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Highlights

- We developed a multisensory VR food environment with visual and olfactory cues
- We compared craving and salivation to food across virtual and real-life settings
- Food-induced craving was weaker in all virtual conditions than real-life
- Food-induced salivation was higher in multisensory VR than unisensory VR
- Food-induced salivation did not differ between multisensory VR and real-life
- Multisensory VR exposure increased presence and state mental imagery

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Abstract

Immersive Virtual Reality (VR) technologies such as virtual supermarkets are an emerging medium to model individuals' eating behaviour. However, existing VR environments elicit weaker responses to food (i.e., craving and salivation) than in real-life, limiting their validity as research tools. We developed an immersive multisensory VR food environment – with both visual and olfactory (smell) cues – and investigated whether it could bridge this gap in food responses, and whether effects may be mediated by an enhanced sense of presence. In a within-subjects lab-based experiment, participants (N = 70) were exposed to food and non-food cues in either a unisensory "vision only" VR condition, a multisensory "vision + olfaction" VR condition, or a real-life setting with a matched physical set-up. Food-specific craving and salivation were measured in all six conditions. Results showed that food-induced craving was weaker in all virtual conditions versus real-life. Salivary responses to food were also lower in unisensory VR exposure versus real-life. Compared to unisensory VR exposure, multisensory VR exposure led to a directional improvement in craving, higher salivary food responses after adjusting for hunger, and enhanced perceptions of presence and mental imagery. While we could not conclude equivalence between multisensory VR and real-life settings, the latter did not differ on salivary responses either. In conclusion, an immersive multisensory VR food environment with olfactory cues can credibly model craving responses, albeit to a weaker degree than in real-life. The added value of this technology may lie in enhancing conceptual mediators and approximating real-life salivation to food.

Keywords: Immersive VR; Virtual supermarket; Olfaction; Food cue exposure; Craving; Salivation; Presence

1. Introduction

Many individuals struggle with making healthier food choices, as evidenced by the growing prevalence of obesity worldwide (World Health Organization, 2020). This is in part because the majority of our food decisions are made in sensory-rich “obesogenic” food environments (e.g., supermarkets) that promote the purchase and consumption of unhealthy foods (Poelman *et al.*, 2021; Swinburn *et al*., 2011). Therefore, in order to encourage healthier food decisions and ultimately improve diets, we urgently need to better understand the mechanisms driving food choice within such contexts. In this paper, we focus on improving the methods for studying eating behaviour in a lab environment.

Immersive Virtual Reality (VR) technology has recently surfaced as a promising medium to study food decision making in naturalistic food environments (Blom *et al*., 2021; Xu *et al*., 2021). Immersive virtual environments are computer-generated three dimensional models that participants can experience and interact with intuitively in real time. Through naturalistic interaction, enabled by a head-mounted display and hand-held controllers that provide a high level of sensory immersion (Slater, 2018), individuals can experience a strong sense of (spatial) presence — i.e., the feeling of being in the virtual environment rather than the physical one (e.g., Lombard and Ditton, 1997; Slater & Wilbur, 1997). Such virtual environments, for example, virtual supermarkets, buffets, and other food environments, have opened up new opportunities for eating behaviour research, allowing researchers to collect food decision-making data in a tightly controlled yet realistic environment, at relatively low cost and with a high degree of flexibility (Xu *et al.*, 2021).

Though previous studies with low-immersive VR (e.g., desktop VR; Waterlander *et al.*, 2015) and semi-immersive setups (e.g., employing multiple screens; van Herpen *et al.*, 2016) have shown that consumer behaviour in virtual environments resembles that in real-life moderately to well, systematic comparisons involving high-immersive VR environments are lacking (for some exceptions see Cheah *et al*., 2020 and Long *et al*., 2023). It is therefore relevant to address this gap (further) because of the expectation that behaviour in highly immersive environments would align more closely with actual behaviour in the real-world due to the stronger level of immersion provided by the medium.

An important prerequisite for immersive technologies to elicit behaviour similar to those in real-world circumstances, and thus serve as accurate tools for measuring eating behaviour, is that basic food cue responses (FCRs) to virtual foods should be similar to those elicited by the same foods in physical (i.e., real-life) settings. FCRs, which include psychological responses (e.g., craving) and physiological responses (e.g., salivation), are necessary to prepare the body for ingestion and represent behaviorally-relevant markers of the cephalic phase of the digestive process. The manifestation of such responses has been found to be a predictor of food choice and food intake (Hill, 2007; Kanoski & Boutelle, 2022; Nederkoorn *et al.*, 2000). However, recent evidence from a highly immersive VR study, in which participants could interact with a virtual versus real-life version of a food, suggests that important psychological FCRs (i.e., craving) tend to be weaker for virtual compared to real-life foods (van der Waal *et al*., 2021). Similarly, fundamental physiological FCRs (i.e., salivation) to virtual food cues show a much larger departure from reality (van der Waal *et al*., 2021). As such, weaker psychological and physiological FCRs currently limit the utility of highly immersive virtual environments for food decision-making research.

Aside from applications in food decision-making research, a second, more clinical, line of work on realistic food-cue responses has emerged from the use of these cues in VR exposure therapy. Within populations with eating disorders, exposure therapy involves repeated confrontation with food cues to reduce craving and food-related anxiety. Research in this area shows that food cues and food-related VR environments (e.g., kitchens or dining rooms) elicit stronger craving (and anxiety) responses than neutral VR environments, both in individuals with eating disorders and in healthy participants (Pla-Sanjuanelo et al., 2017). . Furthermore, VR environments featuring high-calorie foods seem to induce stronger craving responses than those depicting lower-calorie foods (Ferrer-Garcia, Gutiérrez-Maldonado, & Pla, 2013), demonstrating sensitivity to relevant stimulus characteristics. Together, these studies offer methodological precedence by showing that immersive VR can evoke ecologically-valid FCRs and can reliably discriminate stimulus categories and participant groups. Minimizing discrepancies between virtual and real-world food stimuli may therefore be critical for both experimental validity and, in clinical contexts, therapeutic efficacy.

We argue that the discrepancy in FCRs between (immersive) virtual and real-life foods is because existing VR technologies only serve the visual sense. Though the visual sense plays an important role in food choice, food choice is a multisensory phenomenon that is also driven by smell, taste, texture, and sound input (Motoki & Togawa, 2022). Here, we take the challenging step of developing and testing a novel immersive multisensory VR food environment – with both visual and olfactory (smell) cues – to help bridge this gap. While the inclusion of visual and auditory senses into VR is widespread, the potential of the sense of smell remains largely untapped (Melo *et al.*, 2020; Neo *et al.*, 2021; Xu *et al.*, 2021). The few studies that have included smell in a digital environment have focused solely on the development of the technology (e.g., usability and feasibility tests; Liu *et al.*, 2023; Niedenthal *et al*., 2023), or they have applied it in a non-food domain such as for the 'gamification' of olfactory cognition testing and training (Andonova *et al*., 2023; Dozio *et al.*, 2021; Olofsson *et al.*,2017). However, smell is an established determinant of flavor perception and food choice (Boesveldt & de Graaf, 2017). Indeed, food odours are known to trigger specific appetite (Ramaekers *et al*., 2014), can enhance the effect of visual food stimuli on self-reported craving (Wolz *et al.*, 2017) and salivation levels (Krishna *et al.*, 2014), and potentially influence food decision-making processes (Morquecho-Campos *et al.*, 2022; Yang *et al*., 2023).

