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ORIGINAL PAPER

The effects of haptic, visual and olfactory augmentations on food consumed while wearing an extended reality headset

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Abstract

The current food production system is unsustainable, necessitating a shift towards plant-based diets. Nutritious options fulfill basic needs but may not satisfy hedonic ones. Our novel approach is to promote healthier eating habits without compromising on the pleasantness of eating by using extended reality technologies and multimodal interaction. We present a multisensory augmentation system integrating augmentations in olfaction, touch, and vision. We studied the experience of eating plant-based balls and meatballs. In an experiment with 40 participants, haptic and visual augmentations were found to have significant effects: augmented meatballs and plant-based balls were perceived as bigger and heavier compared to non-augmented versions. However, olfactory augmentation did not produce a similar effect: participants did not notice a stronger aroma with augmented balls compared to non-augmented balls, and the augmented plant-based version had a less appealing scent than its non-augmented counterpart. Moreover, the findings of the study indicate that our multisensory augmentation system had no significant effect on taste perception.

Keywords Multisensory augmentation · Eating experiences · Olfaction · Haptics · Mixed reality · Augmented reality

1 Introduction

The current food production system is unsustainable and there is an acute need to shift towards plant-based dominated diets. While healthy and sustainable foods can satisfy our basic physiological needs, they may not always fulfill our desire for pleasure, creativity, and enjoyment associated with eating. A promising avenue for promoting balanced and health-conscious eating experiences is the integration of extended reality (XR) and multimodal interaction technologies. For a thorough summary of multimodal interaction technologies available for XR systems, we refer to a recent scoping reviewed by Rakkolainen et al. [1].

Consuming food is a multisensory event, engaging all five basic human senses to shape our perception of flavor [2] and the eating experience [3]. Researchers in human–computer interaction (HCI) and human-food interaction (HFI) have explored various techniques to enhance food flavor and

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the eating experience through visual [4–6], auditory [7], haptic [8], olfactory [9, 10], and gustatory [11, 12] modalities. Previous studies have demonstrated, for instance, that sugar-free coffee together with chocolate odor may enhance the perceived sweetness compared to the case with no added scent [13], altering the visual size of a cookie can reduce its consumption [14], and that aroma cues can influence the perceived sweetness of desserts [9]. However, most prior research employed single sensory modalities for augmentation. In this study, we introduce a multisensory augmentation system that simultaneously utilizes olfactory, visual, and haptic cues to enrich the consumption of the test foods. Multisensory augmentation was used in an experiment with 40 participants, wherein the eating experiences of plant-based balls and meatballs were enhanced using these three sensory modalities. The objective results and subjective feedback from the participants, collected through questionnaires and interviews, shed light on their perceptions of the augmented food experiences.

There exists previous research that involves the use of virtual reality (VR) in augmented eating experiences. An example is the study conducted by Waal et al. [15], where the authors introduced virtual chocolate and observed that virtual food cues closely mimic real-world cues in evoking food cravings. Meanwhile, Li and Bailenson [16] investigated the impact of touching and smelling a virtual donut in an immersive virtual environment. Additionally, in Weidner et al.'s study [17], participants consumed raw zucchini mash while simultaneously receiving visual and olfactory cues of various foods through a system based on a VR headset, an odor-dispensing spoon with a fan, and motion tracking. In contrast, only few studies have made use of augmented reality (AR). Ueda et al. [18] delved into the effects of changing the luminance distribution in food images through AR. Additionally, Nakano et al. [19] explored the influence of visual modifications on food recognition, revealing that visual alterations had a more pronounced impact compared to changes in the taste perception.

We continue by summarizing the related work both in sensory augmentation technologies and augmentations applied in XR eating contexts. Then, we present the design of our multisensory augmentation system, including the olfactory, haptic, and visual augmentation technologies used. This is followed by the design and results of the experiment. Finally, we discuss the results in the context of previous work, the limitations and potential future work, followed by the conclusions.

2 Related work

We start by presenting previous work in sensory augmentations for eating experiences. Extended reality (XR) is an umbrella term covering virtual reality (VR), augmented reality (AR) and mixed reality (MR). VR is as a fully immersive experience different from AR/MR. Even though we discuss selected relevant studies in VR, we are focusing here on AR and MR research. Typically, MR refers to systems where sensory augmentations are co-located with the real physical objects or locations that are augmented. AR is used to present additional information that may or may not have any direct connection to the real environment. However, the use of these terms is not fully established, and they may have been used interchangeably in the previous work. Due to this, we group all the AR/MR augmentation studies under AR.

2.1 Sensory augmentations for eating experiences

Researchers in human–computer interaction (HCI) and human-food interaction (HFI) have explored various techniques to enhance food flavor and the eating experience through many kinds of augmentations. Concerning auditory approaches, Velasco et al. [7] highlighted the significance of food and drink-related eating sounds in human-food interaction design. Notable systems in this context include Koizumi et al.'s "Chewing Jockey" [20], which uses mastication sounds to enhance the food texture perception and enjoyment, and Kadomura et al.'s "EducaTableware" [21], consisting of a fork and a cup that generate sounds based on resistance values during eating and drinking to encourage better eating habits, especially among children. Related to auditory approaches, in Wang's et al. [22] study, researchers used time intensity to measure weather alterations in the auditory stimulus could induce changes in the intensity of a particular taste element in wine. Their experiment involved utilizing two consecutive soundtracks, one comprising of 15 s of "sour" music followed by 15 s of "sweet" music, and the other with the reverse order of music. The soundtracks were played while participants drank the same wine in each trial and rated its sourness and sweetness. Their findings revealed that the perception of wine's sweetness decreased when transitioning from sweet to sour in the soundtrack, while it increased when transitioning from sour to sweet. Their findings suggested that the changing auditory soundtrack could influence individuals' taste evaluations over time, even when the beverage itself remains unchanged.

Hirose et al. [8] developed "Gravitamine Spice", a system using a fork and seasoning called "OMOMI" to let users change the perceived weight of their food by adding seasoning to it, thus creating a method for the haptic augmentation. For larger food items like muffins, Farooq et al. [23, 24] used silicone pellets injected with mR fluid embedded within the edible product to augment its weight [25, 26]. These pellets were created using injected molding with OOMOO 30 Silicone Molding kit (Smooth-Cast 300). Clepper et al. [27, 28] applied a similar design to ensure stability and dynamic adjustability while maintaining the edibility of the food items in their haunted house setup. However, in most cases the food item in question is not completely edible or simply actuated to provide tactile or proprioceptive feedback before consumption of unmodified items. Additionally, due to hygienic requirements, augmenting each item scheduled for consumption can be difficult and time consuming. Regarding olfaction, Aisala et al. [9] designed an olfactory system to infuse custom rye-based cakes with reduced sugar content with specific odors. Their findings indicated that enhancing a reduced sugar rye-based cake with localized odors such as maltol, vanilla, and strawberry led to a higher perception of sweetness when compared to an odorless cake. Other studies have shown that sugar-free coffee together with chocolate odor may enhance the perceived sweetness compared to the case with no added scent [13].

Finally, concerning the gustatory augmentations, Ranasinghe et al. [11] created the "Digital Taste Synthesizer", which involves stimulating the tip of the human tongue with a pair of silver electrodes. This technology integrates electrical and thermal approaches to mimic fundamental taste perceptions, uniting these methods into a unified system that offers improved control through a linked computer. With a different approach, James et al. [29] conducted a user study to examine how six different types of video content, including nature, cooking, and the emerging food video genre called "mukbang" [30–32], influence people's perceptions of taste sensations, liking, and emotions while consuming plain white rice. The research findings highlighted significant differences in participants' perceived taste sensations based on the various video content types. For instance, participants reported feeling "calm", "satisfied", and "peaceful" emotions when watching nature videos depicting serene natural scenes while eating, despite the taste of the food remaining unchanged. In contrast, when exposed to mukbang videos where individuals consumed spicy food, participants reported sensing spiciness and saltiness in their rice merely by observing the streamer's facial expressions. These findings suggested that videos watched during meals can amplify taste sensations without the addition of physical or chemical flavorings.

2.2 VR applications in augmented eating experiences

There exists previous research that involves the use of VR in augmented eating experiences. VR has emerged as a valuable tool for creating realistic environments in food sensory research. It offers promising opportunities for innovative studies in food and consumer behavior, especially for investigating challenging real-life scenarios, like the impact of in-store factors on purchasing decisions [33]. Pennanen et al. [5] found that VR could enhance eating experiences and promote healthier food choices by positively affecting product evaluations. In addition, multiple studies have shown that VR can effectively elicit psychological responses like food cravings and aversions [15, 34, 35]. An example is the study conducted by van der Waal et al. [15] where participants were exposed to either food or non-food cues, both in a VR environment and in real life. In the food-related condition, four different chocolate flavors were presented to increase the chances of evoking food-related responses, as chocolate is widely considered a treat. In the non-food condition, wooden blocks resembling chocolates in shape and size were used as cues. In their study, it was found that virtual food cues closely resemble real-world cues in stimulating food cravings. However, physiological responses, such as salivation, were not significantly influenced by exposure to virtual food cues.

