Appetite 194 (2024) 107171

Contents lists available at ScienceDirect

Appetite

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

Meat- and plant-based products induced similar satiation which was not affected by multimodal augmentation

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ARTICLE INFO

Keywords:
Satiation
Meat alternatives
Augmented reality
Multisensory augmentation
Liking
Wanting

ABSTRACT

Little is known about how plant-based products influence satiation compared to corresponding meat-based products. As augmented reality (AR) intensifies sensory experiences, it was hypothesized to improve satiation. This study compared satiation between intake of meatballs and plant-based balls and plant-based balls intensified with AR for visual, olfactory, and haptic sensory properties. Intake order of the meatballs, plant-based balls, and augmented plant-based balls, eaten on separate days, was randomized. Satiation was measured from twenty-eight non-obese adults as *ad libitum* intake of the balls and extra snacks, and as subjective appetite sensations. Liking and wanting to eat the products were also investigated.

There were no differences between the products in satiation. Before tasting the augmented plant-based balls were less liked than the meatballs ($p = 0.002$) or plant-based balls ($p = 0.046$), but after eating the first ball or eating the *ad libitum* number of balls the differences in liking disappeared. Wanting evaluations were similar for each product and decreased during eating ($p < 0.001$). A group of participants susceptible to AR was found ($n = 11$), described by decreased intake when augmentation was applied. Among the sub-group, wanting to eat the augmented balls was lower before tasting ($p = 0.019$) and after eating the first ball ($p = 0.002$) and appetite was less suppressed after eating the balls *ad libitum* ($p = 0.01$), when compared to non-susceptible participants.

We conclude that meatballs and plant-based balls were equal in inducing satiation, and multisensory augmentation did not influence satiation. However, the augmentation decreased liking evaluations before tasting. Further studies are needed to explore differences between consumer groups in susceptibility to augmentation.

1. Introduction

In the current obesogenic environment, it is crucial to identify new strategies to encourage people to moderate their food consumption. It has been shown that people with obesity and healthy weight have similar eating frequencies but those with obesity consume more calories during single eating occasions highlighting the importance of a suitable meal size for weight management (Gibbons, Hopkins, Beaulieu, Oustric, & Blundell, 2019). Optimally, foods should bring about good satiation, being at the same time palatable, health-promoting and environmentally sustainable. Modern plant-based alternatives to traditional meat products possess potential to meet these criteria. However, a shift from animal-based to animal-alternative products is slow among consumers. For example, plant-based products are perceived as less filling or satiating, more processed, more difficult to prepare, and less nutritious compared to meat-based products among omnivorous and carnivorous consumers (Spendrup & Hovmalm, 2022; Varela et al., 2022). There are also challenges in replicating meaty flavor and structure using plant-based ingredients to meet the expectations of meat-eating consumers (He, Evans, Liu, & Shao, 2020). To the best of our knowledge there are no earlier studies comparing the satiation effects of corresponding meat- and plant-based food products. Also, the potential of using augmented reality (AR) for improving satiation is not known.

Dietary interventions with appetite-reducing foods have been shown

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https://doi.org/10.1016/j.appet.2023.107171
Received 27 June 2023; Received in revised form 22 November 2023; Accepted 13 December 2023
Available online 17 December 2023

to be promising strategies to improve weight maintenance (Hansen, Andersen, Astrup, Blundell, & Sjödin, 2019). Appetite during a meal is related to satiation (also termed as intra-meal satiety) which is a series of processes that brings a specific eating episode to an end (Blundell et al., 2010; Cunningham & Rolls, 2021). In other words, satiation controls meal size. There are several factors related to physiology, food characteristics, and eating environment that play a role in meal termination (Cunningham & Rolls, 2021). Physical satisfaction mediated either via subjective feelings oras increased gastric volume, intestinal signals, and fluctuations in satiety hormones influence satiation as well as external cues like food labelling (content, portion size), variety of options, size of the offered portion, and paying attention or priority to eating and remembering the preceding eating episode (Cornil, 2017; Cunningham & Rolls, 2021). Of these, food characteristics perceived by human senses are of interest in this current study.

Palatability is a sensory property of a food that generally increases its intake (Sørensen, Møller, Flint, Martens, & Raben, 2003). However, there are other sensory properties that are not connected to palatability such as perceived amount or volume or size, and color of a food. They all influence satiation since they are associated with earlier post-ingestive experiences about the satiating capacity of the specific food (Mccrickerd & Forde, 2016). A preload of milk shake with increased volume (achieved by incorporating air) as compared to an isocaloric preload of milk shake with smaller volume has been shown to suppress appetite by lowering energy intake during the following meal, reducing hunger, and increasing fullness (Rolls, Bell, & Waugh, 2000). Even a mere belief of consuming a larger portion of fruits in a smoothie compared to a smaller portion of fruits has been shown to enhance satiety after a meal and for a three-hour post-prandial period (Brunstrom, Brown, Hinton, Rogers, & Fay, 2011). Also, an illusion of a heavier weight of a food, created by visually similar but a heavier container, has been shown to enhance expected satiety which might enhance also satiation (Piqueras-Fiszman & Spence, 2012). It has been shown in some studies that foods with increased taste intensity (such as high saltiness) enhance satiation more than milder-tasting foods (such as low saltiness) that are equally palatable (Mccrickerd & Forde, 2016). Little is known about the impact of perceived odor intensity of a food on bringing about satiation but exposure to odors signaling high or low energy-dense sweet and savory foods did not show any impact on the consumption of these foods (Zoon, He, de Wijk, de Graaf, & Boesveldt, 2014).

AR refers to technologies that modify human perception by overlaying digital data on it (Dargan, Bansal, Kumar, Mittal, & Kumar, 2023). Sense augmentation is achieved by "interpreting available sensory information and presenting content to the human through selected human senses" (augmented vision, hearing, haptic sensation, smell, and taste) (Raisamo et al., 2019). AR technologies have been used in various fields such as education, medicine, and entertainment. In recent years AR has been increasingly used to modify sensory experiences during eating (Gayler, Sas, & Kalnikaite, 2022). Most of the studies have focused on changing the taste or visual appearance of food or drink but also smell, touch, and audio properties have been augmented. The primary platforms for displaying AR information currently are smartphones and tablets, and AR-enabled head-mounted displays (Crofton, Botinestean, Fenelon, & Gallagher, 2019). In addition, for example local aroma diffusors (Hathaway & Simons, 2017) and head-mounted olfactory displays (Narumi, Nishizaka, Kajinami, Tanikawa, & Hirose, 2011) and vibrating utensils (Hermsen, Mars, Higgs, Frost, & Hermans, 2019) have been used to augment olfactory and tactile perception related to food.