A mechanism by which an immersive multisensory VR food environment with both visual and olfactory cues may elicit responses more similar to those in real-life is the increased levels of spatial presence within the virtual environment. We propose that the additional olfactory cues enhance the sense of presence, which in turn triggers more realistic responses to the environment. An environment that closely resembles real-life sensory input is expected to give users a greater feeling of actually "being there". Indeed, it has been shown that more sensory-rich (i.e., where more senses are stimulated) VR environments evoke stronger levels of (tele) presence (Goncalves *et al.*, 2020; Galace, 2012), though research on the specific addition of only smell is limited. The few studies that looked at the isolated effect of (environment-congruent) smell exposure added to a VR application generally found positive effects on levels of spatial presence (Archer *et al*., 2022; Baus *et al*., 2017; Baus *et al*., 2022; Brengman *et al*., 2022; Persky & Dolwick, 2020; Munyan III *et al*., 2016), though some null findings have also emerged (e.g., Baus *et al*., 2018).

Several studies have shown that spatial presence is a central conceptual mediator of many VR applications (Barranco Merino *et al*., 2023; Slater & Wilbur, 1997). Intuitively, when people have a stronger sense of actually being in the virtual environment, they are more likely to respond to stimuli in this environment as they would in physical (i.e., real-life) settings. Indeed, it has been shown that high presence in a virtual environment leads to behaviours more similar to those in real-life circumstances. For instance, in a non-immersive virtual supermarket, participants who reported higher levels of presence had greater similarity in product purchases between virtual and real-world (i.e., non-lab) environments (Waterlander *et al*., 2015). Even though some evidence exists for the effect of olfaction on spatial presence and the role of spatial presence in eliciting real-life purchasing behaviours, the mediating effect of spatial presence is rarely investigated in food decision-making contexts. Understanding this is crucial, as presence-enhancing factors like smell can improve the ecological validity of virtual supermarkets, and help provide a powerful tool for studying food decision-making. However, the merits of an immersive multisensory VR food environment in this context have yet to be fully assessed.

Therefore, the key objective of the present research was to systematically examine the validity of an immersive multisensory VR food environment, which includes visual and olfactory food cues, for modelling FCRs as measured in a real-life lab setting. Here we address the following research questions: 1) To what extent do individuals' psychological (i.e., craving) and physiological (i.e., salivary) FCRs differ between a unisensory (vision only) VR environment versus a multisensory (vision + olfaction) VR environment versus a real-life setting? 2) What psychological mechanisms underlie FCR-enhancing effects of the multisensory VR environment?

We hypothesized that food cues would lead to stronger craving and salivation responses compared to non-food cues in general (H_{1A}), but that these food-specific cue responses (FCRs) are smaller in the Unisensory VR environment compared to both Multisensory VR (H_{1B}) and Real-life exposure (H_{1C}). We did not expect a difference in FCR profiles in the latter two exposure modes, in that FCRs would be similar across Multisensory VR and Real-life environments (H_{1D}). Finally, we expected that the difference in FCRs (ΔFCRs) between Multisensory VR and Unisensory VR exposure is (partially) mediated through an enhanced sense of presence (H_2). That is, Multisensory VR exposure will lead to higher levels of presence than Unisensory VR exposure, and presence perceptions will positively correlate with FCRs.

2. Methodology

2.1 Design

This lab-based experiment had a 3 (*Exposure Mode*: Real-life versus Unisensory VR versus Multisensory VR) by 2 (*Stimulus Type*: Non-food versus Food) within-subjects design. We chose a within-subjects design in light of high individual variability in salivary flow rates (Dawes, 1987; Ship *et al.*, 1991). Participants visited the lab twice for screening and the test session, respectively, with a washout period of at least one day. Test sessions were planned between 9:00 and 17:00, since this interval spans typical mealtimes and circadian rhythms governing salivary flow tend to peak around this period (Dawes, 1975; Dawes, 1996).

During test sessions, participants performed all six experimental conditions of a cue exposure task (cf. section 2.4.1) in a hungry state. Hunger was expected to trigger the strongest (psychological and physiological) responding to food cues (Brunstrom *et al.*, 2004; Burgess *et al.*, 2016; Loeber *et al.*, 2013; Steel *et al.*, 2006), as well as better differentiate food cue responses between virtual and real-life conditions (cf. van der Waal *et al.*, 2021). Notably, we pseudorandomized the order of exposure modes and counterbalanced the presentation of stimulus types across participants **(Figure 1).** The study design, hypotheses, and analytical plan were pre-registered and are available with study data on the Open Science Framework (Project URL: osf.io/n8gm3/).

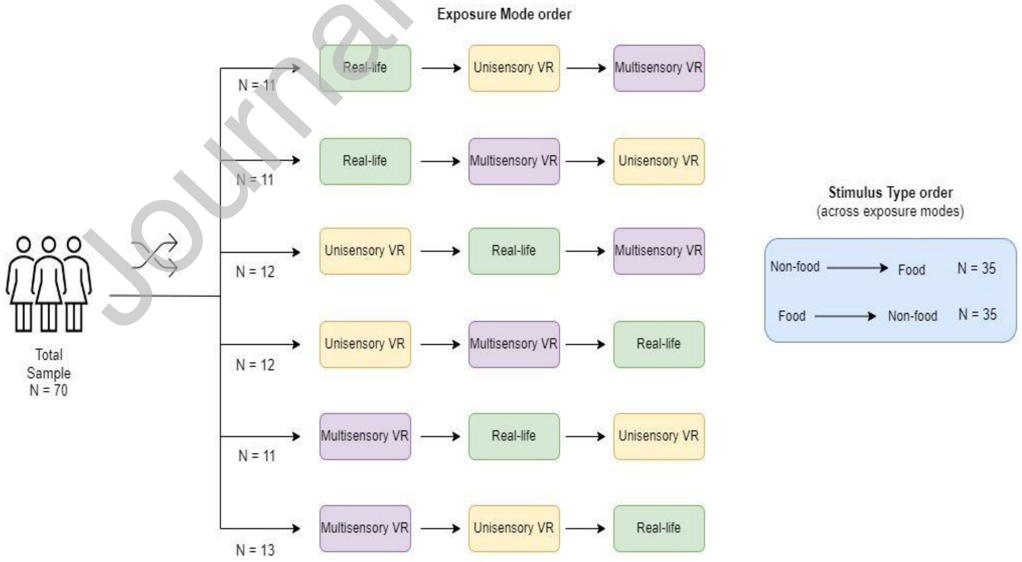

Figure 1. Randomization of participants into the different orders of exposure modes. The order in which stimulus types (within an exposure mode) was presented was fixed per participant and counterbalanced across our sample.

2.2 Participants

A total of 70 participants (59 % F; Age = 20.71 (SD = 2.55) years; BMI = 22.39 (2.67) kg/m2) were included in the study. *A priori* power calculations based on a small expected effect (f = 0.14) of exposure mode on FCRs (van der Waal *et al.*, 2021) indicated that a minimum sample size of 54 individuals was required to achieve sufficient statistical power. We recruited and tested approximately 30% more participants to account for potential exclusions due to eligibility (e.g., olfactory performance), non-adherence to hunger manipulations, and/or measurement errors (cf. van der Waal *et al.*, 2021). All participants were English-speaking university students from various educational backgrounds (i.e. under- and postgraduate). Participant recruitment was achieved through advertisement of study posters and flyers on university buildings, social media platforms and the participant pool of the university department. Individuals were included in the study if they were healthy at the time of study (self-reported) and had a normal olfactory ability, as assessed using age-specific cut-offs from the 16-item Sniffin' Sticks identification test (Hummel *et al., 2*007). Individuals were not allowed to participate if they reported a restriction or aversion to test stimuli (cf.

section 2.4.3), a presence or history of eating disorder(s), neurological, and/or olfactory disorder(s), identified as being a habitual smoker, or were pregnant and/or lactating at the time of the study. All participants provided written informed consent prior to testing and were compensated with study credits. This research was approved by the Ethical Review Board of the Tilburg School of Humanities and Digital Sciences (Tilburg University; file number: REDC2023.62).