Li and Bailenson [16] explored how touching and smelling a virtual donut in an immersive virtual environment affected subsequent donut consumption. The participants interacted with a virtual donut in two ways: feeling its touch and smelling its scent or not. The results showed that touch or scent cues increased participants' connection to the virtual donut. The hunger levels remained consistent across conditions. However, when both touch and scent cues were present, the participants consumed fewer donuts. Those who touched the virtual donut felt more satisfied, as did those who smelled it, particularly if they did not touch it. In summary, touch or scent cues in VR heightened the perception of interaction and increased satisfaction. However, when both cues were combined, the donut consumption decreased without significantly altering the amount eaten. VR systems are not in the main scope of the present work, but most of the technologies applied in VR are also applicable in AR which makes them relevant to our present needs.

2.3 AR applications and uses in food context

In a review conducted by Chai et al. [36], the authors examined past research to explore the utilization of AR technologies in the context of food. Their investigation revealed that AR technology is predominantly employed in the following domains: dietary assessment, tracking food nutrition, conducting research on food sensory perception, applying it to retail food industry scenarios, employing it in food-related educational and training contexts, and utilizing it for precision agriculture purposes. For the scope of this research, our focus was on analyzing the applications of AR technology in the field of food sensory science.

2.3.1 Augmentation for changing sensory perception of food

In the field of food sensory science, AR technology has increasingly been examined for its capacity to enhance the perception of food consumed via gustatory, visual, olfactory, haptic, and auditory cues [37]. Most of the studies utilizing AR have focused on changing the appearance of food. Ueda et al.'s study [18] explored how altering the luminance distribution of food images using AR influenced not only the perceived visual texture but also taste and flavor experiences. Visual cues are pivotal in stimulating the desire to eat, setting expectations for taste, flavor, and overall palatability, impacting acceptance and consumption patterns. Their findings indicated that changes in luminance distribution not only impacted the expected taste and flavor attributes of the food, such as moistness, wateriness, and deliciousness, but also influenced how the taste properties of food were perceived. Additionally, Nishizawa et al. [4] developed a projective-AR system to change the visual appearance of food and plates. In experiments, they discovered that the perceived sweetness of castella, a Japanese sponge cake, increased with higher color saturation (chroma). However, when they applied the system to potato chips, they noted varying color saturation, indicating potential associations between specific colors and flavors.

AR augments real-world settings by adding digital sensations, enriching food sensory perception. Nakano et al.'s research [19] further delved into the influence of AR on food perception. The participants found it challenging to eat while wearing a Head-Mounted Display (HMD), reporting intensified taste sensations for visually presented "target" foods. Notably, AR significantly altered food recognition without altering taste perception. In their main experiment, Nakano et al. [19] continued exploring the impact of visual modulation on food recognition, revealing that visual changes had a stronger effect than taste perception. Not all participants felt they were consuming the visually presented food, but the system successfully manipulated gustatory sensations, aligning perception with visuals. However, the quality of visual images was critical, and the system could reduce perceived food taste. Eating with the HMD worn in the head was challenging and affected the overall experience. In summary, AR technologies offer a unique capability to augment or modify environments or objects by adding digital sensations to real-world settings, making it a valuable tool for enhancing the sensory perception of food [36].

2.3.2 Augmentation for changing eating behavior

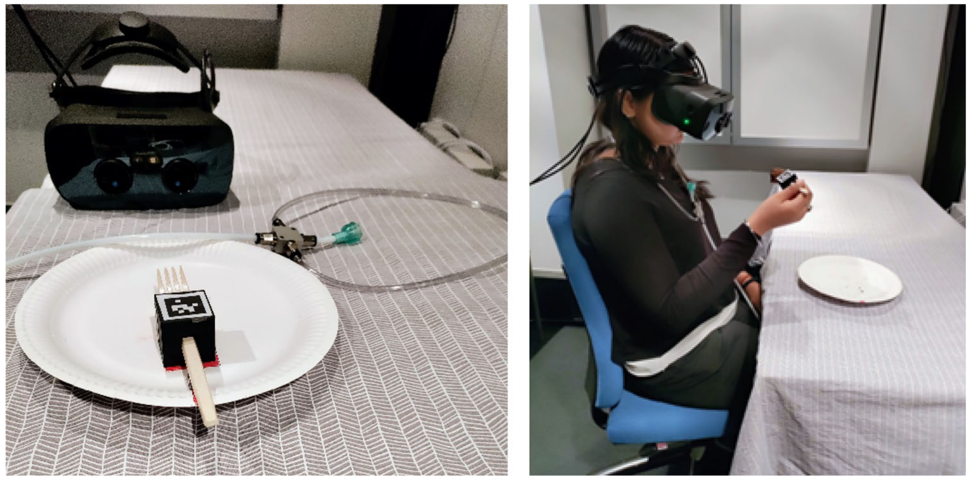
Another aspect worth exploring is how AR technology can impact eating behavior. It is of note that AR technology does not make a product healthier but can contribute to healthier or even more sustainable eating habits. Several environmental factors, including the size of plates or packaging, the type of food, and the eating context or environment, have been identified as influential factors in eating behaviors [38, 39].

Especially, visual cues influence chosen and consumed meal size. Visualizing the portion size and appearance of food affects expected satiety and thus determines the amount of food planned to be consumed [40]. In a previous study, Narumi [41] proposed the use of HMD-based AR system to visualize food portions and transform them to appear larger than their actual sizes. The results of this study revealed that altering users' visual perceptions of food size through AR was linked to food consumption. Specifically, when the augmented food size was portrayed as larger than reality, it led to reduced food consumption. MetaCookie + [10] is a technology that alters the perceived taste of a cookie by adding visual and olfactory cues using a special AR marker pattern. The system allows users to experience different flavors by adjusting visual and olfactory cues without altering the cookie's actual ingredients. The presented system has the capability to transform the taste of nutritionally regulated meals from unpalatable or bland to delicious and desirable. In further studies, it has been found that altering the visual size of a cookie can reduce its consumption [14]. These findings shed light on how AR technology can be applied to potentially influence and modify eating behavior, particularly in relation to portion size perception and consumption patterns [36].

2.4 Multisensory integration

Multisensory integration (MSI) is the cognitive process through which information from various sensory systems is combined to form a unified perceptual experience [17]. This process significantly influences our behavior and overall sensory experiences [42]. Generally, MSI is more straightforward when the sensory input aligns in terms of their identity or meaning, a phenomenon known as semantic congruency [43]. Leveraging the concept of multisensory integration, research has demonstrated the potential of AR and VR to manipulate the perceived taste of food and beverages by presenting congruent stimulus. A study conducted by Ammann et al. [34] investigated how a simple change in the color of a cake (yellow for lemon/sour and brown for chocolate/sweet) influenced participants' perception. The results indicated that when the cake's color was altered, the individuals experienced greater difficulty in accurately identifying the actual flavor, suggesting a conflict in the MSI process.

In Weidner et al.'s study [17], the participants consumed raw zucchini mash while simultaneously receiving visual and olfactory cues of various foods (banana, carrot, tomato, and cucumber) through a VR headset, an odor-dispensing spoon with a fan, and a motion tracking system. Their participants were presented with both incongruent and congruent pairs of olfactory and visual stimuli and were asked to identify the food and rate its pleasantness and intensity. The results showed that participants had difficulty merging visual and olfactory cues when consuming a tasteless food item. Some of them could not identify a specific food and simply called



A. B.

Fig. 1 The multisensory augmentation system composed of an XR headset, a prototype olfactory necklace display, and a fork with a QR code marker providing haptic feedback (**A**). A user utilizing the system while eating an augmented meatball (**B**)

it a "vegetable" or "fruit." This suggests challenges in synthesizing a unified perceptual experience from multisensory inputs. Interestingly, this difficulty was equally prevalent in trials with tri-modal incongruency (36 out of 360 trials, 10%) and congruent visual-olfactory trials (10 out of 120 trials, 9.2%). Notably, during tri-modal incongruency, many responses (201 out of 360 trials) did not relate to the presented stimuli, underscoring the complexity of multisensory integration in these situations.

3 Multisensory augmentation system

The aim was to design a multisensory augmentation system that can enhance the eating experience of a person when consuming real food products. The augmentation technology, depicted in Fig. 1, consisted of a Varjo XR-3 extended reality headset [44], a prototype olfactory necklace display created by the authors, and a fork providing haptic feedback generated through electromagnetic actuators and equipped with a visual QR code marker, which was also created by the authors. With this system, it was possible to augment different food products that could be eaten with the fork. The three augmentation modalities could be independently enabled or disabled as needed. In the following subsections, we provide a detailed explanation of the components of each augmentation modality.

The components of the multisensory augmentation system are presented in Fig. 2. Olfactory augmentation (Fig. 2, left) represents the pathway of odor delivery, starting from the compressor and leading to the participant's nose. Haptic augmentation (Fig. 2, center) consists of the components of the haptic feedback system, from the fork with the QR code cube, the electromagnetic actuators, and their control for perception modification. Visual augmentation (Fig. 2, right) is based on a visual feed modification process, beginning with the Varjo XR-3 headset cameras, supported by the tracking mechanism using the 3D-printed QR cube on the fork, and completing with the mixed reality representation of the food item which completely replaces the real image of the food item.