Previous studies have shown the capability of AR to influence sensory perception. For example, odors associated to sweet taste delivered by local odor display increased perceived sweetness of a cake (Aisala et al., 2020) and a system that changes virtual weight sensation of a fork by controlling the center of gravity with a motor slider inserted in the fork interface modified perceived weight of chocolate (Hirose et al., 2015). To the best of our knowledge only one preliminary study has augmented senses with the aim to modify the perception of food to improve satiety sensations (Narumi, Ban, Kajinami, Tanikawa, & Hirose, 2012). The research group used head-mounted displays to scale the perceived size of a cookie real-time either shrinking or enlarging the apparent size. In a small user study, they showed that less cookies were consumed in "enlarged" condition compared to "shrunk" condition.

This study aimed to compare the satiation effects of meatballs- and their plant-based counterparts. In the light of previous studies showing that intensified sensory experiences and impression of a larger portion may improve satiation, AR technologies were explored as a potential means of adding an extra layer of perception to the food to enhance satiety. Multisensory (visual, olfactory, and haptic) augmentation was applied on a plant-based product alternative to meat to explore its effects on *ad libitum* food intake and post-meal appetite sensations. We hypothesized that corresponding meatball- and its plant-based alternative close to similar in their appearance, nutrient content, and structure induce similar satiation and that a more intense sensory experience created by multisensory augmentation enhances satiation, measured as *ad libitum* food intake. This study provides new understanding about the effects of meat- and plant-based alternative products on satiation and novel insights on how multisensory augmentation could be exploited to control meal size and to modify the eating experience.

2. Methods

2.1. Study design

A within-subject design including three randomly assigned study visits for each participant on separate, non-consecutive weekdays was applied. The study included two visits in the absence of AR with meatballs at one visit and its plant-based alternative at the other visit. In addition, there was one visit that was performed in the presence of multisensory AR to intensify sensory perceptions of the plant-based alternative. The participants were not informed when or how the multisensory augmentation would be implemented during the experiments. At each study visit, participants were instructed to eat until they feel pleasantly full, and *ad libitum* number of the study product eaten was recorded without informing the participants. Also, the participants evaluated their appetite sensations and product liking and wanting before and after eating. The study visits were organized at the VTT's human research laboratory in Kuopio, Finland. All participants gave their informed, signed consent to participate before the study began. The study was conducted according to the ethical principles and good research practices described in the European Code of Conduct for Research Integrity. The study aim, design, procedure, and personal data management were evaluated and approved by the ethics committee of VTT Technical Research Centre of Finland Ltd on the 21st of June 2022.

2.2. Participants

Voluntary participants were recruited through email and poster advertisements at Savilahti campus area in Kuopio aiming to reach students and teachers and other employees of research and educational organizations and companies near the study location. Interested volunteers filled in an online questionnaire assessing their suitability to participate in the study and providing background information including questions about eating behavior. The inclusion criteria were adults habitually eating breakfast every morning, aged between 18 and 65 years with body mass index (BMI) of 19–28 kg/m^2 and stable body weight. Participants had to be able to eat ingredients the study products included (beef and pork, pea, egg, lactose-free milk, onion). Exclusion criteria were smoking, impaired sense of smell or taste due to recent covid-19 infection or chronically blocked nose, hypersensitivity to scents, previously noted feeling of nausea from using virtual reality goggles, use of reading glasses due to substantially impaired near vision (wearing glasses was not possible with the AR goggles), pregnancy or lactation. Also, those who were familiar with AR in their work or studies were not included in the study.

After filling in the online questionnaire, suitable participants were contacted via phone by a study researcher who shortly interviewed them and agreed on study visits that were synchronized with their habitual breakfast time. The recruited participants were sent an invitation via email containing general information about the study and its purpose and personal data management, and instructions to follow their habitual eating and exercise habits and avoid alcohol over the day preceding the study visit. The information also contained a short 2.5 min video describing the course of the study visits, the AR devices, and the study products. Also, participants were informed that they will get a ready-made salad after eating the study products at the end of each visit. It was highlighted that the breakfast time, content, and size shall always be the same preceding each three study visits, and no eating or drinking was allowed between the breakfast and the subsequent study visit.

Except one drop-out, altogether 28 participants (twenty females and eight males) attended all the three study visits (Table 1). They were 39 ± 11 years old with BMI fulfilling the inclusion criteria (19–28 kg/m^2) except for one male participant who reported his BMI to be 32 kg/m^2. Based on the eating behavior questionnaire (Three Factor Eating Questionnaire Revised 18 (TFEQ-18)) (Karlsson, Persson, Sjöström, & Sullivan, 2000), the participants were characterized by a common eating behavior. The higher the value of the eating behavior the stronger is the tendency for restraint eating, uncontrolled eating, or emotional eating (Karlsson et al., 2000).

2.3. Study products

Two commercial products were used in the study: meatballs (Atria, Finland) and plant-based balls (Meeat, Finland) (Fig. 1). These ready-made balls were chosen based on their similarities in appearance, nutrient content, energy density, structure, and seasoning (Table 2) as compared to other commercial products in the market. The balls were stored frozen and before each study visit, 15–20 balls were melted by heating them up in a microwave oven for 3 min. Each ball was weighed and if needed, a small bit was cut out to standardize the weight of each ball to 15.0–15.5 g. The balls were covered and left to steady in room temperature for 30–60 min before serving.

2.4. Augmentations and related technologies

2.4.1. Visual augmentation

The aim of visual augmentation was to give the participants an impression of a bigger plant-based ball (Table 3). Earlier research has shown that visual cues about bigger portion size may decrease intake (Mccrickerd & Forde, 2016). The visual augmentation was achieved using a Varjo XR-3 head-mounted display (HMD) for extended reality which houses stereo cameras, meaning that all visual information is fully digital and allows for per-pixel manipulation of what is shown to the user (Fig. 2). The benefit of this HMD over traditional AR headsets is its ability in completely occluding real-world elements with virtual artifacts, whereas more traditional devices commonly produce translucent artifacts with real-world elements still visible under the virtual content.