2.3 Procedure

Experimenters communicated the cover story that the study aimed to investigate effects of VR exposure on cognitive performance. Interested individuals were first screened on their eligibility in a first lab (screening) session, in which their olfactory ability was examined. Eligible participants then received instructions to adhere to prior to the second lab session (test session), including a restriction on using fragranced products (e.g., perfume, chewing gum) and a directive to drink enough water (as per usual consumption) on the day itself. Importantly, to experimentally manipulate hunger states, we also instructed participants to not consume anything (except water) for at least three hours prior to testing (cf. van der Waal *et al*., 2021). Participants were emailed a reminder for these instructions 24 hours before their test session.

At the onset of a test session, participants filled in a questionnaire on their current hunger level, pre-test adherence checks (e.g., time of last meal), and demographic (e.g., *Gender*, *BMI*) and control measures (e.g., *familiarity with VR*, *trait sensory imagery*). Next, they were asked to rinse their mouths with distilled water, which was done to help participants practice the spitting method (cf. section 2.5.1), as well as stabilize salivary levels prior to the cue exposure task (section 2.4.1). To familiarize participants with the VR equipment and the virtual supermarket, they first engaged in a short practice round where they were instructed to pick-up an object in a separate section of the virtual supermarket.

Next, they had to complete a cue exposure task in each of six experimental conditions, in a randomized order. Participants had a two-minute break in-between experimental conditions, in which they (re)rinsed their mouths and performed a timed (non-food) distractor task that was related to the cover story (e.g., memory and spatial rotation tests). Attentional checks and honesty reminders were administered at main procedural checkpoints (e.g., before craving ratings following cue exposure in each condition). Upon finishing the cue exposure task in the last (sixth) condition, participants were debriefed and compensated.

2.4 Apparatus and Stimuli

2.4.1 Cue exposure paradigm. Individuals were instructed to "*imagine you are grocery shopping in a supermarket, when you come across a promotional stand for a new product*". They were then told to explore a sample of the new product up-close, by picking it up from its display (i.e., bowl) and to interact with the sample as they wished to for one minute. They were also informed not to explore any other objects or navigate away from the promotional stand during this time.

For each condition, participants had to interact with the (non-food or food) product for a duration of one minute. Prior to the interaction with the product, individuals were required to swallow immediately before they picked-up the sample. The pace at which participants picked-up the sample was self-determined across conditions to help them comply with instructions. Every 30 seconds after (i.e., twice in total), they would then receive a verbal cue from the experimenter to drop the sample back into its bowl and to spit their saliva into an empty pre-weighted cup. Importantly, in line with the spitting method of Navazesh (1993), individuals were explicitly told not to swallow their saliva – but to let it pool or collect in their mouths – during each 30-second interval. After the timed cue exposure, they answered questionnaires (e.g., craving, state gustatory mental imagery, and presence in virtual conditions only) related to their interaction with the product on a provided tablet. This procedure was repeated for each experimental condition. We measured salivary volume as our physiological FCR, while reported craving was our psychological FCR outcome.

2.4.2 Exposure mode. The immediate (visual) environment was standardized as much as possible across exposure modes. In all conditions, participants stood in front of a promotional stand that consisted of a table with a packaged product and unpackaged sample (within a bowl) on display, as well as an accompanying signboard that stated “New Product – Try Me!”. We opted for participants to interact with the unpackaged sample within the bowl to stimulate consumption beliefs (or imagery) in food cue conditions, which may be a prerequisite for salivary responses to occur (Spence, 2011).

In the *Real-life* exposure condition, the promotional stand (i.e., table, promotional sign, packaged product and unpackaged sample within a bowl) was recreated in a separate lab room, with actual (non-food and food) stimuli that participants could interact with **(Figure 2).**

In the *Unisensory VR* (i.e., vision only) condition, this promotional stand was placed in a virtual supermarket (VirtuMart; Blom *et al.*, 2021; van der Laan *et al.*, 2022; **Figure 2)**. The VirtuMart is a virtual supermarket modelled in Blender and implemented in Unity. The layout and products of this supermarket were modelled to mimic one of the most well-known Dutch supermarket chains. The assortment of VirtuMart comprises 240 products across twenty product categories, including bread, desserts, meat, fruit, and vegetables. An immersive experience of the virtual supermarket was delivered by using an HTC Vive head-mounted display; two hand-held controllers allowed for picking up products using virtual hands. The promotional stand was placed in front of the virtual bread aisle.

The *Multisensory VR* (i.e., vision + olfaction) exposure mode was identical to the unisensory VR condition described above, except that virtual products were further accompanied by olfactory cues (see **section 2.4.4** for details on odour delivery). The multisensory VR infrastructure entailed an additional portable olfactometer (*Sniff-O* device developed by *CyNexo srl*) that was connected to an air pressure generator (operating at 3.5 to 4 bar). *Sniff-O* had six odour channels that were equally divided among (non-food and food) stimulus types. Each odour channel had a respective odour jar containing a scented cotton ball and downstream tubing, which ran from the jar and converged into a user manifold that had two main output tubes. The user manifold was fastened to a body harness that was placed at a comfortable distance (i.e., on the center of the chest bone) and directed odours towards the nose of the participant – adjusting the placement of the manifold per individual as needed **(Figure 2).** This "free-hanging" construction allowed for hand controllers to be used during the cue exposure task.

2.4.3 Stimulus type. *Non-food* stimuli encompassed small-to-medium sized scented wood chips (Whiskey wood chips; *Weber*). This product was chosen because wood was previously validated as a suitable non-food reference (cf. van der Waal *et al.*, 2021), contextually appropriate for the supermarket scenario, and matched prominent visual characteristics (e.g., shape, size, and colour) of the food stimuli.

Food stimuli consisted of unwrapped (pure) milk chocolate pieces. Chocolate is widely recognized as a rewarding food and has been demonstrated to be a potent stimulus for inducing strong appetitive responses (Kemps & Tiggemann, 2009; Proserpio *et al.*, 2017).

For virtual conditions, the same three-dimensional (unwrapped) chocolate model from van der Waal *et al.*, (2021) was used. All remaining virtual products (e.g., packaged chocolate, and (un)packaged wood) were developed from scratch using Blender software and modelled as closely as possible to real-life variants.

2.4.4 Odour delivery. To seamlessly deliver odours into the virtual food environment during multisensory VR exposure, *Sniff-O* interfaced with the VirtuMart Unity platform using an Arduino-based architecture. At any one time, two odour channels of *Sniff-O* were operational (i.e., one per stimulus type). Virtual "triggers" were programmed into the VR

Unity platform, such that the appropriate (non)food odour channel of *Sniff-O* automatically opened (with a delay of less than four milliseconds) when the corresponding virtual product was picked-up and immediately closed when the object was dropped. In addition, when an odour channel closed, a clean-air channel was simultaneously activated (with less than a millisecond delay), which produced a continuous flow of odourless air and prevented the cross-contamination of odours within main output tubes.

For both wood (AllSense-Voit Aroma Factory No. 821; 1.2% in propylene glycol) and chocolate (IFF SC048015; 5% in propylene glycol) odours, odour solutions were first created and a small volume of each was then pipetted into cotton balls for insertion into *Sniff-*

Figure 2. Illustration of the Real-life, Unisensory VR, and Multisensory VR exposure modes, across stimulus types (Non-food versus Food). In the Multisensory VR condition (last panel), visual cues were additionally accompanied by olfactory cues that were administered by a novel portable olfactometer device (*Sniff-O*). Odours were “triggered” as soon as a participant picked up the corresponding object (i.e., wood versus chocolate) in the virtual food environment.