3.1 Olfactory augmentation

A custom odor display was designed for augmenting food products with natural odors. The odor display used a headspace technique based on pushing air through a glass bottle containing an odor source. A compressor (HBM 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. 3). The effectiveness of this odor delivery method was ensured in a pilot test where participants indicated that they could perceive the presented odor.

The odor materials used in the glass bottles were the meatball and the plant-based ball. At the beginning of a study visit, the experimenter heated up one meatball for 20 s, sliced it in four pieces, and put it in the bottle. The same procedure was done with the plant-based ball. The meatball-containing bottle was connected to the odor display and used in the augmented meatball condition, whereas the plant-based ball odor was utilized in the augmented plant-based ball condition.

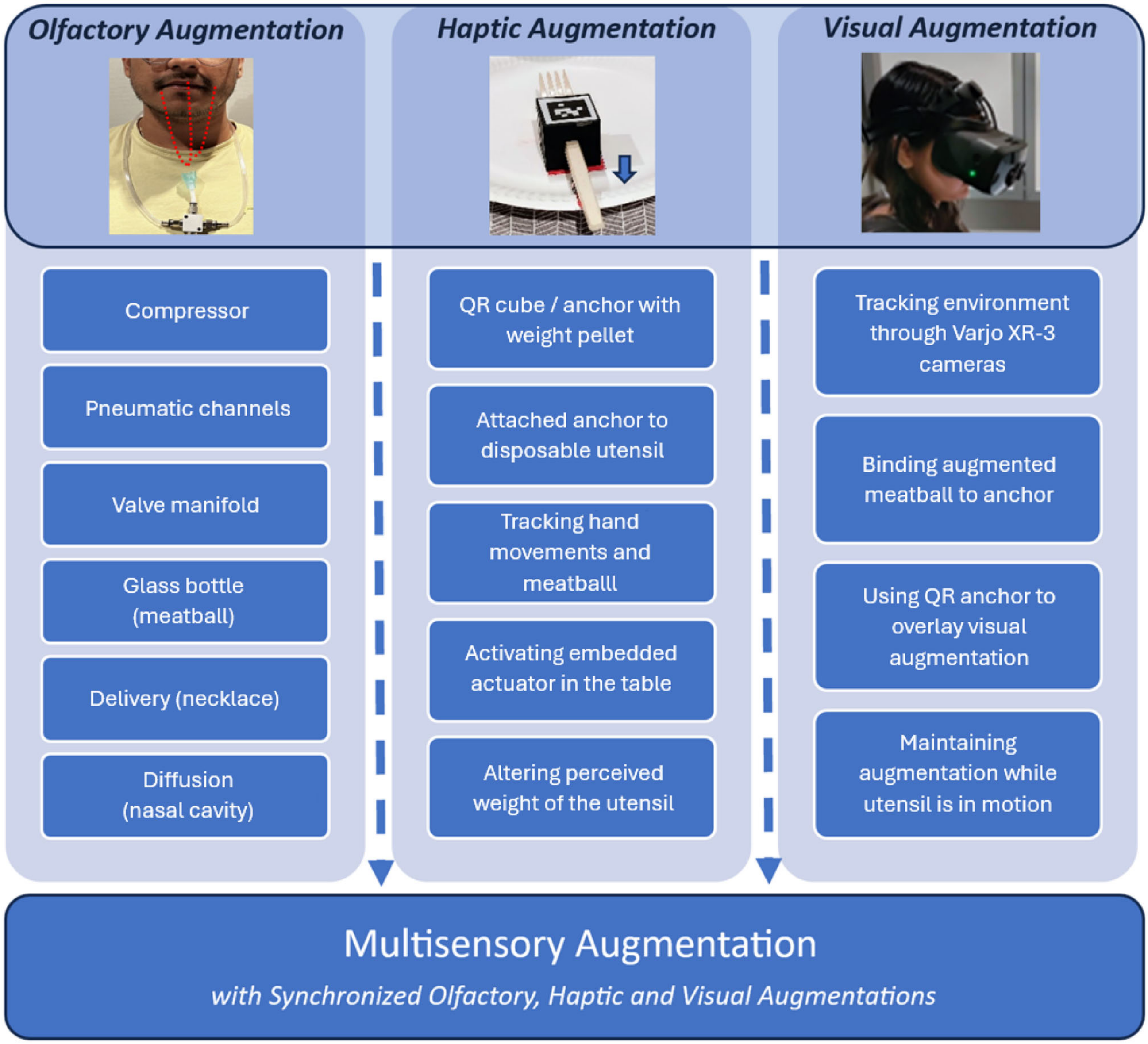


Fig. 2 The components of the multisensory augmentation system—olfactory, haptic, and visual augmentations—are produced in parallel and synchronized to provide a true multisensory extended reality experience. The vertical axis represents the order in which the individual steps of each augmentation were carried out. For example, the olfactory augmentation started from producing compressed air (top) and ended with diffusion of odorous air (bottom)

When the products were presented with no augmentation, a similar glass bottle was filled with 20 ml of tap water and attached to the odor display to emit fresh air. In this experiment, the compressor ran continuously, and its operation was not directly linked to the odor output. When odor was not required, clean air was expelled through an extra valve. When a scent was required, the valve in use was switched to allow air to flow through the scent bottle to the necklace. The odor exposure duration when eating a single meatball or plant-based ball was typically between 5 and 10 s. Additionally, to minimize any noise disturbance, the compressor was situated in an adjacent room separate from the experiment room.

3.2 Haptic augmentation

The haptic augmentation was designed to modify the perceived weight of edible products and investigate the role of weight on users' eating behavior specifically on satiety. Various techniques were piloted to dynamically adjust the structure, weight and overall feel of the products while

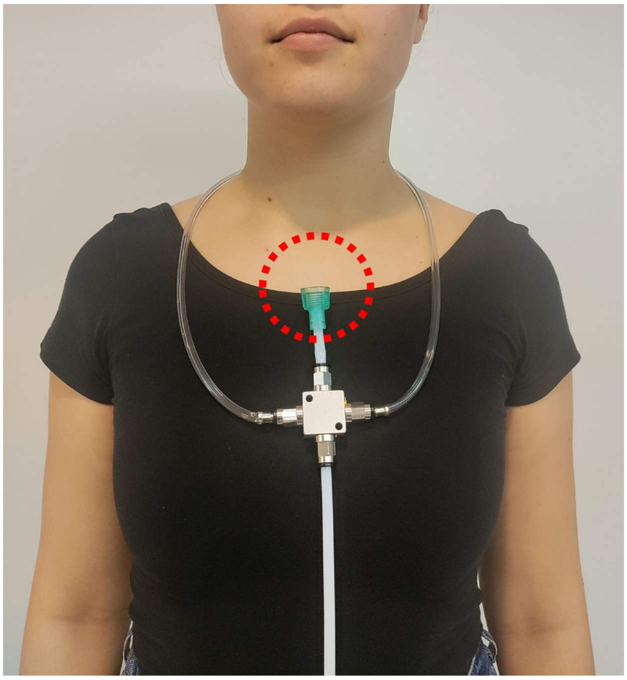


Fig. 3 A user wearing the olfactory necklace display; the tube outlet that directed odorous air towards the nasal area is highlighted with a circle

ensuring their edibility. Electrorheological (eR) and magnetorheological (mR) fluids were shortlisted as the most promising technologies to achieve the desired effect. For indirect food consumption where utensils such as forks, knives and spoons are utilized, it is possible to augment perceived weight by attaching custom-developed metal pellets onto the utensils yet ensure hygiene requirements. In combination with powerful electromagnetic actuators recessed within the tabletop along with the custom designed utensils, it is possible to dynamically adjust the perceived weight and provide haptic feedback for a wide range of food items keeping them edible and safe for consumption within various experimental setups.

We tested a wide range of weight augmentations by adjusting the perceived force vectors of the utensil. This user study utilized a plastic fork that weighed ~ 4.3 g with no additional augmentations or attachments. In our testing we found that the perceived weight of the fork depended on the actual force vector necessary to lift the fork (magnetic attraction between the fork and the magnetic actuators) and the attached food item (ball) as well as the fulcrum point (i.e. point where the fork handle was grasped while lifting). Therefore, both variables needed to be fixed across the user study. To achieve the latter, we asked all participants to grasp the fork from the same location on the handle and this was rehearsed during the initial practice phase of the session.