The fork the participants used to eat the balls was augmented with a 3D printed cube with a QR-code-like marker that the HMD cameras tracked for the reference point of where to render the virtual artifacts. This allowed the user to move and rotate the fork, and by extension the virtual artifact, to experience the visual augmentation naturally. The visual augmentation software was built using Unity 2019 and the default Varjo markers were used for tracking the fork.

Table 1
Characteristics of the study participants (n = 28 of which twenty females and eight males).

	Mean	SD	Range
Age	39	11	19–65
Three Factor Eating Questionnaire			
"Cognitive restraint"	37	17	6–67
"Uncontrolled eating"	33	15	11–59
"Emotional eating"	28	23	0–78

Fig. 1. Study products: a meatball (left) and a plant-based ball (right).

Table 2
Nutrient content and ingredients of the study products.

/100 g	Meatballs	Plant-based balls
Energy (kcal/kJ)	255/1058	259/1078
Fat (g)	18	14.8
Carbohydrates (g)	4.6	14.1
Dietary fiber (g)	2.4	4.5
Protein (g)	17	15
Salt (g)	2	1
Ingredients	Meat 78 % (beef, pork), egg, lactose free cooking cream, onion, pea fiber, potato flake, iodized salt, seasonings (black pepper, allspice), garlic, color (caramel color)	Water, texturized pea protein (25 %), rapeseed oil, maize flour, onion, stabilizers (methylcellulose, cellulose), salt, seasonings (black pepper, allspice), color (caramel color), maltodextrin (maize)

Table 3
Description of multisensory (visual, haptic, olfactory) augmentation.

	Goal of augmentation	Change	Technical equipment
Visual	Bigger appearance	1.3-fold bigger visual area [1]	Varjo XR-3 head-mounted extended reality display
Olfactory	More intense and meaty odor	1.5-fold stronger perceived odor intensity [2]	Semi-local odor display
Haptic	Heavier perception	2.5-fold heavier [1]	Electromagnetic actuator and pellets

[1] Measured.
[2] Pre-tested (unpublished results).

2.4.2. Olfactory augmentation

The flavor of a food is significantly contributed by olfactory stimuli (Yeomans, 2006). Olfactory augmentation aimed to associate a perception of meaty flavor with the plant-based balls by adding meat odor in the air with a semi-local olfactory display. Meaty flavor associates with meat products which are generally perceived as powerful in creating satiety (Fiszman, Varela, Díaz, Linares, & Garrido, 2014). Intensity of taste has been shown to suppress the intake of foods (Mccrickerd & Forde, 2016). We assumed that intense odors could act in a similar manner.

The odor display used a headspace technique based on pushing air through the glass bottle containing the odor source. A compressor (HBM

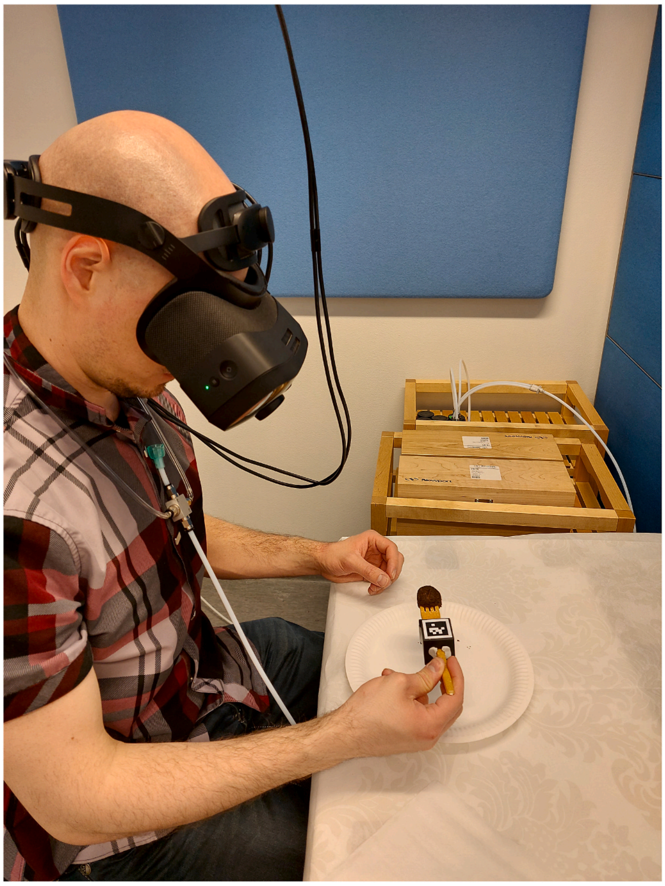

Fig. 2. Augmentation technologies in action at a study visit. Participants wore a head-mounted extended reality display for visual augmentation and an odor necklace with the green tube outlet positioned towards the nasal area for olfactory augmentation. The haptic augmentation was created by an electromagnetic field between actuators embedded in the table surface under the tablecloth and pellets inside the cube attached to the fork.

AS-48, Waddinxveen, Netherlands) produced air that was used as the carrier gas. The air was purified with a cylinder containing activated carbon. The flow of the carrier gas was set to 1.3 L/min with a Q-flow rotameter (Vögtlin Instruments, Switzerland). The air was then directed to a valve manifold (VX210A08, SMC Corporation, Japan) that enabled and disabled air flow to the bottle when needed using an Arduino system. From the bottle, the odorized air was delivered to the participant via polytetrafluoroethylene tubing. The tube was connected to a necklace placed on the participant's chest so that the tube outlet directed the odorous air towards the nasal area (Fig. 2).

The odor material used in the glass bottles was the study meatball. At the beginning of a study visit, a research assistant heated up one meatball, sliced it in four pieces, and put it in the bottle with little hot water at the bottom. The research assistant attached the meatball-containing bottle to the odor display. In the case of the study visits when no augmentation was implemented, a similar glass bottle was filled with 20 ml of tap water and attached to the odor display. In a pre-test with ten (six females, four males; aged 24 ± 6 years) voluntary participants from University of Tampere the odor of the meatball was shown to be 1.5 times the intensity of the native odor of the plant-based ball (unpublished results).