O (3 and 2 millilitres for wood and chocolate, respectively). To arrive at effective odour levels, we conducted a pilot test beforehand in a separate sample of students (N =35; 63% F; M_{Age} = 23.50, SD_{Age} = 4.55). Results confirmed that odour solutions were perceived at medium-high intensities (i.e., 55-75 mm on a 100 mm VAS) and were similarly liked between non-food and food stimuli (**Table 1**). Furthermore, final odours were consistently (i.e., more than 80% of the time) correctly categorized as (non)food and matched with their associated object significantly more frequently than chance level (**Table 1**).

During odour administration, a total flow rate of 3.5 standard liters/minute was used:

The clean-air (constant flow) channel was delivered at a flow rate of 2 standard liters/minute and odour channels were set to deliver at a flow rate of 1.5 standard liters/minute. These values were informed by previous literature (cf. Albayay *et al.*, 2022) and pre-tests with the study team to achieve a sufficiently stable perceived odour intensity throughout the (one-minute) cue exposure time. Flow rates were calibrated at the beginning of each test day and scented cotton balls were replaced regularly (i.e., every 2-3 test days) to maintain a consistent odour intensity. Finally, in line with best practices (e.g., Lundstrom *et al.*, 2010), odour tubes were "flushed" at the end of each test week, by running clean pressurized air throughout the entire tubing system.

Table 1. Pilot results on (non)food odour solutions for use in the multisensory VR condition.

Odour Attribute	**Wood Odour**	**Chocolate Odour**	**Test statistic**	***p***
Liking [a] *Median (IQR)*[a]	54 (50)	50 (50)	t(161) = -0.87 [b]	.385
Perceived Intensity [a] *Median (IQR)*	59 (34)	67 (32)	t(162) = 1.75 [b]	.081
Classification as (non)food *(% correct)*	83.9%	87.1%	Z_{Wood}= 3.77 [c] $Z_{Chocolate}$ = 4.13 [d]	<.001* <.001*
Matching odour to object *(% correct)*	25.8%	64.5%	Z_{Wood}= 3.79 [c] $Z_{Chocolate}$ = 11.88 [d]	<.001* <.001*

[a] Pilot ratings (on a 100 millimeter (mm) Visual Analogue Scale). The median and IQR are reported due to high observed standard deviations for all ratings (anchored from 0 to 100 mm on a Visual Analogue Scale).

[b] Significance value of t test for group comparisons from a linear mixed model analysis, controlling for participant as a random effect.

[c] Significance value of Z test for a difference from chance level (i.e., null proportion π_0 = 0.5 or 50% for two possible choice options).

[d] Significance value of Z test for a difference from chance level (i.e., null proportion π_0 = 0.08 or 8% for 13 possible choice options).

2.5 Measurements

2.5.1 Primary outcome variables. To assess psychological cue responses, we asked individuals to rate their subjective *craving* for chocolate in all six experimental conditions. *Craving* was determined by the statement "*How much do you desire to eat* *chocolate at this moment”* rated on a 100 mm VAS anchored from “Not At All” to “Very Much” (Hill, 2007; van der Waal *et al.,* 2021). We then took the difference in *craving* between food and non-food stimuli to accurately quantify psychological FCRs in each exposure mode.

We measured individuals’ physiological cue responses by collecting whole-mouth *salivary volume* using the spitting method (cf. Navazesh, 1993) and weighing the difference (in grams; *g*) of a salivary cup before and after cue exposure in each condition (Morquecho-Campos *et al.,* 2019; van der Waal *et al.,* 2021). Similarly, we used the difference in *salivary volume* between food and non-food stimuli in each exposure mode as a proxy for physiological FCRs.

2.5.2 Process indicators. *Presence* in virtual conditions was examined using the 14-item Igroup Presence Questionnaire (Schubert *et al.,* 2001), which focuses on the concept of “being there” or one’s degree of engagement with the virtual as opposed to real (physical) world (Grassini & Laumann, 2020). The questionnaire is divided into three subscales: spatial presence (e.g., “Somehow I felt that the virtual world surrounded me”), involvement (e.g., “I was not aware of my real environment”), and experienced realism (“The virtual world seemed more realistic than the real world”), all rated on a five-point Likert scale. The scale had a good internal reliability, Cronbach’s α = 0.88.

We also explored *state gustatory mental imagery* as a possible mediator of multisensory VR exposure, as effects may be contingent upon the extent to which an individual can mentally simulate the consumption of a food (Spence, 2011). *State gustatory mental imagery* was assessed in all conditions using three items (e.g., “To what extent were you able to imagine/picture yourself eating the chocolate”) rated on a 100 mm VAS with endpoints “Not At All” to “Image as clear and vivid as real-life” (cf. Tiggemann & Kemps, 2005). The scale displayed good consistency, Cronbach’s α = 0.95.

2.5.3 Manipulation and debriefing checks. To assess whether our manipulation of hunger was successful, we asked participants to rate their *hunger* level at the beginning of test sessions on a 100 mm VAS (anchored from “Not at all” to “Very Much”). We similarly examined whether participants perceived the food stimulus (i.e., chocolate) as sufficiently rewarding by asking them to rate *liking* for chocolate on a 100 mm VAS (anchored from “Not At All” to “Very Much”).

A debriefing check (Robinson *et al.,* 2018) was performed at the end of test sessions, to check if our implemented controls (i.e., cover story and distraction tasks) successfully diffused participants’ awareness of study aims. The debriefing questionnaire probed study suspicions using a mixture of open-ended questions (e.g., “Did you hear about this study from other people, prior to participating”?) and one multiple-choice question. The latter required individuals to guess the real study aim from an array of 11 possible options.

2.5.4 Control variables. We examined one’s *familiarity with VR technology* using a five-point Likert item (anchored from 1= “I do not know of or recognize VR technology” to 5 = “I regularly use VR technology”; adapted from Tuorila *et al.,* 2001). Furthermore, demographic and anthropometric characteristics (i.e. *sex, age*, *self-reported height* and *weight*) were collected at the onset of testing. Self-reported height and weight were used to calculate participants’ *BMI* (in kg/m^2).

Finally, as exploratory individual-level correlates, we measured one’s ability to form mental representations (i.e., trait mental imagery) arising from different sensory input: *Trait olfactory sensory imagery* (Cronbach’s α = 0.76) and *trait gustatory sensory imagery* (Cronbach’s α = 0.68). Both were assessed via respective (five-item) subscales of the Plymouth Sensory Imagery Questionnaire (Andrade *et al.,* 2014).

2.6 Data Analysis

We conducted all data analysis using R (version 4.4.1; R Core Team, 2024) and the *brms* package (Bürkner, 2017). Because we hypothesized parameter equality (H_{1D}), we adopted a Bayesian approach for our main analyses, as it facilitates assessing evidence for equivalence (i.e., treatment differences equal to zero). For our Bayesian models (H_{1A} to H_2 and exploratory counterparts; **sections 3.2** to **3.6**), to align our inferences with the traditional 0.05 cutoff value, we decided *a priori* to declare estimates as credibly non-zero, or *credible*, if their 95% confidence interval excluded zero (for non-directional hypotheses) or if their posterior probability of direction (p^+: proportion of posterior draws in hypothesized direction; Bayesian equivalent to 1-one-sided *p*-value; Marsman & Wagenmakers, 2016) exceeded 95%. For non-Bayesian analyses (e.g., manipulation checks; cf. **section 3.1**), we used the traditional 0.05 cutoff value for statistical significance. We discuss modelling details below where appropriate. Our analyses were pre-registered (URL: osf.io/6hjax) and blinded, meaning that the dataset was initially analysed with anonymized condition labels.

