 (44%) consumed at least 1 tablespoon (30 g) of food less with the calibrated plate than with the control plate. In terms of energy, 29 of the 61 women (48%) reduced their energy intake by at least 10% (or about 39 kcal) in the laboratory meal when using the calibrated plate vs. the control plate.

By BMI group, lean women consumed similar amounts of all foods in both plates, except for rice which remained significantly lower with the

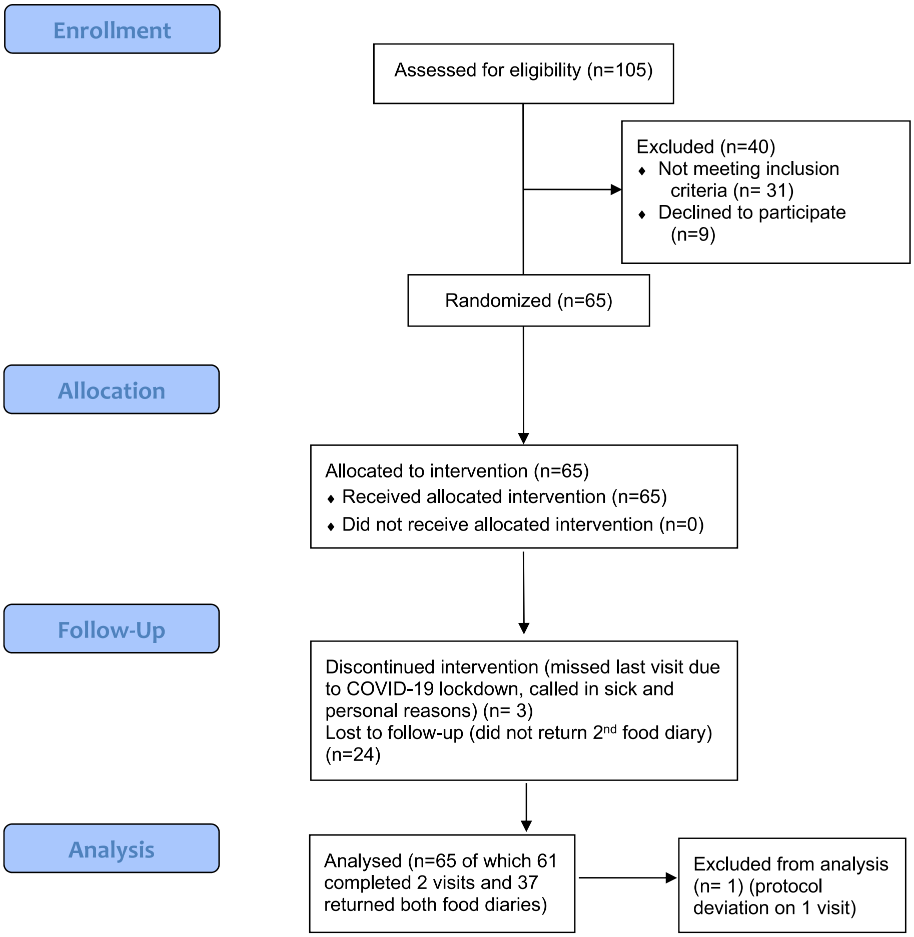


Fig. 3. CONSORT flow diagram. From the Consort Group (Consort Group, 2015).

Table 1
Participant's characteristics for the whole sample and by BMI group.
Sample size is indicated in brackets. Values are means ± SD; percentage. *Abbreviations*: BMI, Body mass index (kg/m^2); SDG, Sociodemographic; TFEQ, Three Factor Eating Questionnaire. There were three missing values for TFEQ scores (two in the normal weight group and one in the group with overweight), and one missing value (normal weight group) for prepared meals at home values.

	All women	With normal weight	With overweight
	(n = 65)	(n = 31)	(n = 34)
Age (years)	43 ± 12	39 ± 13	46 ± 11*
BMI (kg/m^2)	26 ± 4	23 ± 2	29 ± 3***
TFEQ scores			
Restraint (0–21)	10 ± 4	10 ± 4	9 ± 4
Disinhibition (0–16)	8 ± 4	6 ± 3	9 ± 4**
Hunger (0–14)	6 ± 3	5 ± 3	6 ± 3
EAT-26 score (0–78)	9 ± 4	8 ± 4	9 ± 4
SDG characteristics			
Ethnicity			
South European	85%	84%	85%
North-European	3%	3%	3%
North- America	2%	0%	3%
Latin-America	11%	13%	9%
Previous experience with PS tools			
None	80%	87%	74%
Yes	20%	13%	26%
Home-made meals frequency			
Never or almost never	12%	13%	12%
Less than once a week	6%	6%	6%
1–3 times per week	3%	3%	3%
Most of the day	78%	77%	79%
Take-away meal frequency			
Never or almost never	65%	58%	71%
Less than once a week-	26%	26%	26%
1–3 times per week	8%	13%	3%
Most of the days	2%	3%	0%
Household composition			
Lives with children/with other adults	94%	97%	91%
Lives alone	6%	3%	9%
Prepared meal			
For self only	14%	13%	15%
For self and others	86%	87%	85%
Fasting blood levels	**(n = 31)**	**(n = 14)**	**(n = 17)**
Glucose (mg/dL)	90 ± 9	88 ± 7	92 ± 10
Insulin (mU/L)	8 ± 11	10 ± 17	6 ± 3
Ghrelin (pg/mL	2028 ± 1429	2580 ± 1711	1490 ± 864**
PP (pg/mL)	264 ± 314	351 ± 397	190 ± 219