2.4.3. *Haptic augmentation*

The perceived weight of the plant-based ball was augmented as heavier aiming to support the impression of a bigger product created with the visual augmentation. Electromagnetic actuators (Heschen Electromagnet Magnet Solenoid "P80/38, OD") embedded in the table surface, on which the food plate was placed, and metallic pellets inside the cube attached to the fork were utilized to create the haptic augmentation. By activating the electromagnetic actuators using the related software, the perceived weight of the plant-based ball in the fork increased. The haptic augmentation was synchronized with the visual and olfactory feedback to ensure the transition was seamless. The electromagnetic actuators were controlled through a 5 V optical relay circuit triggered by an Arduino system. The system exhibited negligible delay, with the optical relays and electromagnetic actuators having less than a 10ms delay, which fell below the perceptual threshold determined during piloting process.

A 2.5-fold haptic augmentation of weight was chosen based on a pre-test. Participants tended to rate the 2.5-fold augmented ball as heavier than the non-augmented ball (Rantala et al., 2023). The combined weight of the plastic fork with the cube, and the ball was 30 g in total without augmentation and 80 g with the haptic augmentation. The weight augmentation remained reliable within a distance up to 2 cm from the table.

2.5. *Experimental procedure*

The participant was instructed to arrive in the study visits 2.5–4 h after breakfast (Fig. 3). The time between breakfast and a study visit was standardized for each participant and study visits. The study visit lasted for about 30 min. The order of the study products was randomized for each participant, and only one study product type was eaten over one study visit. The participant was seated at a table covered by a white

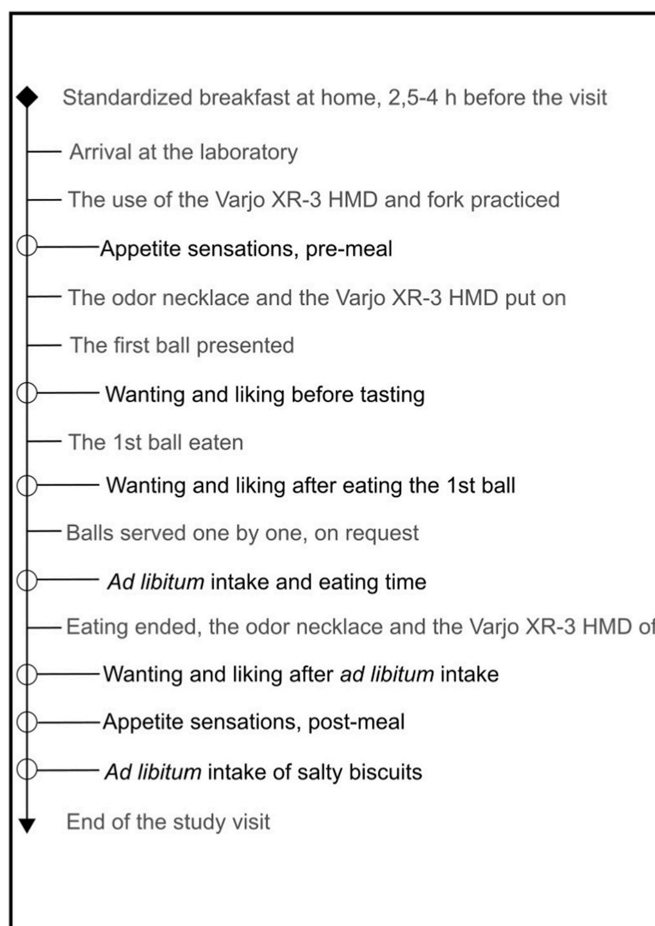

Fig. 3. Experimental procedure (grey font) and measures (black font) at each study visit. HMD, head-mounted display.

tablecloth in a laboratory room. The room was divided by a blank screen so that the participant was not able to see the research assistant's activities and the computer containing the software that was used to switch the augmentation technologies on and off.

First, the participant was asked to put on the Varjo XR-3 HMD and practice holding and lifting the fork in the right position so that the QR-code in the cube attached to the fork was facing towards the participant. Readable QR-code by the HMD was essential for functionality of the visual augmentation. Visual augmentation was switched on for practicing purposes and the participant saw a colorful virtual ball positioned to the fork. After practicing, the HMD was taken off, and the participant was asked to answer the first questions in an online questionnaire regarding gender and age (only at the first study visit) and content and time of eating the breakfast. Appetite sensations were evaluated before and right after eating *ad libitum* number of the non-augmented meatballs or plant-based balls, or the augmented plant-based balls.

The participant was asked to put on the odor necklace and the HMD. While wearing the AR devices, the participant was served the first covered ball by the research assistant who placed a disposable plate on the table at the point where the electromagnetic actuator was embedded in the table under the tablecloth. There was a glass of water on the table and the participant was instructed to take a sip of water after eating each ball. The research assistant instructed the participant to uncover the ball in the fork for evaluation. During the study visit with the multisensory augmentations were switched on by the research assistant using a keyboard at the same time the participant uncovered the ball: The virtual plant-based ball appeared in the fork, the necklace started to provide meatball odor, and the electromagnetism was created between the actuator in the table and the battery pellets in the cube of the fork. In the case of the study visits with the plant-based or meatball without the multisensory augmentation, the assistant just tapped the keyboard without any function to create similar sound as during the augmentation study visit. When the participant was allowed to eat the ball, the research assistant switched the visual augmentation off just when the ball disappeared from participant's vision on the way to the mouth. The olfactory and haptic augmentation technologies were kept on during eating the *ad libitum* number of the augmented plant-based balls. Serving of the balls and switching on and off the visual augmentation when needed was repeated similarly as many times as the participant was willing to eat the balls one by one.

The participant evaluated verbally the liking and wanting of the study product before tasting, after eating one ball, and after eating the *ad libitum* number of the balls and the research assistant inserted the evaluated value in the questionnaire. After eating the served balls until feeling satiated, as instructed in the first place, the participant was allowed to take the necklace and the HMD off. The participant was asked a reason for stopping eating. After all evaluations the participant was served an extra snack (salty biscuits) *ad libitum* to further confirm that a comfortable state of satiety was achieved.