3. Results

3.1 Manipulation and debriefing checks

First, we tested whether mean *liking* and *hunger* scores were different from the scale midpoint (50) with respective one-sample z-tests. *Liking* was significantly higher than the midpoint (76 versus 50 *mm*, 95% CI = [72, 80]), Z = 11.85, *p* < .01, indicating that participants perceived the food stimulus (i.e., chocolate) as sufficiently rewarding. Conversely, *hunger* ratings were not significantly higher than neutral (54 versus 50 *mm*, 95% CI = [48, 59]), Z = 1.21, *p* = 0.20. We additionally examined whether *hunger* scores were significantly different from those of an earlier investigation that employed the same hunger manipulation (cf. van der Waal *et al.*, 2021). A one-sample z-test revealed that participants' *hunger* level was significantly lower than the previous study (54 versus 62.95 *mm*, 95% CI = [46, 56]), Z = -4.45, *p* < .01. Taken together, these results suggest that hunger state was not successfully manipulated. Consequently, we made exploratory adjustments for hunger in our main models (cf. **section 3.4**) to circumvent potential floor effects on our primary research aims.

Debriefing checks with a one-sample exact binomial test showed that 20 out of 70 individuals (i.e., 29%, 95% CI = [.18, .41]) guessed the study's aims correctly. Consequently, we re-ran our main confirmatory models excluding individuals who correctly guessed study aims. Findings from these hypothesis tests did not change initial conclusions, so we will not discuss them further.

3.2 Psychological and physiological FCRs *within* exposure modes (H_{1A})

To examine whether *craving* and *salivary volume* between food and non-food stimuli (i.e., psychological and physiological FCRs, respectively) were credibly different across exposure modes (H_{1A}), we formulated a Bayesian multilevel regression model for each outcome measure. In each model, we specified main and interaction effects of *Stimulus Type* and *Exposure Mode* as fixed effects, *Participant* as a random effect, and *Familiarity with VR technology*, *Sex*, *Age,* and *BMI* as (centred) covariates in the fixed part of the model.

Results yielded a main effect of *Stimulus Type* on psychological FCRs: *Craving* was systematically higher for food versus non-food in Unisensory VR (Mean Difference $_{\text{F-NF}}$: 12.43 *mm*, 95% CI = [6.45, 18.33]), Multisensory VR (Mean Difference $_{\text{F-NF}}$: 17.21 *mm*, 95% CI = [11.31, 23.20]), as well as Real-life conditions (Mean Difference $_{\text{F-NF}}$: 29.80 *mm*, 95% CI = [23.81, 35.59]), all p^+ = 100.00% (**Figure 3**).

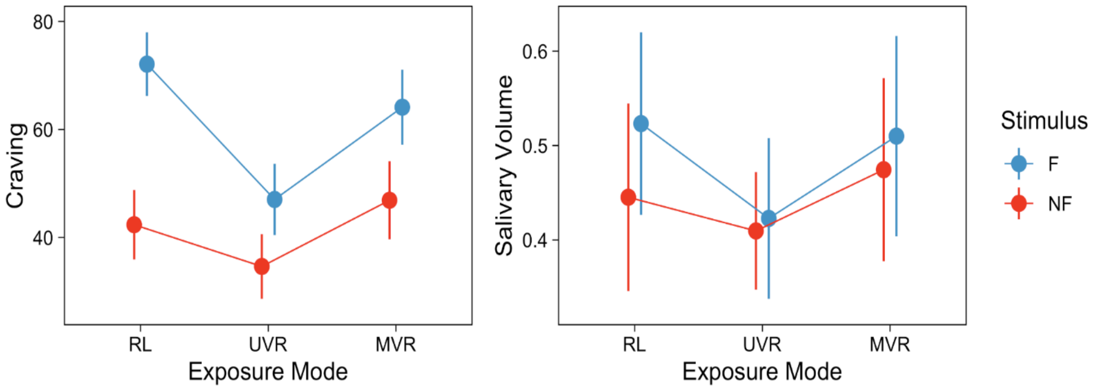

Figure 3. Means and 95%CIs of craving (left) and salivary volume (right) across the experimental conditions. RL = Real Life, MVR = Multisensory Virtual Reality; UVR = Unisensory Virtual Reality; F = Food; NF = Non-food.

While *salivary volume* was greater on average after interacting with food versus non-food stimuli in all exposure modes **(Figure 3)**, an interaction between *Stimulus Type* and *Exposure Mode* was detected as physiological FCRs were only credible in the Real-life setting (Mean Difference $_{\text{F-NF}}$: 0.08 *g*, 95% CI = [0.03, 0.13]), p^+ = 99.90%. Therefore, partial evidence was found for H_{1A}.

3.3 Psychological and physiological FCRs *between* exposure modes (ΔFCRs; H_{1B} -H_{1D})

We then examined differences in psychological and physiological FCRs (ΔFCRs) *between* exposure modes (H_{1B} – H_{1D}) from the model described above. As H_{1D} required testing for *equivalence* (i.e., zero treatment difference), it merited a different approach: We treated FCRs whose difference was within 0.1 standard deviations of the respective outcome ($SD_{craving}$ = 30.13, SD_{volume} = 0.39) from zero as equivalent to one another. Then we calculated the proportion of the respective posterior distribution within that interval (i.e., region of practical equivalence; ROPE) to ascertain confidence in the equivalence statement (Kruschke, 2011; Kruschke, 2018). Note that this procedure is similar to the frequentist concept of equivalence testing, a practical method for assessing evidence for an interval-null hypothesis.

First, we expected that psychological and physiological FCRs would be stronger in Multisensory VR relative to Unisensory VR conditions (H_{1B}). As displayed in **Figure 4A** and **4B**, while differences were in the expected direction, Multisensory VR exposure did not trigger systematically higher food-specific *craving* (Mean Difference $_{\text{MVR-UVR}}$: 4.79 *mm*, 95% CI = [-3.52, 13.17]), p^+ = 86.92%, nor greater *salivary volume* towards food versus non-food cues (Mean Difference $_{\text{MVR-UVR}}$: 0.02 *g*, 95% CI = [-0.05, 0.09]), p^+ = 73.83%, compared to Unisensory VR settings. Thus, H_{1B} was not supported. That said, we also did not find evidence for equivalence (i.e., *zero* difference) in craving profiles between Multisensory VR and Unisensory VR exposures **(Figure 4B)**.

Moreover, we anticipated that psychological and physiological FCRs would be greater in Real-life relative to Unisensory VR exposure (H_{1C}). **Figure 4B** shows that H_{1C} was supported: In Real-life, the difference in *craving* between food versus non-food stimuli was indeed bigger compared to the Unisensory VR condition (Mean Difference $_{\text{RL-UVR}}$: 17.38 *mm*, 95% CI = [8.87, 25.67]), p^+ = 100.00%. Likewise, food-induced *salivary volume* was greater in Real-life than in Unisensory VR settings (Mean Difference $_{\text{RL-UVR}}$: 0.06 *g*, 95% CI = [-0.01, 0.13]), p^+ = 96.16%.

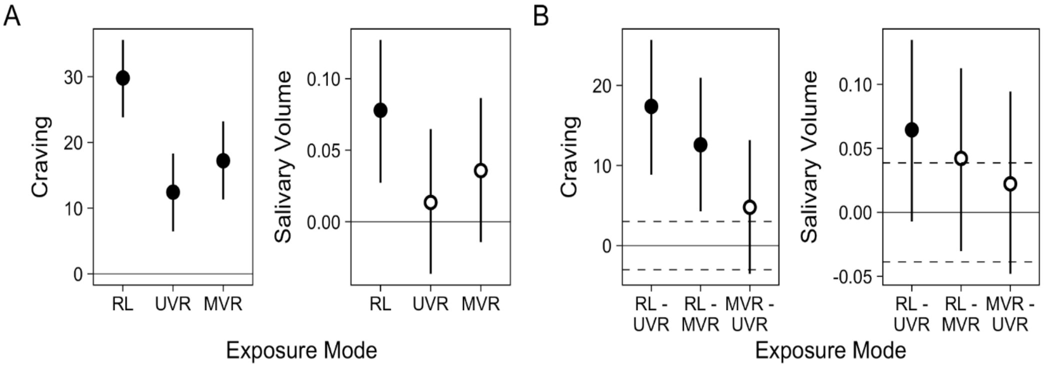

Figure 4. **A)** Psychological (craving) and physiological (salivary volume) responses to food versus non-food cues (i.e., FCRs) across exposure modes. RL: Real Life. UVR: Unisensory VR. MVR: Multisensory VR. Points and intervals are posterior means and 95% CIs. Filled points denote credible (non-zero) differences between food and non-food stimuli. **B)** Differences in psychological and physiological FCRs (i.e., ΔFCRs) between different exposure modes. Dashed lines indicate limits of the region of practical equivalence (ROPE) to zero. ROPE is the percentage of the posterior distribution in the region of practical equivalence to zero, and thus assesses evidence for the null of no difference (i.e., *equivalence* between conditions). Points and intervals are posterior means and 95% CIs. Filled points denote credible (non-zero) differences between conditions.