To ensure the force vector remained constant and relevant to the visual augmentation, we tested various attractive forces between the fork and the recessed actuator hidden within the table. We chose a fork attached to a physical cube with a QR code housing the metal pellets (Fig. 4D), ensuring that actuation can be delivered directly to the utensil. The cube was 3D printed to minimize any extra weight to the fork, and to house the pellets seamlessly. Electromagnetic actuators embedded in the table surface, on which the food plate was placed, were utilized to activate haptic augmentation. By activating the electromagnetic actuators using the experimental interface, the perceived weight of the plant-based ball and meatball on the fork increased. We found that to simulate a perceptually significant force a ratio of twice the weight of the meat/plant-based ball with augmentation compared to without augmentation (X = 40: Y = 60: Z = 140) [or simplified to (2:3:7)] was ideal, where "X" was the reference force needed to lift the fork (via the fulcrum position) with the 3D printed anchor (with metal pellet) and no food item or attachment. "Y" was the force needed to lift the fork, 3D printed anchor and the attached meatball. Lastly, "Z" was the force needed to lift the fork and the 3D printed anchor augmented through the electromagnetic actuator within the table.

Haptic augmentation was synchronized with visual and olfactory feedback. The electromagnetic actuators were controlled through a 5 V optical relay circuit triggered by an Arduino system and powered by Heschen Electromagnet Magnet Solenoid (P80/38, OD:80 mm, 150 kgf) running at 24 V/3.7 A. We measured a delay of less than a 10 ms between the optical relays and electromagnetic actuators. This delay fell below the perceptual threshold determined during pilot studies. Apart from modifying the perceived weight, no other haptic augmentation such as vibration was used.

3.3 Visual augmentation

Visual augmentation was achieved using the Varjo XR-3 extended reality headset (Fig. 4A). This device is capable of providing eye-resolution visual view streaming the users' surroundings onto the headset displays using video see-through via its built-in stereo cameras. This allows the device to produce fully opaque virtual artefacts completely occluding the food items in a mixed reality view, unlike many traditional augmented reality headsets only capable of producing translucent virtual content. The visual augmentation consisted of virtual versions of the plant-based ball and the meatball (see Fig. 5). By completely replacing the real item with a co-located virtual representation, it became possible to freely alter the size and appearance of the food item.

A 3D-printed cube with dimensions of 3.5 cm × 3.5 cm × 3.5 cm was fitted on the fork that the participants used to consume the food items. This cube featured a QR code (Fig. 4C) that was used for tracking the fork by the headset's cameras, thus serving as the reference point for the virtual content. This ensured that the virtual content remained in place at

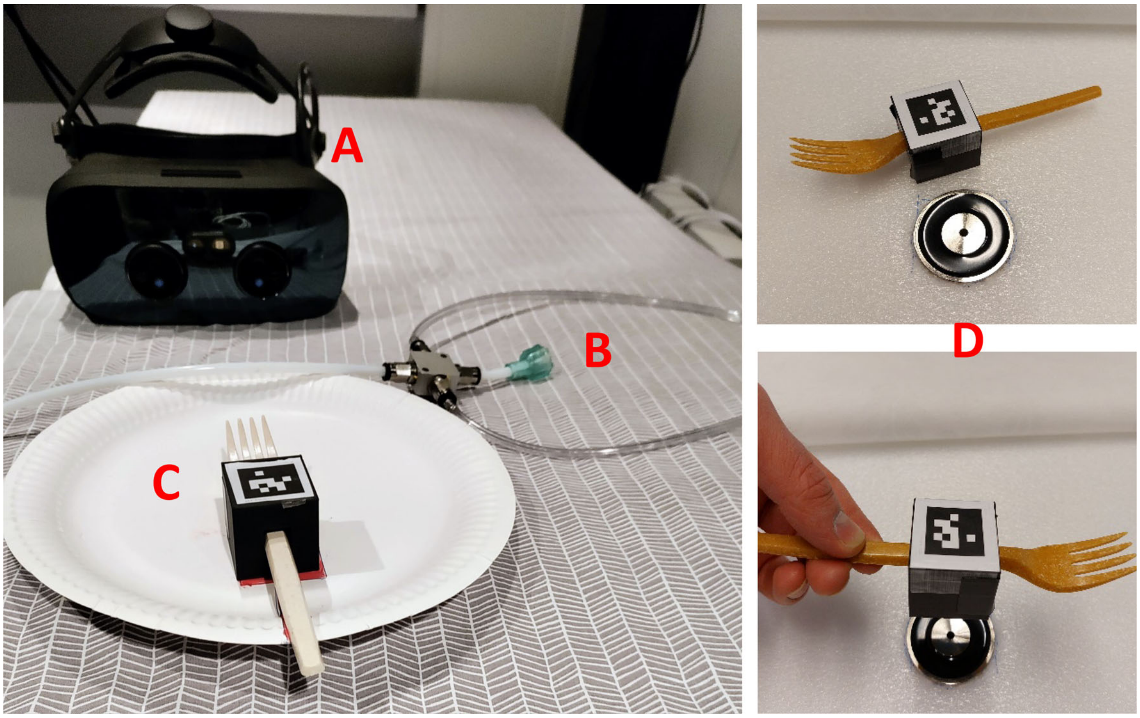


Fig. 4 The Varjo XR-3 (**A**), the necklace to defuse olfactory feedback (**B**), the disposable plate and fork with 3D-printed QR anchor used to track meatball and plant-based ball movements in real time and create visual and weight augmentation (**C**), as well as the recessed electromagnetic actuator (**D**) within the top surface used to produce weight augmentation

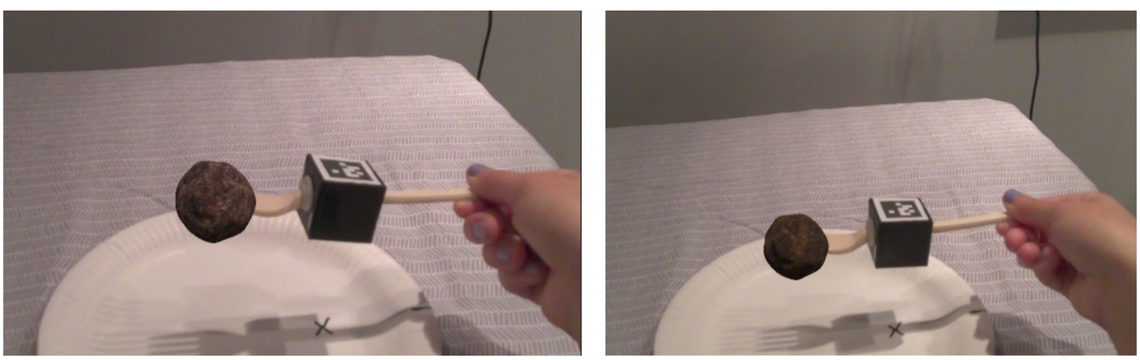


Fig. 5 Augmented visual views for an enlarged meatball (left) and an augmented plant-based ball (right)

the tip of the fork occluding the real food item. Although adding markers on all sides of the cube would have allowed for a full 6 degrees of freedom of movement, it was decided that tracking only the top marker is sufficient when using the fork normally. In addition, changing the tracking origin could have introduced jittering as the offset from the tracking origin would have to be re-calculated. The advantage of tracking the fork using a QR code is that this approach is independent of the actual food product, thus enabling the augmentation of products of different sizes, shapes, and colors.

Figure 6 illustrates how the multisensory augmentations were synchronized when eating a meatball or plant-based ball. All augmentations were switched on by the experimenter using a keyboard when the food was uncovered. The augmented visual view appeared in the headset, the necklace started to provide an odor, and the electromagnetism was created between the actuator in the table and the pellets inside the cube of the fork. The augmented weight was perceived once the participant lifted the fork. Because the force of the weight augmentation depended on the magnetic attraction between the fork and the magnetic actuators, the perceived additional weight decreased when the fork was raised to eat the food. When the food was placed in the mouth and was no longer visible to the headset's cameras, all augmentations were turned off by the experimenter. The exact durations of

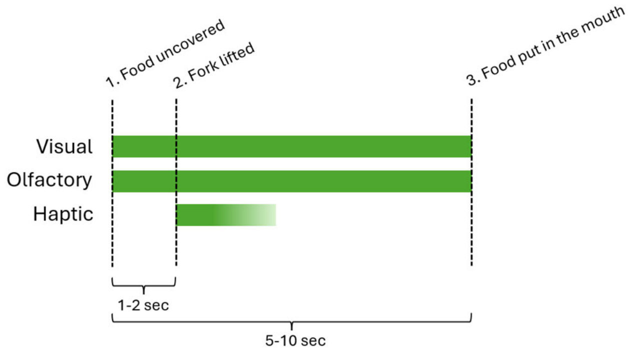


Fig. 6 Synchronization of the three augmentation modalities when (1) the food was uncovered, (2) the fork was lifted and (3) the food was put in the mouth

the multisensory augmentations depended on the time each participant took to place the food in their mouth, but typically the time varied between 5 and 10 s.

4 Experiment

The novel multisensory augmentation system was used to conduct an experiment where participants were asked to consume either plant-based balls or meatballs while utilizing the headset (Fig. 4A), necklace (Fig. 4B), and fork (Fig. 4C). This investigation took place in a controlled laboratory environment, and its purpose was to determine whether the three augmentation modalities had any influence on the participants' eating experiences and how they were influenced. The main ingredients of the plant-based balls and the meatballs utilized in this experiment, as well as their brands, are presented in Table 1. The aim was to find meat and plant-based products that had a similar appearance, size and weight.