2.5.1. Measures

Eye Question® Software (Logic8 BV, the Netherlands) was used to collect the background information and the evaluations during the study visits. Appetite sensations were evaluated using visual analog scales (VAS) of 0–10 where 0 = not at all and 10 = extremely. The middle point of the scale was marked with a tick and a value of 5. The evaluated sensations were hunger, fullness, desire to eat, prospective food consumption ("How much could you eat right now?"), and satiety. Liking and wanting were evaluated on a numeric rating scale of 1–5 (1 = not at all, 5 = very much). Ready answer options were given to the participants regarding the reasons for stopping eating (1 = "I got satiated", 2 = "I got bored with the taste", 3 = "I hesitated to ask for more", 4 = "I was busy") with also a possibility of giving an open explanation. The research assistant documented the eating time starting from presenting the second ball to the participant (after tasting the first ball and giving the evaluations related to tasting) until the end of *ad libitum* meal, and recorded the number of balls and salty biscuits eaten *ad libitum* without informing the participant.

2.6. Data handling and statistical analyses

The primary outcomes were the effect of the study product (either meatball or plant-based ball) and multisensory augmentation on the number of balls eaten *ad libitum*. The other outcomes were the effects of the study products and multisensory augmentation on appetite sensations, and product liking, wanting and *ad libitum* intake of salty biscuits. Average appetite scores were calculated from the separate appetite sensations as follows: [desire to eat + hunger + (10-fullness) + prospective food consumption]/4. The average appetite score ranges from 1 to 10; the higher the score the higher the feelings of general appetite. Changes from baseline values for the appetite sensations and the average appetite score were calculated by subtracting the evaluations done before eating from the evaluations done after eating. Change from baseline values exclude possible small differences in the baseline values among the study visits. The results are presented as mean ± SD. The criterion for statistical significance was p-value ≤ 0.05.

IBM SPSS Statistics 28.0 software (United States) was used for statistical analyses. A general linear model with Huyng-Feldt correction for the repeated measures was used to study whether there is a within-subject effect of product on the appetite sensations, the average appetite scores and eating times. The within-subject factor had three fixed levels (i.e. plant-based balls, meatballs, and augmented plant-based balls). Friedman's non-parametric test for related samples was used to compare the evaluations of liking and wanting, *ad libitum* intake of balls and salty biscuits. Further, Wilcoxon Signed Rank Test for pairwise comparisons was used to test differences in product liking and wanting. Pearson's bivariate correlation coefficients were used for analyzing dependencies between the *ad libitum* number of balls eaten at different study visits.

After observing a high variation in the number of the plant-based balls eaten *ad libitum* at the augmentation study visit we decided to further analyze the characteristics of the group of participants susceptible to the multisensory augmentation. Those participants who ate less plant-based balls with the augmentation than without the augmentation were defined as "susceptible". Independent samples *t*-test was used for parametric variables (age, average appetite score) and independent samples Mann-Whitney *U* test for non-parametric variables (number of balls eaten *ad libitum*, product liking and wanting) to compare differences between the susceptible and the non-susceptible participants at the augmentation study visit.

3. Results

3.1. Appetite ratings

There were no differences in the ratings of hunger, fullness, desire to eat, prospective consumption, satiety, or calculated average appetite score after the *ad libitum* meal of meatballs, plant-based balls, or augmented plant-based balls (Fig. 4).

3.2. Liking and wanting

Before tasting, evaluated liking of the presented food product differed among the meatball, plant-based ball, and the augmented plant-based ball (Fig. 5A). The augmented plant-based ball was less liked than the meatball or the plant-based ball with no augmentation. After eating the first ball or after eating the *ad libitum* number of balls there were no differences in liking ratings between the balls. Liking of the augmented plant-based ball differed among the evaluation times by increasing after eating the first ball and after eating the *ad libitum* number of the balls as compared to the evaluation done before tasting (p = 0.008).

There were no differences between the balls in wanting to eat before

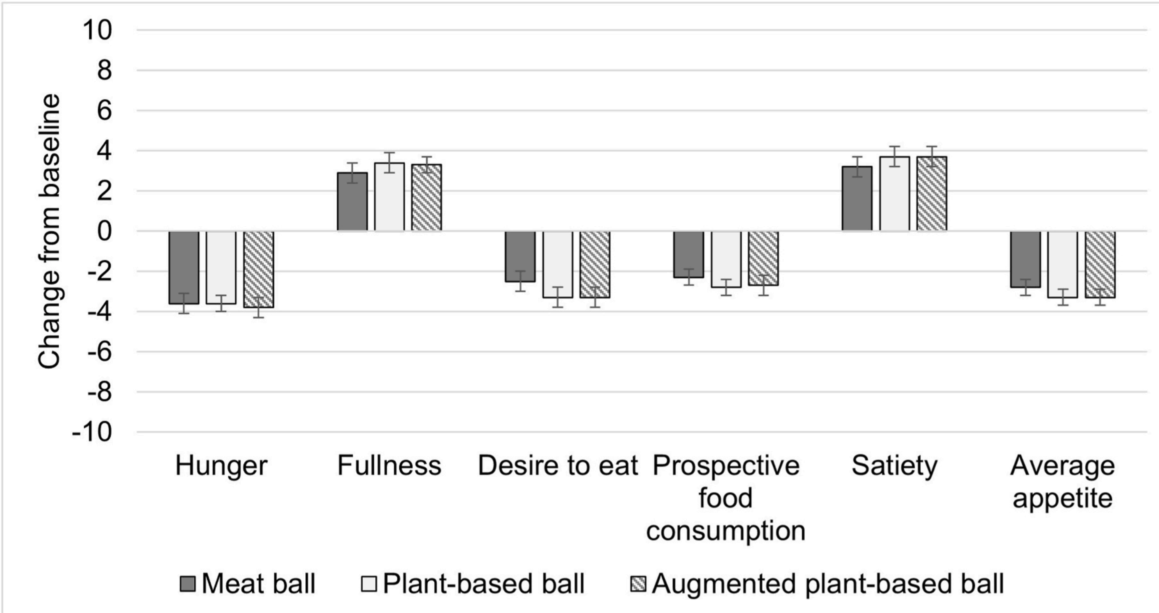

Fig. 4. Appetite ratings (hunger, fullness, desire to eat, prospective food consumption and satiety) and calculated average appetite score after eating *ad libitum* number of balls. All values are relative to the baseline. Bars represent means with standard errors of the means. General linear model with Hyung-Feldt correction for repeated measures showed no differences among the products.

tasting, or after eating the first ball, or after the *ad libitum* number of balls (Fig. 5B). For each type of ball, wanting to eat decreased during the visit ($p < 0.001$). Wanting to eat each of the balls was significantly lower after eating the *ad libitum* number of the ball compared to wanting to eat the same ball before tasting or after eating the first ball.