* Differs from the normal weight group with $p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

calibrated plate (68 ± 26 vs 91 ± 33 g, $p < 0.01$) and water, which remained significantly higher (141 ± 92 vs 106 ± 80 g, $p < 0.05$) (Table S1 in Supplementary material). This was reflected in reductions in mean overall amounts served (294 ± 78 g with calibrated vs 326 ± 88 g with control plate, $p < 0.01$) and in mean overall amounts consumed by this group (317 ± 86 g with calibrated vs 347 ± 93 g with control, $p < 0.01$). The amounts served and consumed by women with overweight were also smaller with the calibrated plate, however differences only reached significance for the rice (mean ± SD 69 ± 23 g for the calibrated vs. 84 ± 27 g for the control plate; $p < 0.001$) (Table S1).

3.3. Impact of plate type on meal micro-structural parameters

Amongst the meal micro-structural parameters explored, the impact of plate type was only significant on bite size (mean ± SD: 3.4 ± 1.0 g vs 3.7 ± 1.0 g; $p < 0.01$ in adjusted models) (Table 3).

BMI-specific regression models revealed that the impact of plate type on bite size and eating rate was modulated by BMI (Fig. 4 and Table S2). Lean women loaded significantly less food on their fork when using the calibrated plate (mean ± SD 3.3 ± 1.0 g) compared to when they used the control plate (3.8 ± 1.1 g) ($p < 0.001$). The lean women also displayed a significant lower eating rate in the calibrated vs. the control plate condition (32.9 ± 9.5 vs 33.7 ± 9.2 g/min respectively; $p < 0.05$). No significant plate effect was detected on meal duration or deceleration rates, either for the total group or when explored within each BMI category ($p > 0.05$ all comparisons).

3.4. Appetite, satiety and liking ratings

In adjusted models, over the complete 3-h period there were no significant differences between plates on subjective ratings of hunger, nausea, and liking for the meal. (Fig. S1 in Supplementary material). The control plate induced slightly higher fullness sensations at 180 min (multivariate adjusted model B = 6.22; 95CI%: 1.97, 10.46; $p < 0.01$) but the difference was small (mean ± SEM calibrated minus control: −5.7 ± 2.0 mm on a 100 mm scale). Differences by plate type on thirst levels over the course of the meal did not reach significance ($p = 0.06$). Volunteers expected the meal self-served on the control plate to be more satiating (mean ± SD: 82.32 ± 20.84 mm) than the meal self-served on the calibrated plate (mean ± SD: 76.40 ± 15.76 mm) (multivariate adjusted model $B = 5.82$; 95CI%: 1.93, 9.71; $p < 0.05$). This pattern was detected in both BMI groups (mean ± SD expected satiety lean group: 77.75 ± 19.75 vs 84.19 ± 13.13 mm and group with overweight: 75.18 ± 14.08 vs 80.61 ± 16.33 mm, calibrated vs control plate, respectively) ($p < 0.05$ in multivariate adjusted models).

3.5. Tool acceptance and perceived self-efficacy to control portion sizes

Both plates were well accepted, although the control plate was rated less favorably (mean ± SD average 5-pt Likert score: 4.4 ± 0.5 vs 4.1 ± 0.7, calibrated vs control plate, respectively) ($p < 0.001$ in multivariate adjusted model). These results held across both BMI groups (lean group 4.5 ± 0.4 vs 4.2 ± 0.6; group with overweight: 4.4 ± 0.6 vs 3.9 ± 0.7, calibrated vs control plate, respectively; effect of plate $p < 0.05$ in both groups). Perceived self-efficacy to control portion sizes did not differ by plate condition (mean ± SD 4-point PCSE score: 3.37 ± 0.8 vs 3.45 ± 0.8; calibrated vs control plate, respectively; $p > 0.05$).

3.6. Portion size norms

Regardless of which plate they used, women reported having selected smaller food portions in the laboratory than those habitually consumed, with no difference between BMI groups (Table S3). A significant effect of plate type on portion norms was detected only for the vegetables. Participants reported a greater portion size reduction for vegetables compared to their normal/habitual portion size when they used the control plate (mean ± SD portion norm score 6.7 ± 1.5 cm) relative to the calibrated plate (6.0 ± 2.0 cm) ($p < 0.01$). This effect was driven by women with normal weight, with a mean ± SD portion norm score of 5.8 ± 2.2 cm vs 6.9 ± 1.3 cm (calibrated vs control plate respectively; adjusted model B = 1.12, 95CI%: 0.34, 1.89; $p < 0.05$). However, these differences did not reach significance in the group with overweight (mean ± SEM vegetables portion norm scores: 6.2 ± 0.3 cm vs 6.5 ± 0.3 cm, calibrated vs control plate respectively; $p > 0.05$). Plate differences in the vegetable portion norms amongst the lean women extended to the whole meal portion norm (multivariate adjusted model for lean women $B = -0.52$, 95CI%: −1.03, −0.02; $p < 0.05$).