Finally, we assessed whether psychological and physiological FCRs were similar across Multisensory VR and Real-life conditions. Contrary to hypothesized (H_{1D}), Multisensory VR exposure elicited systematically weaker food-specific *craving* than in Real-life (Mean Difference $_{\text{RL-MVR}}$: 12.59 *mm*, 95% CI = [4.28, 20.95]), p^+ = 99.80%. On the other hand, and congruent with expectations, *salivary volume* towards food (versus non-food stimuli) did **not** credibly differ between Multisensory VR and Real-life settings (Mean Difference $_{\text{RL-MVR}}$: 0.04 *g*, 95% CI = [-0.03, 0.11]), p^+ = 87.79% – although we could not conclude equivalence (i.e., *zero* difference) in salivary profiles either **(Figure 4B)**.

3.4. Exploratory corrections for hunger state (sensitivity analysis)

Given that earlier checks indicated an unsuccessful hunger manipulation, we explored whether correcting for participants’ hunger state would better distinguish psychological and physiological FCRs between exposure modes. Thus, we adjusted for hunger state by including a main effect of (grand mean-centered) *Hunger* and its interactions with *Stimulus Type* and *Exposure Mode* as predictors in otherwise identical models (cf. **section 3.2**).

In **Table 2**, we show differences in FCRs between exposure modes at one standard deviation (i.e., 24 units) above (+1 SD) and below (-1 SD) mean hunger. Results confirmed weaker food-specific *craving* in both virtual conditions relative to Real-life – even at matched levels of hunger. Similarly, a lower salivary response to food (versus non-food) in Unisensory VR compared to Real-life settings was replicated, as well as the previous finding that salivary profiles did not credibly differ between Multisensory VR and Real-life exposure. That said, correcting for hunger revealed an additional difference in physiological FCRs between virtual exposure modes in line with H_{1B}: Food-induced *salivary volume* was 0.11 units lower (95% CI = [-0.20, -0.01]) in the Unisensory VR compared to the Multisensory VR setting, even when individuals reported higher (+ 1 SD) hunger levels in the former condition. Interestingly, within Unisensory VR exposure, higher (+1 SD) hunger levels were associated with weaker salivary responses **(**B = - 0.13, 95% CI = [-0.22, -0.03]; **Table 2)**.

An alternative sensitivity check that excluded individuals who did not correctly adhere to pre-test fasting instructions (N = 13) yielded largely consistent findings (see osf.io/n8gm3/ for complete results). However, in the latter case, food-specific *craving* did not significantly differ between Real-life and Multisensory VR conditions at either higher (+1 SD) or lower (-1 SD) hunger levels, nor between Real-life at lower hunger levels versus the Unisensory VR condition at higher hunger levels.

Table 2. Psychological and physiological FCRs between exposure modes (ΔFCRs) at specified levels of hunger (i.e., 1 SD above and below mean hunger).

FCR Outcome	Contrast	Estimate and 95% CI (p^{+})
Craving	UVR (hunger$_{-1\ SD}$) - RL (hunger$_{-1\ SD}$)	**-14.16 [-25.45, -2.47] (99.21%)**
Craving	MVR (hunger$_{-1\ SD}$) - RL (hunger$_{-1\ SD}$)	**-10.70 [-22.17, 0.69] (96.61%)**
Craving	MVR (hunger$_{-1\ SD}$) - UVR (hunger$_{-1\ SD}$)	3.46 [-8.30, 14.85] (72.07%)
Craving	RL (hunger$_{+1\ SD}$) - RL (hunger$_{-1\ SD}$)	6.85 [-4.50, 18.34] (88.05%)
Craving	RL (hunger$_{+1\ SD}$) - UVR (hunger$_{-1\ SD}$)	**21.01 [9.62, 32.25] (99.99%)**
Craving	RL (hunger$_{+1\ SD}$) - MVR (hunger$_{-1\ SD}$)	**17.55 [6.14, 29.11] (99.81%)**

Craving	UVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	**-13.59 [-25.25, -2.02] (98.78%)**
Craving	UVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	0.57 [-11.03, 12.15] (53.31%)
Craving	UVR (hunger$_{+1\ \mathbf{SD}}$) - MVR (hunger$_{-1\ \mathrm{SD}}$)	-2.90 [-14.52, 8.88] (69.19%)
Craving	UVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{+1\ \mathbf{SD}}$)	**-20.44 [-32.08, -8.83] (99.97%)**
Craving	MVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	-7.37 [-18.72, 4.09] (89.44%)
Craving	MVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	6.79 [-4.89, 18.26] (87.69%)
Craving	MVR (hunger$_{+1\ \mathbf{SD}}$) - MVR (hunger$_{-1\ \mathrm{SD}}$)	3.33 [-7.95, 14.74] (71.42%)
Craving	MVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{+1\ \mathbf{SD}}$)	**-14.22 [-25.68, -2.74] (99.34%)**
Craving	MVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{+1\ \mathbf{SD}}$)	6.22 [-5.54, 17.91] (84.85%)
Salivary Volume	UVR (hunger$_{-1\ \mathrm{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	0.00 [-0.09, 0.10] (53.30%)
Salivary Volume	MVR (hunger$_{-1\ \mathrm{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	-0.02 [-0.11, 0.08] (64.14%)
Salivary Volume	MVR (hunger$_{-1\ \mathrm{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	-0.02 [-0.12, 0.07] (67.08%)
Salivary Volume	RL (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	0.01 [-0.09, 0.10] (56.07%)
Salivary Volume	RL (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	0.00 [-0.09, 0.10] (52.52%)
Salivary Volume	RL (hunger$_{+1\ \mathbf{SD}}$) - MVR (hunger$_{-1\ \mathrm{SD}}$)	0.02 [-0.07, 0.12] (69.92%)
Salivary Volume	UVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	**-0.13 [-0.22, -0.03] (99.52%)**
Salivary Volume	UVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	**-0.13 [-0.22, -0.03] (99.45%)**
Salivary Volume	UVR (hunger$_{+1\ \mathbf{SD}}$) - MVR (hunger$_{-1\ \mathrm{SD}}$)	**-0.11 [-0.20, -0.01] (98.60%)**
Salivary Volume	UVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{+1\ \mathbf{SD}}$)	**-0.13 [-0.23, -0.04] (99.60%)**
Salivary Volume	MVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{-1\ \mathrm{SD}}$)	-0.06 [-0.16, 0.04] (88.88%)
Salivary Volume	MVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{-1\ \mathrm{SD}}$)	-0.06 [-0.16, 0.03] (90.50%)
Salivary Volume	MVR (hunger$_{+1\ \mathbf{SD}}$) - MVR (hunger$_{-1\ \mathrm{SD}}$)	-0.04 [-0.14, 0.05] (80.83%)
Salivary Volume	MVR (hunger$_{+1\ \mathbf{SD}}$) - RL (hunger$_{+1\ \mathbf{SD}}$)	-0.07 [-0.16, 0.03] (91.71%)
Salivary Volume	MVR (hunger$_{+1\ \mathbf{SD}}$) - UVR (hunger$_{+1\ \mathbf{SD}}$)	0.07 [-0.03, 0.16] (90.71%)