4.1 Participants

Forty individuals participated in this study, comprising of twenty-one females, eighteen males, and one who chose not to specify their gender. When questioned about their dietary preferences, only one participant expressed a preference for plant-based diets, while 36 participants favored a combination of meat and plant-based products, and three participants opted for meat-based diets. Among these participants, thirty-one were identified as students or researchers. All participants volunteered for this study and, as an acknowledgment of their time, they received a movie ticket.

4.2 Procedure

The participants arrived at the laboratory, where they were explained the purpose and procedures of the study. Prior to participating, they signed an informed consent form and filled out a background information form. Subsequently, they received assistance in putting on the XR headset and the odor necklace display.

The participants were then given a few minutes to practice using the fork while observing a colorful virtual ball through the headset. They were provided with guidance on the appropriate speed and technique for moving the fork and where to grip it. Once the practice session concluded, the participants progressed through the four distinct test conditions, in randomized order, described in Table 2.

The participants were served one ball at a time, each of which had been preheated for twenty seconds. Additionally, they were asked to consume it in a single bite. For the augmented balls conditions (APB – AMB), the participants were monitored as all augmentations were manually activated simultaneously with their actions. When the participants received the plate with the ball at the table, the augmentations were ON and remained activated while the participant picked up the fork and positioned the ball in their mouth. Subsequently, once the ball was inside their mouth, the augmentations were deactivated. In total, the participants received four balls in a randomized sequence. After completing the four test conditions, the augmentation system was removed.

4.3 Data collection and analysis methods

Following each condition, the participants were asked to fill out a questionnaire, available in Appendix 1, where they assigned ratings using 7-point semantic differential scales. Custom scales designed by the authors were used because there were no standard questionnaires that would have been suitable for assessing the studied augmentation modalities. The scales measured the perception of the ball's weight and its suitableness, the intensity and appeal of the odor, the visual size of the ball and its suitableness, the appeal and flavor of the ball, balls' overall pleasantness during the eating experience, and their willingness to consume more of the presented ball.

Upon completing all the test conditions, the participants were asked a series of open-ended questions for further feedback and notes were taken from their answers. The semi-structured interview inquired into various aspects of their experience, including their impressions of the served balls, their eating experiences while wearing the XR headset and necklace, their preference among the balls for future consumption, whether the size of the balls allowed eating them in one bite, if any ball felt noticeably heavier or lighter in comparison to the others, the perceived quality of the ball's aroma, whether any ball was deemed more or less flavorful than the rest, whether the augmentations had any discernible impact on their eating experiences, and if the overall pleasantness of eating was enhanced by the augmentations.

Table 1 Main ingredients and (unaugmented) appearance of each type of ball

	Name/brand	Ingredients	Appearance
Plant-based balls	MUU balls—Meat	Water, pea (23%) rapeseed oil, gluten free breadcrumb (rice flour, corn flour, corn starch, dextrose), onion, salt, stabilizers (E461, E460), aromas (i.e., paprika), spices (black pepper, all spice), caramelized glucose syrup, caramel color, maltodextrin, potato starch, glucose syrup	
Meatballs	Meatballs (lihapyörykkä)—Atria	Meat 53% (pork, chicken, beef), water, soy protein, potato flour, breadcrumbs (wheat), rapeseed oil, spices (onion, black pepper, paprika, all spice, peppercorns, fenugreek), emulsifier sunflower lecithin, iodized salt, sugar, caramelized sugar, acidity regulators (potassium chloride, E 300), wheat fiber, flavors	

Table 2 Test conditions used during the experiment

Condition	Food product	Olfactory augmentation	Visual augmentation	Haptic augmentation
Plant-based ball (PB)	Plant-based ball	Off	Off	Off
Augmented plant-based ball (APB)	Plant-based ball	On	On	On
Meatball (MB)	Meat-based ball	Off	Off	Off
Augmented meatball (AMB)	Meat-based ball	On	On	On

The IBM SPSS Statistics software (Version 28, IBM Corp, Chicago, IL, USA) was used for statistical analysis. Paired sample t-test and ANOVA with a *p*-value of 0.05 as the significance threshold were applied to analyze participants' evaluations between augmented plant-based ball (APB) versus non-augmented plant-based ball (PB) and augmented meatball (AMB) versus non-augmented meatball (MB). To explore the role of flavor appeal and taste between the different meatballs with and without weight augmentation we also conducted regression analysis. The method of content analysis [45] was utilized to analyze the qualitative data. The qualitative data included the information collected from the semi-structured interviews.

4.4 Results

4.4.1 Questionnaire results

The average results of each condition obtained from the quantitative assessment can be seen in Fig. 7 and they are summarized in Table 3.

Regarding the weight, on average the APB was considered heavier than the PB ($M_{APB} = 5.15$, $SD = 1.49$, $M_{PB} = 3.25$, $SD = 1.43$, $t(39) = 6.10$, $p < 0.001$) on a scale of 1–7 (light–heavy). Similarly, the AMB was considered heavier than the MB on the same scale ($M_{AMB} = 5.13$, $SD = 1.40$, $M_{MB} = 3.70$, $SD = 1.22$, $t(39) = 4.27$, $p < 0.001$), demonstrating that the weight augmentation influenced the weight perception. However, the suitableness of the weight of the APB was ranked lower compared to the PB ($M_{APB} = 3.95$, $SD = 1.57$, $M_{PB} = 5.28$, $SD = 1.40$, $t(39) = -3.49$, $p = 0.001$) on a scale of 1–7 (unsuitable–suitable). The AMB and MB showed similar tendency, but they did not differ statistically ($M_{AMB} = 4.65$, $SD = 1.53$, $M_{MB} = 5.00$, $SD = 1.34$, $t(39) = -1.30$, $p = 0.20$). These results suggest that the participants preferred the actual weight of the ball instead of the added one by the weight augmentation. Furthermore, they indicate that the heaviness of the AMB was contemplated more suitable than the APB.

Concerning the olfactory perception, the odor intensity of the APB was perceived similar than the PB ($M_{APB} = 2.95$, $SD = 1.66$, $M_{PB} = 3.28$, $SD = 1.78$, $t(39) = -0.90$, $p = 0.37$) on a scale of 1–7 (weak–strong). The same applied to the AMB and MB ($M_{AMB} = 3.78$, $SD = 1.31$, $M_{MB} = 3.50$, $SD = 1.74$, $t(39) = 0.96$, $p = 0.34$). The perceived appeal of the APB odor was reduced compared to the PB ($M_{APB} = 3.70$, $SD = 1.51$, $M_{PB} = 4.20$, $SD = 1.64$, $t(39) = -2.00$, $p = 0.05$) on a scale of 1–7 (unappealing–appealing). No difference was detected between the AMB and MB ($M_{AMB} = 5.00$, $SD = 1.09$, $M_{MB} = 4.70$, $SD = 1.31$, $t(39) = 1.08$, $p = 0.29$).