3.7. Dietary intake

Only thirty-seven women of the total sample of completers (n = 61/65) provided full dietary records on both visits, resulting in a sample of 100 returned food diaries (59 after using the calibrated plate and 41 after using the control plate). This represented 79% of the total number of diaries expected (122 from the 61 subjects completing two visits and 4

Table 2

Impact of plate type on selected and consumed portion sizes at a lunch buffet meal.

Results of univariate and multivariate (in footnote) linear mixed effect models. Values are mean grams ± SD. There were four missing values for the calibrate plate (three participants who failed to attend the 2nd visit and one who deviated from the protocol). Significant effects are indicated in bold type ($p < 0.05$). *Abbreviations*: B, unstandardized regression coefficient; CI, confidence interval.

	All women ($n = 65$)		Univariate Model (Plate alone)			Multivariate Model		
	Calibrated Plate (g)	Control Plate (g)	**B**	95% CI for B	p	**B**	95% CI for B	p
Total served (exclusively on the plate) (g)[a]	296 ± 69	317 ± 78	21.35	(3.75; 38.89)	**0.0185**	21.6998	(4.13; 39.26)	**0.0167**
Total consumed (exclusively on the plate) (g)[b]	287 ± 71	309 ± 79	21.99	(4.99; 38.95)	**0.0123**	22.5020	(5.52; 39.49)	**0.0105**
Total consumed (with bread and oil) (g)[b]	316 ± 78	336 ± 85	20.61	(2.27; 38.90)	**0.0286**	21.0760	(2.76; 39.38)	**0.0253**
Rice (g)[b]	69 ± 24	88 ± 30	18.88	(12.53; 25.20)	**0.0000**	18.5461	(12.13; 24.92)	**0.0000**
Meatballs (g)[d]	106 ± 33	111 ± 38	5.16	(−2.31; 12.65)	0.1750	5.0083	(−2.83; 12.23)	0.1865
Vegetables (g)[b]	112 ± 41	110 ± 47	−2.06	(−11.56; 7.41)	0.6680	−1.7150	(−11.20; 7.77)	0.7202
Bread (g)[c]	25 ± 19	23 ± 18	−1.28	(−4.53; 1.96)	0.4350	−1.4594	(−4.34; 1.82)	0.3479
Fruit (g)[c]	95 ± 73	90 ± 62	−4.21	(−18.62; 10.19)	0.5630	−4.6512	(−18.83; 9.51)	0.5160
Olive oil (g)[d]	4 ± 4	4 ± 4	−0.02	(−0.59; 0.55)	0.9530	−0.0179	(−0.57; 0.54)	0.9495
Water (g)[e]	147 ± 93	132 ± 87	−15.07	(−32.79; 2.66)	0.0958	−15.3693	(−33.16; 2.38)	0.0903

Total consumed food excludes fruit and water.

[a] Multivariate model fitted with plate type, age and plate sequence.

[b] Multivariate model fitted with plate type and plate sequence.

[c] Multivariate model fitted with plate type and baseline hunger levels.

[d] Multivariate model fitted with plate type, baseline hunger levels and TFEQ-H score.

[e] Multivariate model fitted with plate type and age.

Table 3

Impact of plate type on meal micro-structural parameters at a lunch buffet meal.

Results of univariate and multivariate (in footnote) linear mixed effect models. Values are mean ± SD. There were 10 missing values for the calibrated plate condition (three participants who failed to attend the 2nd visit, one who deviated from the protocol, six with invalid UEM recordings). Significant effects are indicated in bold type ($p < 0.05$). *Abbreviations*: B, unstandardized regression coefficient; CI, confidence interval.

	All Women ($n = 65$)		Univariate Model (Plate)			Multivariate Model		
	Calibrated Plate	Control Plate	B	95% CI for B	p	B	95% CI for B	p
Eating Rate (g/min)[a]	33.0 ± 9.0	34.7 ± 12.8	1.7370	(−0.75; 4.21)	0.1690	1.5151	(−0.26; 3.28)	0.0941
Bite Size (g)[b]	3.4 ± 1.0	3.7 ± 1.0	0.3603	(0.12; 0.58)	**0.0029**	0.3302	(0.10; 0.54)	**0.0044**
Deceleration Rate (mg/sec^2)[b]	1.05 ± 0.55	1.14 ± 0.98	0.09061	(−0.11; 0.29)	0.3860	−0.2361	(−1.002; 0.53)	0.5432
Meal Duration (seconds)[c]	605.5 ± 187.2	627.9 ± 218.8	20.9100	(−16.31; 58.18)	0.2680	8.0493	(−25.92; 41.91)	0.6382

[a] Multivariate model fitted with plate type, meal duration and total served food.

[b] Multivariate model fitted with plate type, baseline hunger levels, TFRQ-R score, meal duration and total served food.

[c] Multivariate model fitted with plate type, BMI and total served food.

from the 4 subjects completing one visit). Energy and macronutrient intake over the 8-h period following the laboratory lunch was calculated from the returned diaries. A significant impact of plate was detected for total energy intake ($p < 0.001$ in multivariate adjusted model) and by macronutrient ($p < 0.05$ for all) in the total sample (Table 4). Overall, participants consumed an average of 223 kcal more after the session where they used the calibrated plate than after using the control plate.