3.5 Indirect mediation of Multisensory VR effects by presence (H_2)

In light of (directional) improvements in food-induced *craving* and *salivary volume* afforded by Multisensory VR over Unisensory VR exposure, we further examined potential psychological processes that might mediate these differences (H_2). To this end, we first calculated mean FCRs for each virtual exposure mode (across *Stimulus Type*), because *presence* (the hypothesized mediator) was measured once per virtual condition. We then specified a multivariate regression model predicting *Presence* from virtual *Exposure Mode* (i.e., Unisensory VR versus Multisensory VR; E -> P), and one predicting FCRs (i.e., *craving* or *salivary volume*) from *Presence* and all covariates as specified in the previous model (P -> FCRs; **Table 3**). We specified both paths (i.e., E ->P and P -> FCR) with by-person random intercepts to account for repeated measures over individuals. We then quantified whether *presence* mediates FCR effects of the Multisensory VR condition by multiplying the virtual *Exposure Mode* to *Presence* path coefficient with the *Presence* to FCR path coefficient (i.e., E->P * P->FCR; **Table 3**).

The mediation model indicated that shifting from the Unisensory VR to Multisensory VR condition increased feelings of *presence* (cf. **Table 3** and **Figure 5A**). However, *presence* ratings did not further predict either *craving* or *salivary volume* (**Figure 5B and 5C**). In other words, while Multisensory VR exposure did enhance experienced *presence* in the virtual environment, the latter did not (indirectly) account for effects on either psychological or physiological FCRs. We therefore did not find support for H_2.

3.6 Exploratory mediation by state gustatory mental imagery

We explored whether (subtle) differences in FCR profiles between virtual conditions could instead be explained by variations in the extent to which one could mentally simulate the consumption of a food (i.e., state gustatory mental imagery). To this end, we formulated an identical mediation model as above (H_2) but with *state gustatory mental imagery* as the mediator.

Results showed that Multisensory VR exposure significantly enhanced perceptions of *state gustatory mental imagery* compared to the Unisensory VR counterpart (cf. **Table 3** and **Figure 5D**). In turn, increased *state gustatory mental imagery* predicted greater *craving* ratings **(Figure 5E)**, but did not correlate with *salivary volume* **(Figure 5F)**. However, *state gustatory mental imagery* ratings did correlate positively with individuals' (baseline) abilities to mentally simulate tasting (i.e., *trait gustatory mental imagery*; r (68) = 0.38, t = 3.39, $p <$ 0.01), as well as smelling products (i.e., *trait olfactory mental imagery*; r = 0.35 (68), t = 3.12, $p < 0.01$).

Table 3. Mediation model results for psychological and physiological FCRs across virtual exposure modes.

FCR Outcome	**Path**	**Mean**	**SD**	**95% CI**	p^+
Model 1: Indirect mediation via presence (H_2)					
Craving[1]	E->P	0.28	0.05	[0.19, 0.38]	**100.00%**
Craving	P->FCR	8.13	6.14	[-4.01, 20.27]	90.87%
Craving	E->P * P->FCR	2.30	1.81	[-1.12, 6.06]	90.87%
Salivary Volume	P->FCR	-0.05	0.06	[-0.17, 0.06]	82.98%
Salivary Volume	E->P * P->FCR	-0.02	0.02	[-0.05, 0.02]	82.98%
Model 2: Indirect mediation via state gustatory mental imagery (Exploratory)					
Craving[1]	E->I	18.58	2.46	[13.72, 23.41]	**100.00%**
Craving	I->FCR	0.61	0.05	[0.52, 0.70]	**100.00%**
Craving	E->I * I->FCR	11.35	1.74	[8.08, 14.88]	**100.00%**
Salivary Volume	I->FCR	0.00	0.00	[0.00, 0.00]	56.06%
Salivary Volume	E->I * I->FCR	0.00	0.01	[-0.02, 0.02]	56.06%

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[1] Path is shown only once because conceptual mediators (i.e., *presence* and *state gustatory mental imagery*) were measured per virtual condition and thus aggregated across FCR outcomes. E: Exposure Mode (Unisensory VR versus Multisensory VR), P: Presence ratings (five-point Likert scale ranging from 1 to 5), I: State gustatory mental imagery ratings (100 mm VAS).

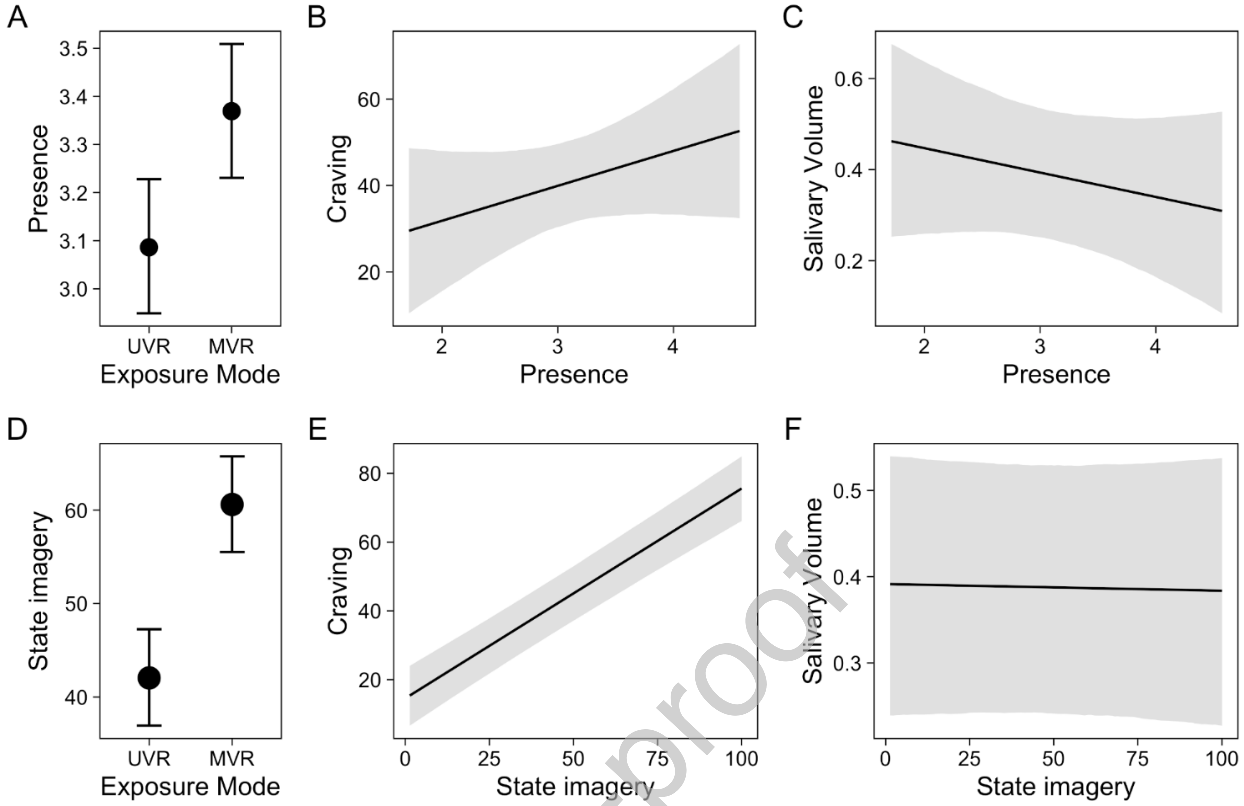

Figure 5. Top row: Results of the mediation model assessing whether *presence* accounted for effects of Multisensory VR exposure on psychological (i.e., craving) and physiological FCRs (i.e., salivary volume). A) Conditional posterior means and 95%CIs of *presence* in Unisensory (UVR) and Multisensory (MVR) VR exposure modes. B) Model's regression line and 95%CI of *craving* on *presence*. C) Model's regression line and 95%CI of *salivary volume* on *presence.* **Bottom row:** Results of the mediation model that explored whether *state gustatory mental imagery* explained effects of Multisensory VR (MVR) exposure on *craving* and *salivary volume*. D-F) As A-C except with *state gustatory mental imagery* as mediator.