3.3. *Ad libitum intake*

The mean numbers of balls consumed *ad libitum* were 7 ± 3 for the meatballs, 7 ± 3 for the plant-based balls, and 7 ± 3 for the augmented plant-based balls (Fig. 6). There were no differences between the study visits in the number of balls eaten. Also, the eating times (7 ± 3, 7 ± 3, and 7 ± 4 min for the meatballs, plant-based balls, and augmented plant-based balls, respectively) were similar.

The reasons to stop eating (reported by the participants) were similar at every study visit. The most frequently mentioned reasons to stop eating were "I got satiated" (depending on the visit, 15–17 out of 28 answers) and the second most frequently mentioned reason being "I got bored with the taste" (depending on the visit, 7–12 out of 28 answers). Four participants defined product saltiness being the reason to stop eating meatballs and one participant stated that eating the habitual number of balls was the reason to stop eating at the study visits where plant-based balls or augmented plant-based balls were eaten.

There were strong correlations between the visits in the number of eaten balls (meatballs vs. plant-based balls: $r = 0.797$, meatballs vs. augmented plant-based balls: $r = 0.618$, and plant-based balls vs. augmented plant-based balls: $r = 0.794$; $p < 0.001$ for all comparisons). Only about half of the participants ate any of the salty biscuits that they were offered after eating the *ad libitum* number of balls at each visit (12/28 participants after eating meatballs and 15/28 participants after eating plant-based balls or augmented plant-based balls). The maximum number of salty biscuits eaten was three at each visit. There were no differences in the amounts eaten among the study visits. Regarding the breakfast preceding each study visit, the contents and breakfast times were similar within the participants (data not shown), and the participants arrived at the study visits in similar average state of appetite (6 ± 1, 7 ± 1, 7 ± 2 for the meatballs, plant-based balls, and the augmented plant-based balls study visit, respectively).

3.4. *Characteristics of the participants susceptible to augmentation*

Eleven out of 28 participants, who were defined as susceptible participants, consumed significantly less the augmented plant-based balls (5 ± 2) than the seventeen non-susceptible participants (88 ± 4) ($p = 0.047$). There were no statistically significant differences in the age of participants in the susceptible (35 ± 10 years) and in the non-susceptible (41 ± 12 years) group, or in the gender distribution (four males in both groups). The susceptible participants evaluated the augmented balls as equally pleasant as the non-susceptible participants. However, wanting to eat the product was lower among the susceptible participants before tasting (susceptible 2 ± 1 vs. non-susceptible 3 ± 1, $p = 0.019$) and after eating one ball (susceptible 2 ± 1 vs. non-susceptible 3 ± 1 ($p = 0.002$). There was no difference between these groups in wanting evaluations after consuming the *ad libitum* number of balls. The average appetite score of the participants who were susceptible to augmentation was less suppressed (−2 ± 2) than the average appetite score of those who seemed not to be affected by the augmentation (−4 ± 2) ($p = 0.01$).

4. Discussion

This pioneering study compared the satiation effects of meatballs and plant-based balls and explored the effectiveness of multisensory (visual, olfactory, and haptic) augmentation to enhance satiation. We hypothesized that meatball and plant-based ball with corresponding properties would induce similar satiation measured with *ad libitum* intake, and that the satiety effect could be boosted by augmenting specific sensory elements of the study product. As hypothesized, meatballs and plant-based balls were equal in inducing satiation. However, these novel results showed that the multisensory augmentation did not decrease the *ad libitum* intake of plant-based balls compared to plant-based balls without augmentation or meatballs, but augmentation reduced liking of the plant-based balls when evaluated based on the visual and olfactory inputs received before tasting the product.

Little is known about nutritional properties such as satiation, postprandial satiety, and protein digestibility of plant-based animal-alternative processed food products in comparison to traditional meat