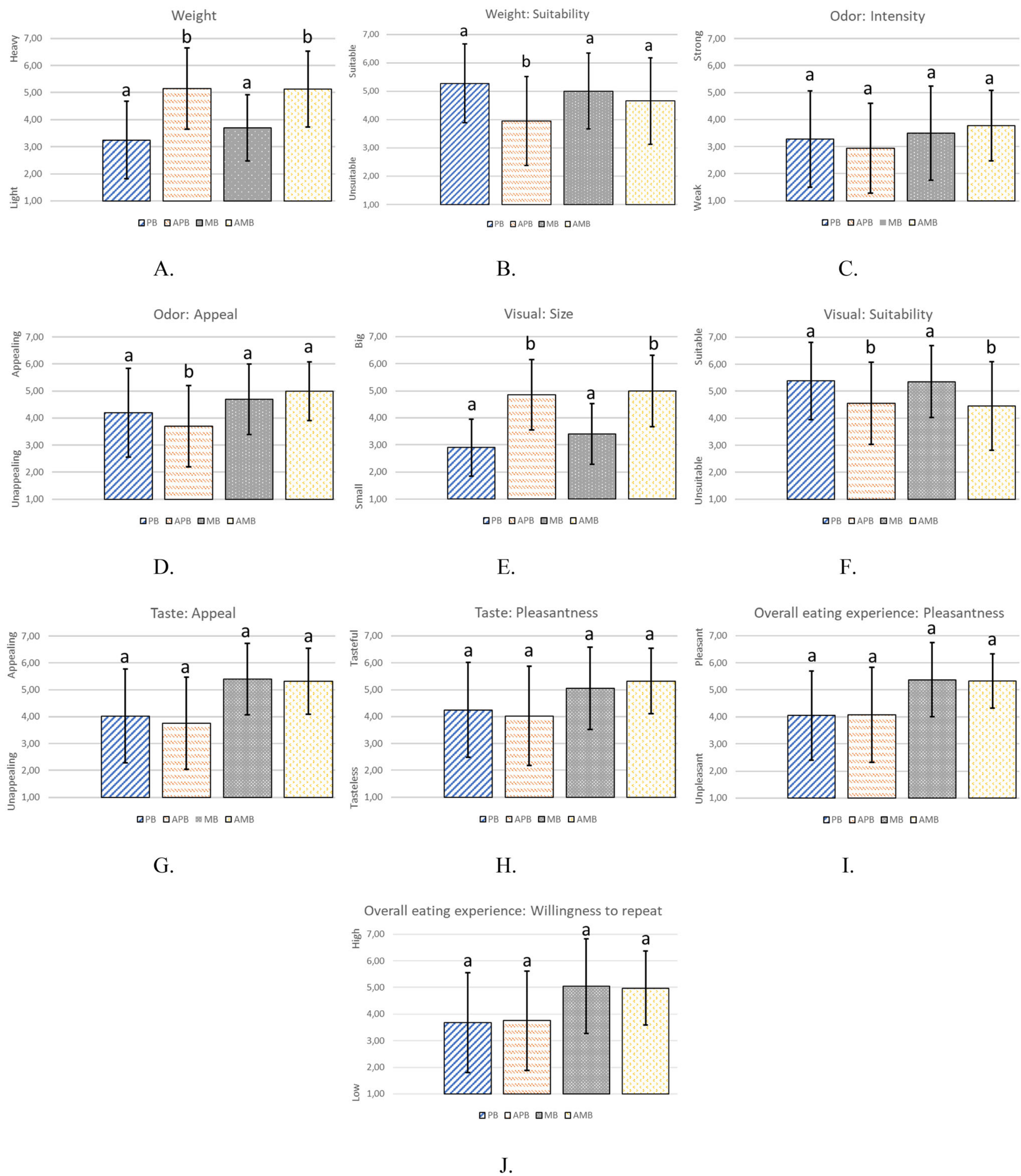


Fig. 7 Mean and standard deviation of the perception of the ball's weight (**A**) and its suitability (**B**), the odor intensity (**C**) and its appeal (**D**), the visual size of the ball (**E**) and its suitability (**F**), the appeal (**G**) and pleasantness of the taste of the ball (**H**), evaluated overall pleasantness during the eating experience (**I**), and participants willingness to consume more of the presented ball (**J**). Different letters above the bars indicate statistically significant difference ($p \leq 0.05$) between the analyzed pairs of samples (PB vs. APB and MB vs. AMB)

Table 3 Average results of each tested condition

Scale	Condition			
	Plant-based ball (PB)	Augmented plant-based ball (APB)	Meatball (MB)	Augmented meatball (AMB)
Weight perception	$M_{PB} = 3.25$	$M_{APB} = 5.15$	$M_{MB} = 3.70$	$M_{AMB} = 5.13$
Weight suitability	$M_{PB} = 5.28$	$M_{APB} = 3.95$	$M_{MB} = 5.00$	$M_{AMB} = 4.65$
Odor intensity	$M_{PB} = 3.28$	$M_{APB} = 2.95$	$M_{MB} = 3.50$	$M_{AMB} = 3.78$
Odor appeal	$M_{PB} = 4.20$	$M_{APB} = 3.70$	$M_{MB} = 4.70$	$M_{AMB} = 5.00$
Visual size	$M_{PB} = 2.90$	$M_{APB} = 4.85$	$M_{MB} = 3.40$	$M_{AMB} = 5.00$
Visual suitability	$M_{PB} = 5.38$	$M_{APB} = 4.55$	$M_{MB} = 5.35$	$M_{AMB} = 4.45$
Taste pleasantness	$M_{PB} = 4.25$	$M_{APB} = 4.03$	$M_{MB} = 5.05$	$M_{AMB} = 5.33$
Taste appeal	$M_{PB} = 4.03$	$M_{APB} = 3.75$	$M_{MB} = 5.40$	$M_{AMB} = 5.33$
Overall pleasantness	$M_{PB} = 4.05$	$M_{APB} = 4.08$	$M_{MB} = 5.38$	$M_{AMB} = 5.33$
Willingness to repeat	$M_{PB} = 3.68$	$M_{APB} = 3.75$	$M_{MB} = 5.05$	$M_{AMB} = 4.98$

In respect of the visual impression, the size of the APB was considered bigger than the PB ($M_{APB} = 4.85$, $SD = 1.31$, $M_{PB} = 2.90$, $SD = 1.06$, $t(39) = 8.51$, $p < 0.001$) on a scale of 1–7 (small–big). The same was detected between the AMB and MB ($M_{AMB} = 5.00$, $SD = 1.32$, $M_{MB} = 3.40$, $SD = 1.13$, $t(39) = 6.91$, $p < 0.001$). These results indicate that the visual augmentation impacted the visual perception. However, the suitability of the APB size was ranked lower compared to the PB ($M_{APB} = 4.55$, $SD = 1.52$, $M_{PB} = 5.38$, $SD = 1.43$, $t(39) = -2.47$, $p = 0.018$) on a scale of 1–7 (unsuitable–suitable) as well as between the AMB and MB ($M_{AMB} = 4.45$, $SD = 1.63$, $M_{MB} = 5.35$, $SD = 1.33$, $t(39) = -2.81$, $p = 0.008$).

Regarding the taste of the samples, no differences in flavor pleasantness were observed either between the APB and PB ($M_{APB} = 4.03$, SD = 1.85, $M_{PB} = 4.25$, SD = 1.78, t(39) = − 0.86, $p = 0.40$) or between the AMB and MB ($M_{AMB} = 5.33$, SD = 1.21, $M_{MB} = 5.05$, SD = 1.54, t(39) = 1.13, $p = 0.26$) on a scale ranging between 1 and 7 (tasteless–tasteful). In respect to product appeal, similar results appeared. The APB and PB were perceived equal ($M_{APB} = 3.75$, SD = 1.72, $M_{PB} = 4.03$, SD = 1.76, t(39) = − 1.32, $p = 0.20$) on a scale of 1–7 (unappealing–appealing). Same applied to the AMB and MB ($M_{AMB} = 5.33$, SD = 1.23, $M_{MB} = 5.40$, SD = 1.34, t(39) = − 0.33, $p = 0.75$).

On the subject of overall eating experiences, the pleasantness of the eating experience was equal between the APB and PB ($M_{APB} = 4.08$, SD = 1.76, $M_{PB} = 4.05$, SD = 1.65, t(39) = 0.11, $p = 0.91$) on a scale of 1–7 (unpleasant–pleasant). The AMB and MB followed similar pattern ($M_{AMB} = 5.33$, SD = 1.00, $M_{MB} = 5.38$, SD = 1.37, t(39) = − 0.21, $p = 0.83$). No differences between the samples emerged in the willingness to repeat (1 = low, 7 = high) either: $M_{APB} = 3.75$, SD = 1.86, $M_{PB} = 3.68$, SD = 1.87, t(39) = 0.28, $p = 0.78$; $M_{AMB} = 4.98$, SD = 1.39, $M_{MB} = 5.05$, SD = 1.77, t(39) = − 0.30, $p = 0.77$).

4.4.2 A closer look at the effects of haptic augmentation

We continued to explore the results of haptic augmentation in more detail by analyzing the correlation and regression (Figs. 8, 9) between the appeal and flavor with and without haptic augmentation. Running ANOVA showed that both datasets had statistically significant differences (appeal $p = 0.0009$; taste $p = 0.0011$) in the ratings among the four types of balls (Fig. 7G, H). Additionally, the F-statistics [F(3,36)] differed slightly between the datasets. The "appeal" data had a slightly higher mean (7.126) compared to the "taste" data (5.984). Therefore, while both datasets indicate statistically significant differences among the four ball types, the differences in group means are slightly more evident in the appeal data compared to the taste data.

Moreover, the regression results indicate positive relationships between the standard and augmented versions of the balls in appeal and taste. The strongest positive correlation exists between APB and AMB (r = 0.653). This indicates that individuals who rate the augmented plant-based ball highly also tend to rate the augmented meatball highly. There's a moderate positive correlation between PB and MB (r = 0.337). The correlations between other combinations are either low or negative. Furthermore, coefficient for the "appeal" (0.651) is slightly higher than that for the taste data (0.582), indicating a slightly stronger linear relationship for "appeal" ratings. Similarly, the relationship between MB and AMB ratings is also statistically significant (0.39) for "taste" but not for appeal.