Although several of the women completing both visits responded to some extent to the calibrated plate by reducing energy intake at the laboratory meal, this reduction was only meaningful in terms of portion size in 44% of participants and only meaningful in terms of energy in 48% of the participants. In addition, most of this energy was compensated for later in the day.

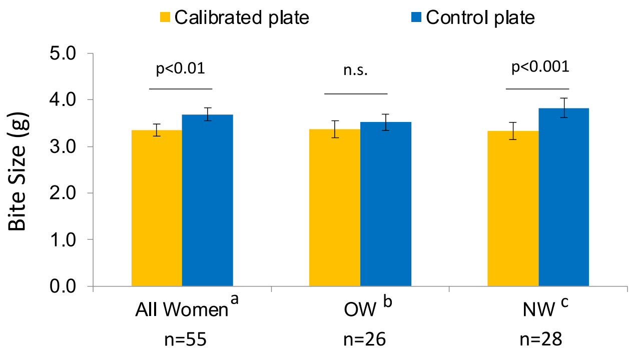
As an indication of the degree of sustained efficacy of the plate when used correctly, energy compensation was calculated for a sub-sample of 20 women who responded as expected to the calibrated plate and for whom paired food diaries were available (visits 1 plus 2). Fourteen out of these 20 (65%) failed to maintain the caloric restriction of the meal by dinner time, of which 12 (60%) overate. Overall, while the 20 women consumed on average (mean ± SEM) 93 ± 21 kcal less at lunch with the calibrated vs the control plate, their intake over the next 8 h far exceeded this difference and was on average 258 ± 91 kcal in excess after using the calibrated plate. In this sub-sample, none of the participants showed perfect adjustment but partial compensation (EC from 8% to 64%) or over-adjustment (EC from 174% to 572%) was detected in 6 of the women (mean ± SEM %EC for these 6 women was 178 ± 1%).

Given that portion-control plates can potentially reduce meal energy density due to their particular design, in a post-hoc analysis, we looked at energy density of the meal consumed at the lab session and at dinner (8 h recall). Energy density of the laboratory lunch was lower when participants used the calibrated plate. This applied to the plated meal as well as the meal plus complementary oil and bread ($p < 0.001$ and $p < 0.01$ respectively in multivariate adjusted models) (Table 4). The energy density of the total food consumed in the laboratory (including fruit but excluding water) and of the food consumed over the following 8 h did not differ by plate.

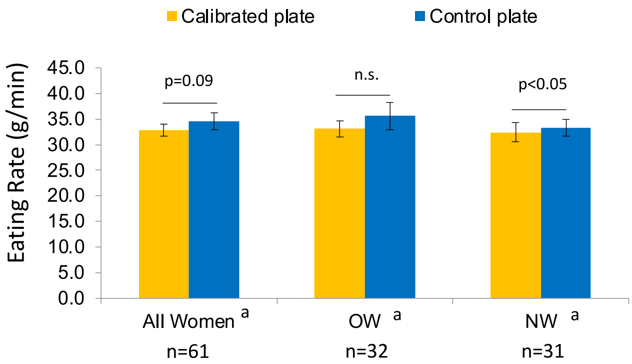
3.8. Cephalic phase response markers

Fasting and post-prandial blood concentrations for glucose, insulin, PP, and ghrelin are shown in Fig. 5. Across the whole subsample ($n = 31$) the impact of plate type was only significant on ghrelin levels, being higher after the calibrated plate condition especially in the first 10 min after starting the meal ($B = -156.47$, 95CI%: -265.80; -47.13; $p < 0.01$) (Supplementary Table S4). Glucose, Insulin and PP profiles did not reveal any plate type effect in multi-variate adjusted models. iAUC values did not differ by condition for any markers (Table 5).

Changes from baseline (CFB) were initially significant for insulin (univariate model $B = -5.86$, 95CI%: -10.24; -1.48; $p < 0.01$), but the effect disappeared after adjusting for total amount of served food. Significant plate type*BMI interactions were detected in both CFB PP values ($p = 0.0041$) and raw PP values ($p = 0.0049$) in all women. BMI was also a significant covariate in the glucose iAUC model for all women. Despite this, differences between BMI groups could not be



[a] Multivariate model fitted with plate type, baseline hunger levels, TFRQ-R score, meal duration and total served food.
[b] Multivariate model fitted with plate type, total served food and baseline hunger levels
[c] Multivariate model fitted with plate type, meal duration and total served food.



[a] Multivariate model fitted with plate type, meal duration and total served food.

Fig. 4. Bite size (top) and eating rate (bottom) measured with the Universal Eating Monitor at a lunch meal buffet using two different plates in a sample of 61 women. Values are Mean ± SEM. Results from linear mixed-effects models are shown across bars. *Abbreviations*: NW, women with normal weight; OW, women with overweight or obesity.

explored due to insufficient sample sizes.

3.9. *Memory test*

The calibrated plate did not improve memory for portion sizes of the previously selected foods, relative to the control plate. Irrespective of plate type, women underestimated the pre-selected portion sizes for rice and meatballs (recall error<0); while they overestimated the portion sizes for the vegetables (recall error>0), with significant differences for all foods except the meatballs (both plates) and the rice (calibrated plate). Across foods, the peas were the foods recalled with least accuracy (Table S5). No impact of BMI was detected when explored in specific models by BMI group.