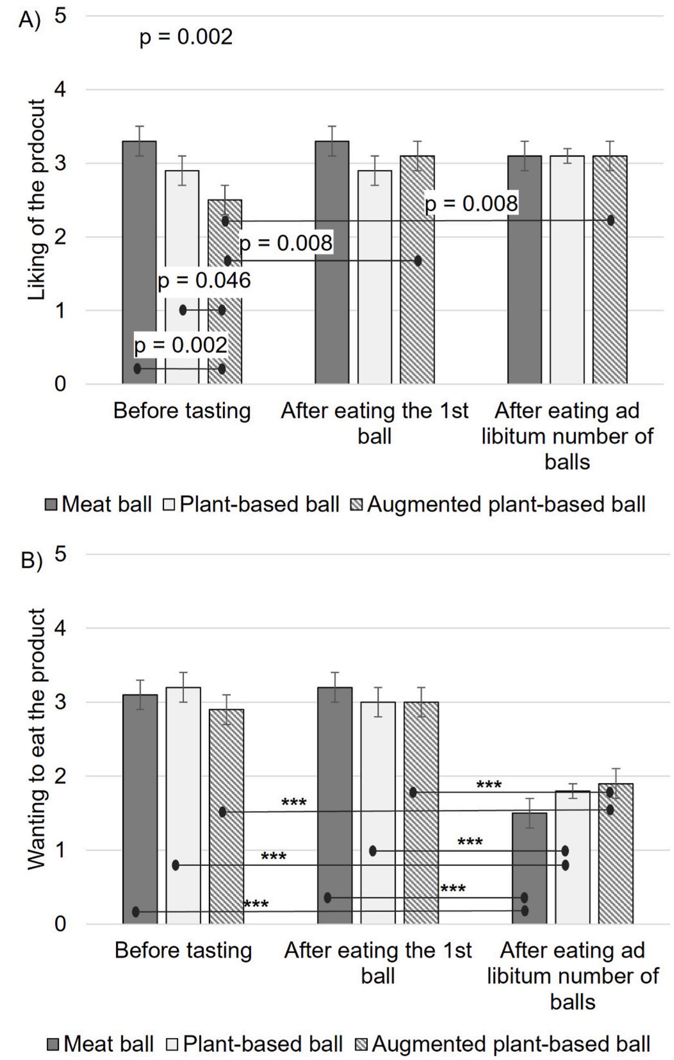

Fig. 5. A) Liking of the product and B) wanting to eat the product before tasting, after eating the first ball, and after eating the *ad libitum* number of balls. Liking and wanting were evaluated with ordinal scale of 1–5 where "1 = not at all …", and 5 = "extremely …". Bars represent means with standard errors of the means. Statistically significant differences between products or within a product between evaluation points (before tasting, after eating the first ball or after eating the *ad libitum* number of balls) are marked with connection lines and exact p-values or with *** when p < 0.001. Friedman's test followed by Wilcoxon Singed Rank test for pairwise comparisons.

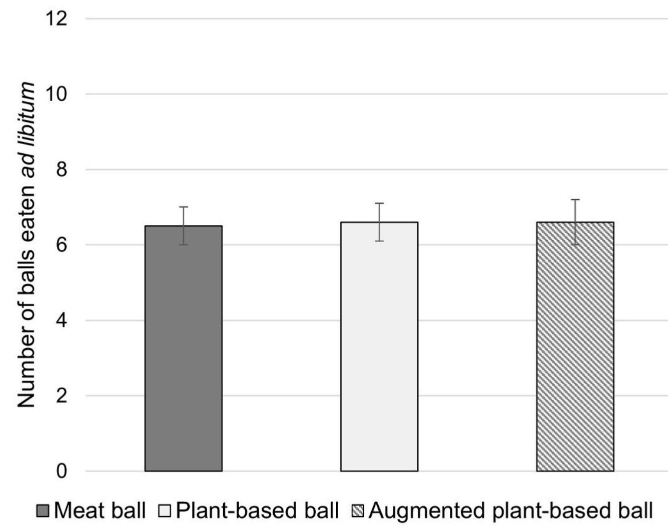

Fig. 6. Number of balls eaten *ad libitum.* Bars represent mean numbers of eaten balls with standard errors of the means. Friedman's test showed no differences among the products.

products (Lappi, Silventoinen-Veijalainen, Vanhatalo, Rosa-Sibakov, & Sozer, 2022). The results show that meatballs and plant-based balls were equal in bringing about satiation when not marked for their content or brand name. Previous studies have shown that plant-based products are either superior (Klementova et al., 2019; Kristensen, Bendsen, Christensen, Astrup, & Raben, 2016; Muhlhausler, Belobrajdic, Wymond, & Benassi-Evans, 2022) or equal (Pham et al., 2022) to meat-based products in maintaining post-prandial satiety. As carnivorous consumers belief plant-based meat alternatives to be less satiating than flexitarians and omnivores (Spendrup & Hovmalm, 2022), these results regarding both satiation and post-meal satiety are essential when aiming to encourage them to the dietary shift towards plant-based diets and simultaneously fighting against overconsumption of food.

The approach of using AR to enhance satiation is novel as there is only one previous published study from this field (Narumi et al., 2012). However, AR has the capability of modifying sensory experiences which, for one's part, guide the decision about a suitable meal-size. Since previous guiding research related to satiety and methods in the field were missing, we designed the augmentations to emphasize the sensory properties of foods that have been previously shown to enhance satiation or are plausibly linked with enhanced satiation (visual and haptic impression of a bigger product, meaty and more intense odor).

The multisensory augmentation applied in this study was not effective in limiting the *ad libitum* intake of plant-based balls among the whole group of participants. Either our hypothesis was proven wrong or there were some other explaining factors such as, the dictating role of the sensory inputs received during eating, learnt satiety determining suitable portion size, or the chosen augmentations that mixed the results. Firstly, the augmented ball was less liked based on the experience prior tasting which indicates that the visual and/or olfactory augmentation did impact somehow on the overall product experience at that point. However, after tasting and eating the product the liking evaluations increased to the same level as those of the other products. This indicates that the augmentation was able to change participants' preconceptions but the closer interaction with the plant-based ball during tasting and eating dispelled the possible doubts concerning the product. Since liking does influence food selection, the augmentation types used in this study could be used for limiting or guiding food intake at the point of selecting food for consumption, for example at a buffet line. It has been shown that people tend to consume the meals they have selected in their entirety (Brunstrom, 2011) and therefore the choice situation in a restaurant setting is crucial. We propose that future studies would focus on exploring the effects of visual, olfactory, and haptic augmentation as applied in this study on food choices pre-meal. Another approach would be to test AR techniques that influence the sensory perception, namely taste and texture during eating. Examples of experimental approaches aiming to impact taste perception are the works where taste perception was influenced either by applying electric current to the tongue or by applying thermal sensations to the skin on the nasal area. Nakamura and Miyashita succeeded to enhance the intensity of perceived taste of fish sausage by applying cathodal current to the tongue via fork during eating (Nakamura & Miyashita, 2013), Ranasinghe and colleagues modified the saltiness and sourness perception of a drink by applying electrical stimulation at the tip of the tongue via a mouth piece (silver electrodes) attached to a cocktail glass (Ranasinghe et al., 2017), and Suzuki's research group developed and tested a system named "Affective Tumbler" that applies thermal sensations to the skin around the nose during drinking to modify flavor perception (Suzuki, Narumi, Tanikawa, & Hirose, 2014). Regarding augmented texture, a preliminary work of Iwata and colleagues describes a prototype “Food Simulator” which is a haptic device that generates force on the user’s teeth to mimic different food textures (Iwata, Yano, Uemura, & Moriya, 2004) whereas Koizumi and colleagues developed a “Chewing Jockey” a system that synchronizes sound effects with jaw motions during eating giving an impression of different textures (Koizumi, Tanaka, Uema, & Inami, 2011). The impact of AR approaches more strongly related to actual eating (taste and texture) on satiation would be worth studying.