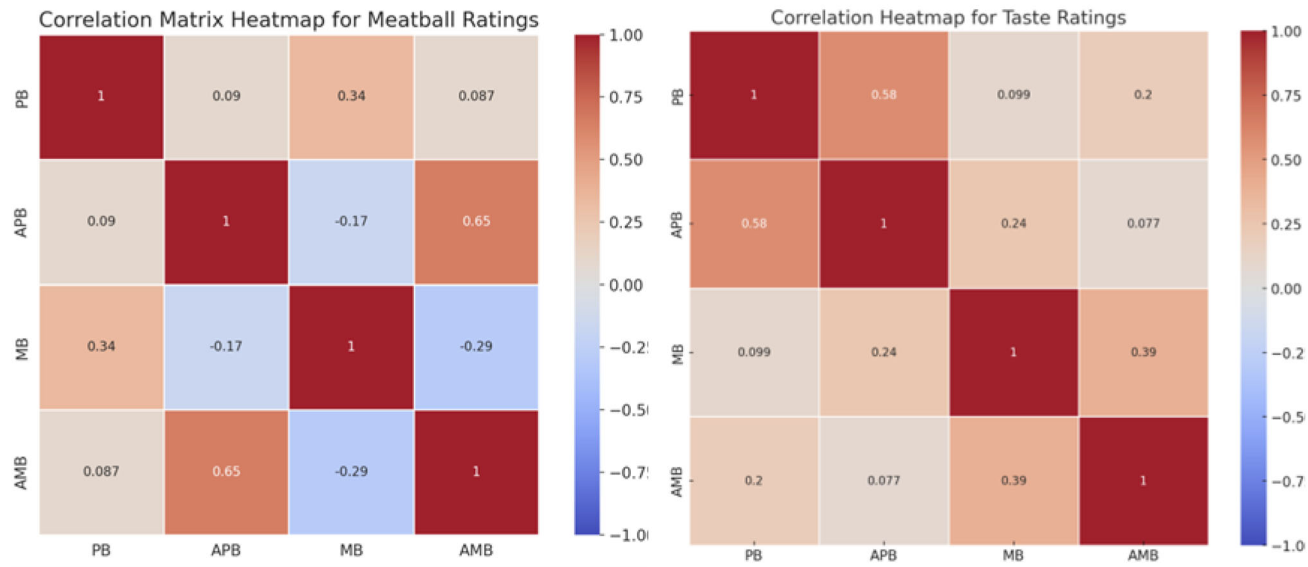


Fig. 8 The heatmap provides a visual representation of the correlation matrix for the meatball ratings for appeal (left) and flavor (right). Darker red indicates a stronger positive correlation while darker blue indicates a stronger negative correlation. From the heatmap, we can observe the strong positive correlation between APB and AMB ratings

4.4.3 Semi-structured interview results

The qualitative findings were derived from the semi-structured interviews. In general, the participants expressed positive feedback regarding their interactions with the served balls, describing their experiences as enjoyable, fun, and reminiscent of real-life scenarios. Concerning the taste of the balls, opinions were divided, with some participants finding them flavorful and others perceiving them as bland. Of the 40 participants, 30 mentioned encountering challenges when attempting to eat while wearing a headset. These challenges included difficulties in visually tracking the ball's position when it was near their mouths due to the headset obstructing their view. Additionally, some participants struggled to chew comfortably because of the weight and size of the headset. Furthermore, distinctions between the lighting conditions in the actual room and those perceived through the headset drew the participants' attention. They noted that the warm lighting in the real room felt more welcoming and encouraged eating, whereas the cold lighting within the headset affected their appetite.

When examining the participants' preferences for products they would choose to eat again, a noticeable inclination toward meat-based options was observed, with 19 participants favoring non-augmented and 13 participants favoring augmented condition. Contrarily, six participants opted for plant-based products, with four choosing the non-augmented version and two preferring the augmented one. Additionally, the participants perceived the augmented balls as the largest ones, influenced by the augmentation. However, determining whether the balls were an ideal size for single-bite consumption did not yield a definitive finding, suggesting that this is heavily dependent on individual preferences and physical attributes, such as mouth size.

The participants noted that the augmented balls felt heavier compared to their non-augmented counterparts, indicating that augmentation influenced their perception of weight. While 17 participants reported that the balls did not emit a strong odor, they found the aroma they did detect to be pleasant. Five participants considered both augmented balls to have the best aroma, three identified the augmented meatball as having the strongest aroma, and seven participants noted that the plant-based products, in both conditions, had the mildest aroma. Aligning with the preferences for balls to eat again, the participants ranked the meat-based products, in both augmented and non-augmented conditions, as the most flavorful, while considering the plant-based products, in both conditions, to be less tasty.

Furthermore, 16 participants expressed that a stronger aroma contributes to a more pleasant eating experience. Additionally, ten participants emphasized that the size of the ball was not a critical factor, and six preferred balls of an average size. Similarly, 15 participants stated that weight augmentation was not significant, but they preferred lighter balls over heavier ones. Regarding the combined augmentations offered by the system, ten participants mentioned that experiencing two or more augmentations enhanced the overall pleasantness of the eating experience. However, another ten participants believed that augmentations did not noticeably impact their eating experiences.

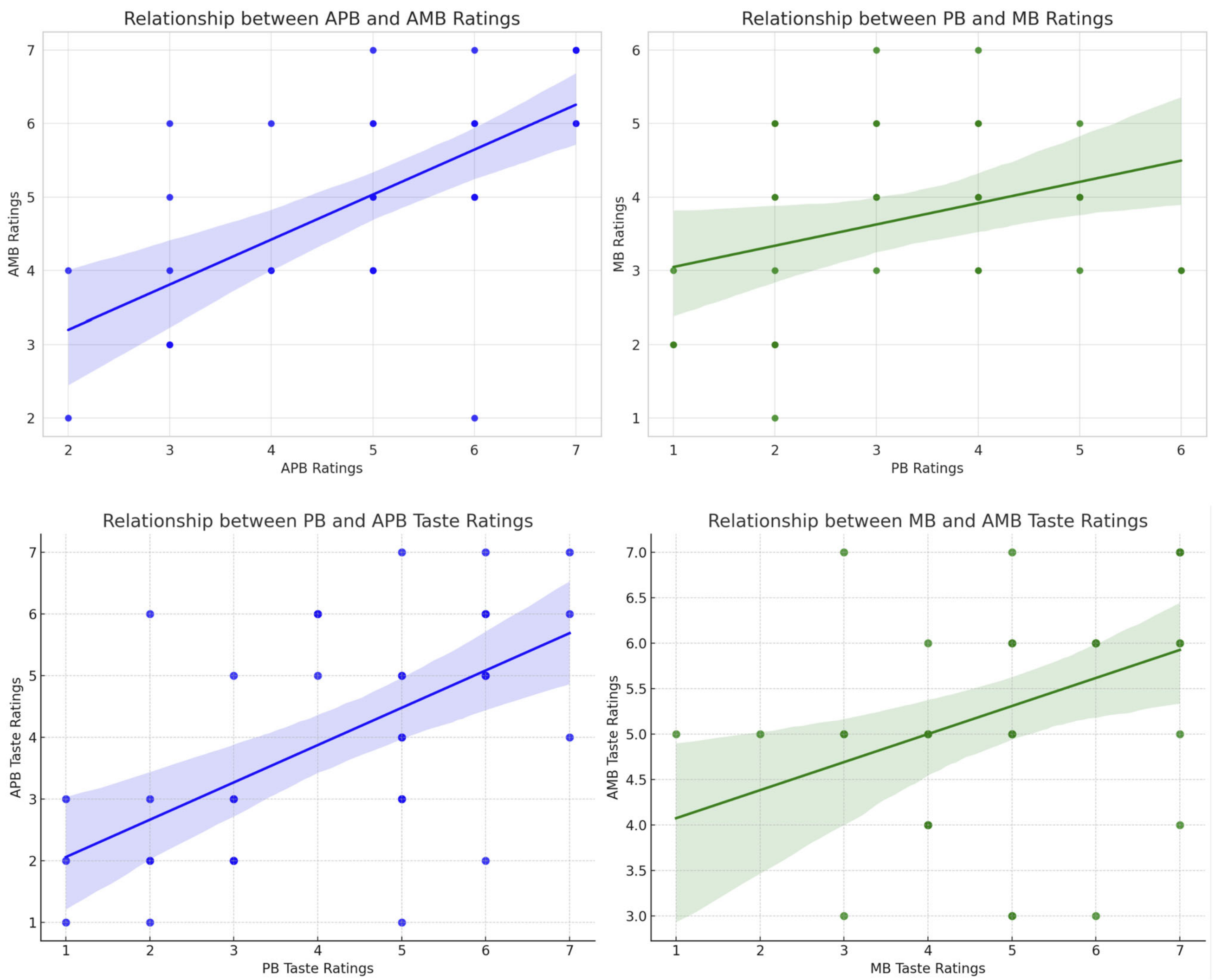


Fig. 9 The scatter plot shows a positive linear trend between the taste ratings of PB and APB, indicating as the taste rating for PB increases the taste rating for APB also tends to increase (top left and bottom left) for both appeal (top) and flavor (bottom). The scatter plot for MB and AMB (top right and bottom right) shows a positive linear trend, suggesting a positive relationship between the taste ratings of MB and AMB

5 Discussion

First, we discuss the contributions of the present study in the context of related previous research. We continue by discussing the limitations of the study and suggest potential future work to continue this line of research.