4. Discussion

According to the initial hypothesis, the use of a calibrated (portion control) plate with visual stimuli for appropriate portions of starch, protein and vegetables resulted in the selection and consumption of smaller food portion sizes of a laboratory meal when compared with a conventional plate. The calibrated plate was effective in 44% of the women in terms of portion size and in 48% in terms of energy intake, however the effects faded over time. In the subsample of 20 responsive women providing full dietary records, only one third maintained the reduced intake without compensatory behaviour later in the day. This suggests that for any effects to be sustained and result in beneficial body weight control, continued use of the tool may be required, or other types of support need to be put in place. The plate impact was mirrored with changes in the cephalic phase responses for ghrelin, although changes were probably BMI-dependent. Despite this observation, the calibrated plate favored behaviours associated with a better control of food intake (Herman et al., 2015; Robinson, Kersbergen, et al., 2014), specifically, reduced bite size and eating rate; and a reduction in the energy density of the meal. Importantly, these effects varied between lean women and those with overweight and obesity therefore, interventions featuring portion control strategies need to account for varying levels of responsiveness. Contrary to our expectations, the calibrated plate did not improve memory for portion sizes previously selected possibly due to the high intra-subject variability in portion size memory. Interestingly, women were more likely to report consuming a smaller than habitual portion of vegetables when using the control plate than when using the calibrated plate. However, there were no significant differences in consumed portion sizes for vegetables between plate conditions. This reflects the well-known human difficulty in estimating food amounts

Table 4

Impact of plate on energy and macronutrient intake plus dietary energy density of the meal and the 8 h period following the test meal.

Values are mean ± SD. Data for 37 women returning both food diaries. There were four missing values for the energy density values under the calibrate plate condition (three participants who failed to attend the 2nd visit and one who deviated from the protocol). The 8 h period includes all foods, caloric drinks and meals consumed over the 8 h after leaving the laboratory (excludes the laboratory meal). Significant effects are indicated in bold type ($p < 0.05$). *Abbreviations*: B, unstandardized regression coefficient; CI, confidence interval; ED, energy density.

			Univariate Model			Multivariate Model		
	Calibrated Plate (n = 59 records)	Control Plate (n = 41 records)	B	95% CI for B	p	B	95% CI for B	p
8 h period total energy (kcal) [a]	665.12 ± 407.07	442.1 ± 25.82	−224.92	(−347.75; −101.34)	**0.0006**	−223.99	(−347.53; −99.56)	**0.0007**
8 h period carbohydrate (kcal) [b]	265.08 ± 197.19	166.2 ± 94.05	−103.04	(−162.41; −42.23)	**0.0012**	−91.46	(−149.38; −31.32)	**0.0055**
8 h period protein (kcal) [a]	150.98 ± 98.98	106.25 ± 54.76	−43.44	(−74.14; −12.93)	**0.0065**	−43.33	(−73.96; −12.89)	**0.0065**
8 h period fat (kcal) [a]	249.70 ± 191.61	169.65 ± 91.82	−79.91	(−143.85; −16.25)	**0.0161**	−79.68	(−142.90; −16.46)	**0.0143**
Plated meal ED (kcal/g) [c]	1.24 ± 0.12	1.29 ± 0.12	0.05	(0.03; 0.07)	**0.0000**	0.05	(0.03; 0.08)	**0.0000**
Lunch ED (kcal/g) [d]	1.40 ± 0.16	1.43 ± 0.15	0.03	(0.01; 0.06)	**0.0188**	0.04	(0.01; 0.06)	**0.0049**
Lunch with dessert ED (kcal/g) [e]	1.25 ± 0.20	1.27 ± 0.17	0.02	(−0.00; 0.06)	0.0926	0.03	(−0.003; 0.06)	0.0782
8 h period ED (kcal/g) [f]	5.07 ± 0.46	5.09 ± 0.42	0.02	(−0,15; 0.20)	0.7660	0.03	(−0.13; 0.21)	0.6734

[a] Multivariate model fitted with plate type and plate sequence.

[b] Multivariate model fitted with plate type, plate sequence and TFEQ-D score.

[c] Multivariate model fitted with plate type, meal duration and total served food. Plated meal refers to the food on the plate exclusively.

[d] Multivariate model fitted with plate type, TFEQ-H score, meal duration and total served food. Lunch refers to the plated meal plus oil and bread.

[e] Multivariate model fitted with plate type, TFEQ-D and TFEQ-H scores. Lunch with dessert refers to the plated meal, oil, bread and fruit, excluding the water.

[f] Multivariate model fitted with plate type, TFEQ-H score and total served food.

even in the presence of portion size aids (Almiron-Roig, Solis-Trapala, Dodd, & Jebb, 2013; Amoutzopoulos et al., 2020; Brogden & Almiron-Roig, 2011), supported by the women's inability to correctly recall portion sizes, especially for peas, in this study.