Secondly, we observed strong correlations in the number of balls eaten during each study visit. This might indicate that the products were equally satiating. Another possible explanation is that people learn to eat a fixed amount of a familiar food based on their previous experiences on a suitable portion size for that specific food (Brunstrom, Shakeshaft, & Alexander, 2010). The individual’s learnt satiety towards the used product category (balls) may have exceeded the possible subtle influence of the augmentation. The fact that the balls were eaten one by one may have also increased the awareness of the amount eaten. To gain more detailed information about the reasons to stop eating, we should have used a validated Reasons Individuals Stop Eating Questionnaire (RISE-Q) (Cunningham & Rolls, 2021). Using RISE-Q might have revealed if the participants ate a pre-planned amount of the balls.

Thirdly, three types of augmentations (visual, olfactory, haptic) were applied at the same time. We cannot rule out whether some of the distinct augmentations would have been effective when applying alone or whether some of those influenced the opposite direction. In a separate study of our group where similar balls were served in a random order at the same study visit, we observed that the liking towards the plant-based ball was increased when applying only olfactory augmentation, but mere visual augmentation, or combined olfactory and visual augmentations, did not have the same effect (Pikkusaari, 2023). Thus, if the meaty odor was perceived pleasant as such, it might have increased *ad libitum* food consumption especially in sensitive individuals (Mccrickerd & Forde, 2016). The Varjo XR-3 HMD is quite heavy and wearing it through the experiment might have distracted the participants. In addition, visual augmentation at this stage of development did not give a realistic impression about the study product which might have distracted the participants. We aimed to influence unconscious perception of product weight. As for pretesting the haptic augmentation, the participants tended to rate the haptically augmented plant-based ball as heavier than the non-augmented plant-based ball and meatball (Rantala et al., 2023). An earlier study (Hirose et al., 2015) raises a question whether 70–100 % increase in virtual weight of the food object attached to a fork system is enough for a perception as if the amount of the food content was increased. The previous studies of this group provide preliminary understanding on the impact of distinct augmentations on participants’ perceptions, but the augmentations were not used as a combination nor was their impact on satiety studied. Additionally, the characteristics of the participants varied from study to study. Therefore, no straightforward deductions to support influence of the selected combined augmentations on satiety can be made based on those.

Several predetermined methodological choices and observed factors indicate that the trial as such was methodologically successful to study satiation. The participants followed the instructions about breakfast content and timing well for controlling their pre-meal appetite state. The chosen meatballs and plant-based balls were close to similar regarding nutrient content, energy density, and structure and volume excluding possible differences in acute physiological responses during oral and gastric phases affecting satiety. They were also equally liked, which is essential in satiation studies for controlling possible differences in satiation due to palatability (Blundell et al., 2010; Sørensen et al., 2003). The expectations towards the following meal are also important for the choice of suitable meal-size (Blundell et al., 2010). The expectations were controlled by informing the participants beforehand about the fact that they would be given a fixed portion of ready-made salad after each study visit. The results show that liking of the products remained the same during the study but wanting to eat them decreased as expected. The participants achieved a similar state of satiety after each *ad libitum* study meal indicating that they managed to follow the instruction to eat until they felt pleasantly full. Also, there were no differences between the number salty biscuits consumed *ad libitum* between the study visits.

Previous research has revealed a high individual variability in satiety responsiveness highlighting the need to further explore subgroups with different responsiveness towards interventions (Gibbons et al., 2019). We divided the participants into those susceptible to augmentation (reducing the *ad libitum* eaten amount of plant-based in response to augmentation) and to those not affected by augmentation. The members of both groups liked the products equally, but the susceptible group expressed lower wanting towards the augmented product before tasting and after eating the first ball. They had higher appetites after the meal indicating that they did not achieve a similar satiety state as the other group did. The reason for the lower wanting to eat the product, which led to smaller number of consumed balls and poorer satiety, remains unclear. The groups were similar regarding age and gender. Food neophobia meaning reluctance to eat new foods (Dovey, Staples, Gibson, & Halford, 2008) could be one factor explaining reduced intake which could be mediated by suspiciousness towards the augmented product in the subgroup of the participants. Unfortunately, food neophobia or attitude towards AR were not measured in this study. In any case, the effectiveness of augmentation on various groups of people and personalizing interventions is a topic worth further investigation.

We consider that the major limitation of this study is that the impact of the selected distinct augmentations on satiety was not pilot tested. Expected satiation would have been an ideal measure to pre-test since it is a simple procedure and predicts actual satiation relatively well (Brunstrom, Collingwood, & Rogers, 2010). Another drawback is that the influence of augmentation on the sensory perception was not quantified, and the participants were not asked about their attitude towards multisensory augmentation or their actual experiences of it during the study. The low technology readiness level of visual augmentation may have affected the results.

5. Conclusions

Meatballs and plant-based balls were equally effective in bringing about satiation which is a promising result supporting the shift towards plant-based diets. Simultaneous visual, olfactory, and haptic augmentation was not effective in enhancing satiation in non-obese adults but decreased liking evaluations before tasting the augmented study product. However, liking evaluations of augmented plant-based ball increased to the same level than those of plant-based balls and meatballs when evaluating liking after eating the first ball or *ad libitum* number of balls. The study products did not differ regarding wanting to eat the product before tasting, after eating the first ball or after eating the *ad libitum* number of balls.

Funding

This work was supported by the Academy of Finland [grant numbers 316804 and 316805].

Ethical statement

All participants gave their informed, signed consent to participate before the study began. The study was conducted according to the ethical principles and good research practices described in the European Code of Conduct for Research Integrity. The study aim, design, procedure, and personal data management were evaluated and approved by the ethics committee of VTT Technical Research Centre of Finland Ltd on the 21st of June 2022.

CRediT authorship contribution statement

Saara Vanhatalo: Conceptualization, Methodology, Visualization, Writing – original draft. **Jenni Lappi:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. **Jussi Rantala:** Methodology, Software, Writing – review & editing. **Ahmed Farooq:** Methodology, Software, Writing – review & editing. **Antti Sand:** Methodology, Software, Writing – review & editing. **Roope Raisamo:** Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing. **Nesli Sozer:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank Dr. Heikki Aisala for conducting preliminary tests to define suitable odor intensity and Mr. Mika Astrèn for assistance in the data collection.

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