5.1 Contributions

We studied multisensory augmentations on food by assessing the subjective ratings of appeal and taste for four different types of balls: standard plant-based (PB), augmented plant-based (APB), standard meatball (MB), and augmented meatball (AMB). In the experiment, we observed that the participants were able to perceive haptic and visual augmentations, but, according to their feedback during the semi-structured interviews, they did not appear to notice olfactory augmentation. Prior research [17] has indicated the difficulty that individuals encounter when exposed to both congruent and incongruent pairs of olfactory and visual stimuli within a virtual reality setting. It has been implied that individuals might face challenges in effectively merging information from haptic, visual, and olfactory augmentations when they are simultaneously presented with the three stimuli. Our findings suggest that this phenomenon occurs even in the presence of augmented reality, aligning with the outcomes detailed in prior VR research by Ammann et al. [34] and Weidner et al. [17]. Looking more closely at the results of haptic augmentation, both appeal and taste ratings showed that augmented versions (APB and AMB) tend to be rated higher compared to their non-augmented counterparts (PB and MB). The highest correlation in ratings, indicating a strong association, was observed between PB and APB. This suggests that individuals who found the standard plant-based ball appealing or tasty also tended to find the augmented plant-based version similarly appealing or tasty.

As olfaction significantly determines perception of flavor [46], our findings about unaffected perceived intensity of odor are consistent with the unaffected pleasantness and appeal of taste. Although the participants were not able to recognize the olfactory augmentation, during the semi-structured interviews they mentioned that smell had an effect on the experienced pleasantness while consuming both meatballs and plant-based balls, with size and weight being less influential. This finding aligns with prior research indicating that smell has been shown to have diverse applications, including enhancing presence [47], managing attention [48], facilitating navigation [49], and regulating the sensation of satiation [16]. Moreover, two studies by Aisala et al. [9] demonstrated the potential to enhance the perceived sweetness of reduced-sugar cakes through the localized delivery of scents. Their findings suggest that it is feasible to increase sweetness while maintaining a lower sugar content, offering benefits to consumers by achieving a sweet perception with reduced caloric intake.

In connection with the sensations experienced while eating, distinctions between the lighting conditions in the physical room and those perceived through the headset were noticed by our participants. They noted that the warm lighting in the real room felt more welcoming and encouraged eating, whereas the cold lighting within the headset affected their appetite and made them feel they needed to eat faster. As presented previously by Ueda et al. [18], the appearance of the food can change depending on the light without having to modify the physical and chemical properties of the product. Nonetheless, our findings suggest that the luminance perceived through the HMD does not only influence the visual perception of food but also impacts the experience of eating within that environment. Prior research reviewed by Stroebele and Castro [50] suggested that warm lighting in physical spaces appears to extend the duration that individuals spend in the setting and is consequently linked to increased food intake, whereas harsh, bright lighting leads to faster consumption. Our results suggest that the earlier finding holds true also within an augmented reality environment, impacting the comfort level of participants and influencing the duration and amount they eat.

Overall, the findings of this research can have significant implications for the food and culinary industries, especially those exploring alternative protein sources or looking to enhance consumer experiences. The positive ratings for haptic and visual augmentations imply that adding multisensory enhancements can elevate the perception of food items. This could be a pivotal strategy for industries aiming to promote plant-based alternatives by making them as appealing and tasty as the traditional meat-based products. By leveraging multisensory augmentations, businesses might be able to drive consumer preference towards more sustainable and environmentally friendly food options. Similarly, the current results can also be utilized in designing experiences to mitigate eating disorders or other food intake requirements, including food waste, and cultivating interest towards healthy and sustainable food consumption.

5.2 Limitations

As noted in a prior study conducted by Nakano et al. [19], our research also encountered a limitation related to the HMD, which had a significant effect on the eating experiences of our participants. 30 of the 40 participants reported difficulties when attempting to eat while wearing the headset. Several participants mentioned that the HMD obstructed their field of vision, making it challenging to track the movement of the balls. This is in line with the findings of Nakano et al. [19] who reported that eating with an HMD required extra effort in coordinating eye-hand movements. Other participants in our current study mentioned that the HMD's weight added difficulty to chewing because the device pressed against their cheeks. This could affect the use of the system in the daily life as noted by Nakano et al. [19]. In relation with the use of the HMD, another limitation was the preconceived notion of visual food augmentation, especially from those participants with previous experience in the use of extended reality devices. In terms of the olfactory augmentation system, some participants commented that they did not always notice the presented odors. This could be due to design of the odor delivery method where the direction of the release nozzle may have changed during the experiment. In the future, the method could be improved to ensure that the nozzle keeps pointing directly towards the participant's nasal area.

Moreover, a limitation related to the chosen haptic augmentation technique is that it required utensils for providing the perception of added weight. For this reason, we chose food products that are typically eaten using a fork to keep the setting as natural as possible. Additionally, in order to hide the electromagnetic actuator and avoid participants to be influenced by it, the actuator was recessed in a foam attached to the table and covered with a tablecloth. This setting introduced an additional preparation step before a participant arrived to ensure that the actuator and printed cube were aligned, and the weight augmentation was perceived as intended. Regarding the overall system, the prototype olfactory necklace display, the extended reality headset, and the fork with haptic feedback present innovative methods for providing multisensory augmentation while consuming food products. Nevertheless, these devices are currently limited to experimental settings and are not feasible for practical implementation in daily life.

Another constraint arose from the selection of the food products, which included meat items containing pork and beef. This choice omitted individuals adhering to plant-based diets from the experiment. Furthermore, individuals with dietary restrictions based on religious beliefs were unable to participate. Notably, most of our study participants exhibited a preference for meat products over plant-based alternatives, potentially influencing their perceptions of taste, aroma, and visual presentation. In future studies, it would be beneficial to assess the system using food items that do not pose dietary restrictions, allowing for greater inclusivity and participation.

5.3 Future work

Given the observed impact of multisensory augmentations, future research could delve deeper into understanding which specific type of augmentation (visual, olfactory, or haptic) has the largest influence on consumer ratings. Moreover, studying the long-term effects of these augmentations on consumer behavior and preference would be insightful. Does repeated exposure to augmented products lead to sustained positive perceptions, or do consumers become desensitized over time? Additionally, exploring the psychological and neurological underpinnings behind these perceptions can offer a more comprehensive understanding of how multisensory augmentations influence food experiences.

One of the limitations we encountered was the size, weight, and dimensions of the HMD, which posed challenges to the eating experiences. In future research, investigators may find value in exploring a multisensory system that integrates a lighter and more ergonomically designed headset. A compact and lightweight headset would enhance the feasibility and practicality of interactions in everyday life. As technology advances, the reduction in the size of headsets and the emergence of eyeglass-sized displays, such as Magic Leap [51] and Apple Vision Pro mixed reality headset, hold promise for facilitating interactions in a more practical manner. Moreover, with further technological developments, the integration of compact olfaction and spatial haptic systems into lightweight eyeglasses-sized displays will allow to create a genuinely seamless and practical multisensory augmentation device. Such advancements could also enable novel social dining experiences, allowing people to share augmented reality meals that enhance the sensory enjoyment of food.

In our experiment, virtual meatball and plant-based ball had identical shapes, sizes and added weights in the augmented conditions. Nonetheless, participants rated the augmented meatball's weight as more suitable and the augmented plant-based ball as less suitable. The main differences between the virtual meatball and plant-based ball were their colors and textures. Future work could delve deeper into the factors and characteristics that make a virtual product and its corresponding weight more suitable compared to others. Building upon the previous notion, additional research is needed to uncover the specific attributes of an aroma that contribute to enhancing the overall pleasantness of an eating experience.

6 Conclusion

Our multisensory system was created to augment eating experiences. The results of the experiment showed that the augmented meatball was perceived as heavier and larger than its non-augmented version. Regarding its aroma, no differences were found in its appeal and intensity between augmented and non-augmented versions. The augmented plant-based ball was also perceived as heavier and larger than the non-augmented one, but with a less appealing aroma. Still, the added weight and increased size were not favored by the participants who preferred regular-sized and weighted food, whether meat or plant-based.

In terms of the overall eating experience, pleasantness was similar for both augmented and non-augmented plant-based and meat-based items. Additionally, the multisensory augmentations did not impact the taste perception which is closely tied to odor. Our research demonstrated the potential to influence perceived weight and size, while olfactory augmentation may potentially be developed in future work. Once the XR headsets become lighter everyday products with multisensory stimulation capabilities, there is a promise that they may be used to facilitate healthier and more sustainable food choices while ensuring enjoyable eating experiences.

Appendix 1

Weight

How would you rate the weight of the ball?

Light						Heavy
1	2	3	4	5	6	7

Unsuitable						Suitable
1	2	3	4	5	6	7

Olfactory

How would you rate the smell of the ball?

Weak						Strong
1	2	3	4	5	6	7

Unappealing						Appealing
1	2	3	4	5	6	7

Visual

How would you rate the size of the ball compared to a regular ball? (Average meatballs are golf ball sized).

Small						Big
1	2	3	4	5	6	7

Unsuitable						Suitable
1	2	3	4	5	6	7

Taste

How would you rate the taste of the ball?

Unappealing						Appealing
1	2	3	4	5	6	7

Tasteless						Tasteful
1	2	3	4	5	6	7

Overall Eating Experience

How would you rate the overall pleasantness of eating the ball?

Unpleasant						Pleasant
1	2	3	4	5	6	7

How would you rate your willingness to eat more of this ball?

Low						High
1	2	3	4	5	6	7

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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