4.1. Impact on portion sizes

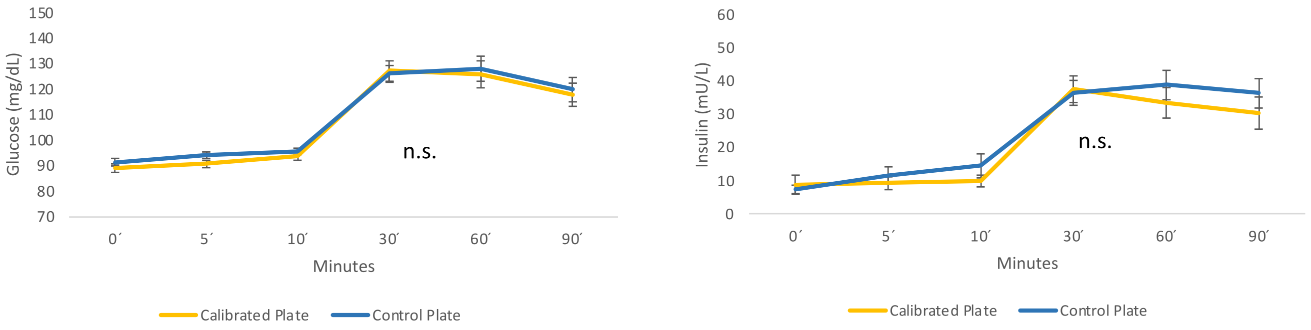
The short-lived nature of the plate effect confirms previous evidence that long-term portion control is challenging (Rolls, Roe, James, & Sanchez, 2017). While strategies based on portion-controlled meals and educational aids (either physical or virtual) have shown limited effects (Almiron-Roig, Forde, et al., 2019), portion control tableware with sectors, holes or calibration marks seem promising (Almiron-Roig, Majumdar, et al., 2019; Huber et al., 2015; Hughes et al., 2017; Jayawardena, Sooriyaarachchi, Punchihewa, Lokunarangoda, & Pathirana, 2019; Kesman et al., 2011; Pedersen et al., 2007). Meta-analyses now suggest that calibrated plates are more effective tools for healthy weight management than merely switching from a larger to a smaller plate or bowl (Jia et al., 2022; Robinson, Kersbergen, et al., 2014; Vargas-Alvarez et al., 2021), perhaps responding to the actual physical restriction of amounts in combination with visual cues derived both from the design elements as well as from the actual amounts of foods once distributed on the plate (Almiron-Roig et al., 2016). In particular, plate demarcations may provide a visual reference for appropriate amounts, assuming the tool is used correctly, i.e. without piling up or having second helpings (Almiron-Roig, Majumdar, et al., 2019; English et al., 2015). Further, these types of tool may promote the selection of food with lower energy density (Smethers & Rolls, 2018). In line with a previous similar study (Hughes et al., 2017), we detected a 7% reduction in the portion size of the plated meal; i.e. approx. 40 calories fewer were consumed with the calibrated plate relative to the control plate. However, our intervention plate resulted in a smaller reduction in the rice portion size (20% vs 40% in (Hughes et al., 2017)) which may be due to differences in plate design, and in particular, differences in the useable plating area for meal components, which was overall smaller in the previous study plate (Hughes et al., 2017). Interestingly, the effects were seen on the amount of rice served without any increase in the other foods. This may reflect the fact that participants were instructed to select at least one vegetable while the buffet was limited to only six foods (rice, meatballs, carrots, peas, bread, fruit). The lack of increase in vegetable intake could also reflect an adherence to a cultural norm. A typical meal in Spain would include the vegetables as either a first course or as side dish. In both cases the plating areas tend to be larger than the actual vegetable area included in the calibrated plate, which may have prompted participants to choose less vegetables.

4.1.1. Impact on bite size and eating rate

Changes in eating rate and bite size in this trial were mainly driven by the lean women, confirming the role of body weight differences on oral processing behaviour (Ketel, de Wijk, de Graaf, & Stieger, 2020; Laessle et al., 2007).

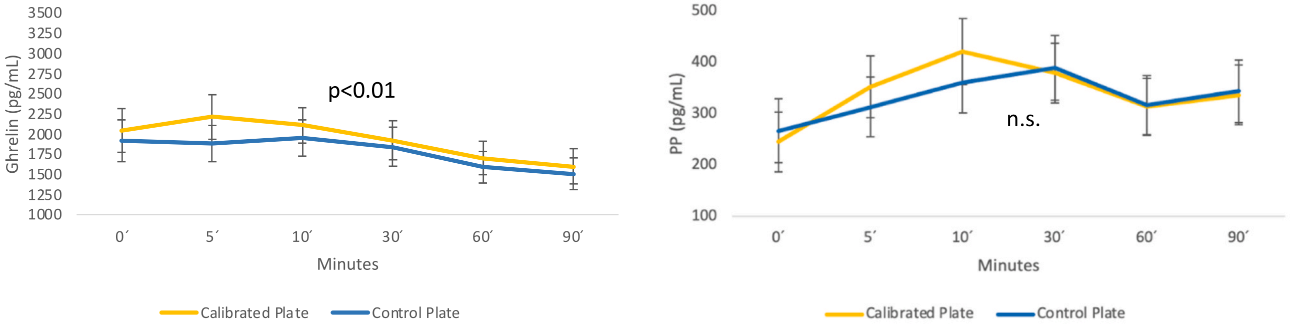
Being exposed to smaller than conventional portion sizes of a meal reduced bite size in overweight women (Almiron-Roig et al., 2015), similar to the present study. Our participants ate the same proportion of the food that they had self-served in both conditions (97%), and took about the same time to finish with both plates. This could be because participants had to serve themselves in one helping (unlike at home or in a "all you can eat" buffet). In addition, people tend to eat more slowly from smaller portions (Areni & Black, 2015; Almiron-Roig et al., 2015). Therefore, it is possible that the smaller portion sizes selected with the intervention plate led participants to load less on their forks but still feel satiated when compared with the control plate.

Increases in bite size may actually be responsible for increased consumption of larger portion sizes even in the absence of visual cues (Burger, Fisher, & Johnson, 2011). On the other hand, in experiments where subjects eat *ad-libitum*, decreasing bite sizes reduces eating rate but may not reduce total energy intake if participants compensate by eating for longer (Spiegel, Kaplan, Tomassini, & Stellar, 1993). In the present study, meal duration was shorter rather than longer in the reduced portion size (bite size) condition and participants consumed overall less energy. This may have been caused by not being able to eat second helpings, perhaps prompting women to load less on their fork and eat slowly in an attempt to make the meal last longer. Satiation due to oro-sensory exposure depends mostly on stimulus exposure time and intensity (Lasschuijt, de Graaf, & Mars, 2021). While intensity of the stimuli was kept constant in our study, the duration of the meal was



Multivariate model fitted with plate type and baseline hunger levels

Multivariate model fitted with plate type and total served food



Univariate model fitted with plate type

Multivariate model fitted with plate type and plate sequence

Fig. 5. Fasting and post-prandial blood concentrations for glucose and gut hormones for a sample of 31 women consuming a hot meal with a calibrated or a control plate (includes 1 missing value for the calibrated plate condition). Values are mean ± SEM. Multivariate linear mixed-effect models were created for glucose, insulin and pancreatic polypeptide (PP) profiles to account for potential covariate effects (no covariate effects were detected for ghrelin). Results of regression analyses are shown. *Abbreviations*: n.s., non-significant.

Table 5
Impact of plate type on post-prandial incremental area under the curve (iAUC) for glucose and gut peptides over 90 min after a lunch buffet meal. Results of univariate and multivariate (in footnote) linear mixed effect models for the complete sample (n = 27 to 31). Values are mean ± SEM. There were sporadic missing values for five women due to failure to attend the 2nd visit and damaged samples. *Abbreviations*: B, unstandardized regression coefficient; CI, confidence interval; PP, pancreatic polypeptide.

	iAUC		Univariate Model (Plate)			Multivariate Model		
	Calibrated Plate	Control Plate	B	95%CI for B	p value	B	95% CI for B	p value
Glucose[a]	2569.06 ± 305.22	2740.08 ± 336.11	158.30	(−603.42; 924.90)	0.6780	147.97	(−612.62; 911.53)	0.6971
Insulin[b]	1835.71 ± 212.53	2219.43 ± 220.53	369.85	(−108.99; 852.52)	0.1300	359.19	(−110.55; 832.97)	0.1336
Ghrelin[b]	6983.52 ± 1882.21	5716.49 ± 1645.32	−1267	(−6141.012; 3606.95)	0.6063	−1445.29	(−6092.78; 3202.18)	0.5378
PP[c]	11444.88 ± 2662.73	11010.08 ± 2188.89	−739.60	(−4577.36; 3133.35)	0.7000	−394.48	(−3998.05; 3265.23)	0.8268

[a] Linear mixed-effects model fitted with plate type and BMI. iAUC units are mg/dL * min.
[b] Linear mixed-effects model fitted with plate type and total served food. iAUC units are mU/L * min for insulin and pg/mL*min for ghrelin.
[c] Linear mixed-effects model fitted with plate type and baseline hunger levels. iAUC units are pg/mL * min.

shorter in the calibrated plate condition. However, these changes did not translate into changes in fullness immediately after the meal, suggesting other factors, including visual cues, may have counterbalanced the impact of the reduced meal exposure time.

4.2. *Impact on CPR markers*

Together with the reduced bite size and eating rate associated with the use of the calibrated plate, we only detected significant, albeit small, changes in the ghrelin profile. It is possible that changes in other CPR markers may have been masked by BMI differences but this could not be confirmed due to small sample sizes. Oral processing, mainly slower eating rate and reduced bite size, can significantly contribute to variability in endocrine responses (Cassady et al., 2009, 2012; Lasschuijt, Mars, De Graaf, & Smeets, 2020), which may explain this effect.

We further hypothesize that the impact of plate type on insulin changes from baseline in unadjusted models was probably related to the amount of consumed carbohydrate rather than sensory aspects, as the effect disappears when taking into account the portion size served. In agreement with this, at 5 min from starting the meal, insulin levels were 50–60% higher from baseline in the control condition (larger rice portion size) vs. no more than 20% higher in the calibrated plate condition. On the other hand, the cephalic phase pancreatic polypeptide response (CPPPR), was around 70% higher from baseline at the 10 min peak in the calibrated plate condition vs. 35% higher in the control condition. Reduced oro-sensory exposure from the smaller portion size could explain these results, however we did not detect an accompanying decrease in eating rate seen in previous studies (Lasschuijt et al., 2020). High variability in the CPRs across individuals and foods may impact the time of onset and magnitude of the CPRs and mask real effects beyond spontaneous fluctuations (Lasschuijt et al., 2020). In the present study, the same combined meal including a variety of textures was employed for comparisons, analyses were conducted within-subjects and the time of onset for the PP peak coincided with the median values reported in the literature (9 ± 4 min after meal onset) (Lasschuijt et al., 2020). However, we did not see an insulin peak coinciding with the theoretical CPR insulin peak value (around 5 ± 3 min). As a whole, these findings suggest that any sensory-related cues observed in the calibrated plate condition impacted on the CPPPR only.

Contrary to our findings, a previous intervention (Lasschuijt et al., 2020) reported that a faster eating rate induces higher PP concentrations. However, a very large amount (1 kg) of semi-solid, sweet food was used in that study, as opposed to a relatively small portion (≈300 g) of the savoury solid meal used here. Given that different sensory modalities are necessary to elicit CPRs in humans (Lasschuijt et al., 2020), this may explain the contrasting findings.

Ghrelin has been mostly associated with meal initiation rather than satiation (Lasschuijt et al., 2020), with some exceptions (Massolt et al., 2010). Ghrelin levels where higher when using the calibrated plate especially in the first 10 min since meal onset, but differences disappeared when fasting levels were considered (CFB and iAUC analyses). Even if the women in this study may have perceived the served portion sizes in the calibrated plate as too small (lower expected satiety ratings), a physiologically relevant CPR-related secretion of ghrelin during the first 10 min due to cognitive effects (Cassady et al., 2012; Crum, Corbin, Brownell, & Salovey, 2011) is difficult to ascertain.

4.3. *Strengths and limitations*

To our knowledge, this is the first trial exploring the impact of a portion control plate on a combination of behavioral, cognitive and physiological outcomes measured in real time, using sophisticated equipment and tightly controlled conditions. According to our results, we estimate that if a user used the plate correctly in at least one meal per day, then this strategy has the potential to reduce starch intake by at least 260 kcal per week. Given that public health guidelines recommend a daily 500 kcal deficit in order to achieve healthy weight loss (U.S. Department of Health and Human Services, 2013; Yumuk et al., 2015), these types of tools may represent an initial useful step towards this goal when used alongside other weight-loss strategies. The success of the plate though will depend on its correct and sustained use. In this trial, many more individuals ended up overcompensating over time than sustaining reductions, which suggests that beyond education on how to use the plate correctly, additional lifestyle changes along the day to reduce compensatory behaviour may be necessary.

The trial was sufficiently powered to detect a role of BMI in modulating the impact of plate type on bite size, eating rate and food intake (although not on the endocrine response to the meal). Despite the significant acute effects observed, the impact of the calibrated plate was relatively small and did not extend over time in all women. In addition, some of them compensated for the energy reduction from the lunch at the next meal, albeit this could only be quantified in the sub-sample who returned both diaries and used the plate correctly. In part, this compensatory behaviour may have responded to the impossibility to have second helpings combined with a participation effect, resulting in smaller than usual portions being consumed. In turn, this may have induced higher hunger levels beyond the 3 h measuring period in some of the women, leading to snacking or larger dinners (Robinson et al., 2014). Added to it, an effect of order of exposure possibly brought about by the educational component of the tool was also detected. To reduce hypothesis awareness, participants were told the study was about healthy eating which may have prompted some individuals to select smaller amounts of certain foods, especially weight- or health-conscious participants. Our data on portion size norms suggest that social desirability effects were present and this needs considering when interpreting the findings.

Future trials should consider how to best reduce or eliminate these biases and evaluate the effect of the plate under free-living conditions in a wider sample of subjects, including men with overweight or obesity. It would also be useful to monitor whether continued use leads to improved eating habits without users feeling bored and ignoring the cues altogether. Continuous, long-term measures in realistic food environments, combined with measures of gastro-intestinal transit time may also provide a more detailed and objective assessment of CPRs and portion size changes (Cassady et al., 2012; Lasschuijt et al., 2020).

5. Conclusion

A portion control plate with visual stimuli for appropriate portion sizes of main food groups (starch, protein and vegetables) reduced self-served and consumed portion sizes especially of starchy food in a buffet meal. The tool impacted women with and without overweight and obesity to a different extent, but promoted an eating style compatible with weight loss in the short-term.

Potential processes involved could include portion size restriction leading to changes in meal microstructural parameters and in specific cephalic phase responses following meal exposure, however these need further investigation.

Author contribution

Study concept: EAR, JAM; data curation: MAVA, AED, EAR; formal analysis: MAVA; funding acquisition: EAR, JAM; methodology: All authors; project administration: EAR; resources and software: JMB, SNC; supervision and visualization: EAR, SNC; validation plus writing first draft of paper: MAVA, EAR; review and editing: All authors.

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Consent to participate and to publish

Participants signed informed consent regarding publishing their data as long as it was non-identifiable. Precise Portions LLC provided written consent for publishing images of the portion control (calibrated) plate.

Ethical statement

The study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the University of Navarra Research Ethics Committee on 27 April 2017 and 17 November 2017 (revised version), with reference number 2017.031mod1.

Declaration of competing interest

The authors have no conflicts of interest to declare that are relevant to the content of this article. The funders and sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2023.106542.

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