4. Discussion

The present lab-based study systematically investigated whether an immersive multisensory VR food environment – with the added presence of olfactory cues – could validly model individuals' fundamental (psychological and physiological) responses to food, thereby bridging the current gap between existing "vision-only" unisensory VR environments and real-life settings. In sum, we found that food cues induced stronger craving than non-food cues across all exposure modes, while this was only true for salivary volume in the (physical) Real-life condition (H_{1A}). Additionally, Unisensory VR exposure consistently elicited weaker psychological and physiological FCRs compared to Real-life (H_{1C}), whereas Multisensory VR exposure led to a directional (non-equivalent) improvement over Unisensory VR settings in food-specific craving and higher salivary food responses after adjusting for hunger (H_{1B}). We could not conclude equivalence between Multisensory VR and Real-life conditions on either FCR outcome, though the latter did not systematically differ from one another on the basis of salivary responses either (H_{1D}). Finally, although Multisensory VR exposure increased feelings of presence, this increase could not account for the differences in FCRs that emerged between virtual conditions. Instead, subtle differences in craving profiles between virtual conditions were mediated by enhanced gustatory mental imagery in the Multisensory VR setting.

The psychological FCR, craving, showed strong and robust effects of the food versus non-food manipulation, with stronger craving for food cues across all exposure modes. This main effect of stimulus type also remained significant after exploratory corrections for different levels of hunger state. As such, our results replicate the findings of van der Waal *et al. (*2021), who demonstrated that *within* an exposure mode, (visual) food cues reliably led to stronger reported craving in both virtual and real-life settings. This is also in line with findings from studies on VR exposure therapy that showed that virtual food cues and food-related environments result in stronger cravings than virtual neutral cues and non-food related environments (e.g., Pla-Sanjuanelo et al., 2017). We now expand on these results by revealing that (visual + olfactory) food cues also lead to higher craving than non-food cues for the multisensory VR condition, which was in line with our expectations.

Besides a main effect of stimulus type, we also observed differences in food-specific craving *between* different exposure modes in our study. We replicate another result by van der Waal *et al.* (2021), showing that while food-induced craving was credible in all exposure modes, its expression was consistently weaker in virtual settings relative to real-life. We anticipated that olfactory cues in the multisensory VR condition would boost one's desire to consume the food, because of previous findings that food odours alone can trigger one's appetite and particularly craving for the corresponding food, as well as foods with similar taste profiles (i.e., "sensory-specific appetite"; Ramaekers *et al.,* 2014; Wolz *et al.*, 2017). However, in line with the meta-analysis of Boswell & Kober (2016), the addition of olfactory cues did not confer a clear advantage over using purely visual food cues for eliciting craving, despite the reliable delivery of (medium-to-high intensity) odours to participants who had confirmed normal olfactory abilities. One possibility for this null finding is a lack of motivation – rather than ability or opportunity – on the part of participants to use olfactory information in their cognitive processing of foods. Research has shown great inter-individual variability in the importance attached to the sense of smell (Croy *et al.*, 2009), general attendance to olfactory stimuli in the environment (Smeets *et al.*, 2008), and consequent use of olfactory information in decision making (Koller *et al.,* 2023), which may have unintendedly diluted craving responses. While we did not directly measure these constructs, positive correlations have been found between odour awareness, as well as the importance of olfaction, with olfactory mental imagery abilities (Zhou *et al.*, 2022). This suggests that some variance in our results pertaining to individual differences in (state/trait) olfactory mental imagery may be applicable to these characteristics.

Alternatively, the absence of notable differences between multisensory and unisensory VR settings may indicate that individuals' food consumption beliefs were still not sufficiently strengthened by multisensory VR exposure (Spence, 2011). Despite the higher degree of sensory fidelity, and possibility of cross-modal correspondences between olfactory and (imagined) gustatory modalities (Zholzhanova *et al.,* 2025), participants were likely still aware that the virtual chocolate could not be physically consumed. This awareness-related perceptual bottleneck could represent an inherent limitation of VR, in contrast to "hybrid" immersive technologies such as Mixed Reality, which more readily support the inclusion of an actual tasting component (Bhavadharini *et al.*, 2023).

It was the case, though, that food-specific craving was directionally higher after multisensory VR exposure, and equivalence also could not be established among virtual conditions, suggesting that the added odour was at least partially (albeit not systematically) successful at increasing craving perceptions (see also Harris *et al.*, 2023). Craving is a marker for one's reactivity to food cues in the environment (Higgs, 2016; Nederkoorn, 2000) and has shown to be a moderate predictor of — and consequent therapeutic target for — an individual's dietary intake (Boswell & Kober, 2016). Taken together, our results therefore support the notion that exposure to (multisensory) food cues in VR can be successful at inducing more ecologically-relevant psychological food responses such as craving, albeit to a lesser extent than in real-life contexts. Practically, these findings suggest that researchers and interventionists need to consider to what extent they expect acute craving to be tied to their main outcome of interest when using VR as a study tool. For interventionists, incorporating odour into VR simulations may help to recreate real-life environmental contexts of therapeutic interest without actual exposure to harmful substances (Hone-Blanchet *et al.*, 2014), while consumer researchers should be mindful that VR-based craving responses may yield conservative effects and potentially underestimate real-life reactions to (food) products.

For physiological FCRs, our study showed increased salivary responses to real food versus non-food cues, thereby confirming the potency of (real) chocolate stimuli in evoking detectable salivary responses that serve to prepare the body for ingestion. Further, in line with our expectations and previous findings of van der Waal *et al.* (2021), we found that food-induced salivary responses were weaker in unisensory VR than in real-life. Though we could not establish that multisensory VR exposure led to equivalent food-specific salivation as in real-life, there was also no significant difference in salivary responses between these conditions, indicating that there may be directional enhancements from adding olfactory cues. Notably, after adjusting for hunger levels—an important motivational factor in food-related behaviors and responses as indicated by previous research (Rogers and Hill, 1989), and considered here due to the unsuccessful hunger manipulation—differences in salivary responses emerged between unisensory and multisensory VR conditions. This finding highlights hunger as a potential boundary condition that influences the effectiveness of multisensory VR applications, suggesting that the added benefit of multisensory stimulation on physiological FCRs may be contingent upon an individual's baseline appetitive state.

Exploring possible mechanisms underpinning effects of multisensory VR exposure on FCRs, we demonstrate that state gustatory mental imagery mediates the subtle difference in craving responses between multisensory versus unisensory VR conditions. State mental imagery is the extent to which participants can imagine, in that specific trial, what eating the food would be like (e.g., ‘To what extent were you able to imagine yourself eating the chocolate’). Our study thus supports prior work showing that mental imagery, and particularly individuals’ ability to cognitively elaborate on the taste of a product, is a prerequisite for developing craving for a food (Croijmans & Wang, 2021; Higgs, 2016). Our findings further underscore that multisensory VR exposure does affect cognitive states, as it led participants to experience stronger state gustatory mental imagery. This in turn predicted higher levels of craving, which may ultimately facilitate later choice for the food, by shifting one’s mindset towards obtaining the target of craving (Boswell & Kober, 2016; Higgs, 2016; Muñoz-Vilches *et al.*, 2020). For instance, enhancing mental simulations by manipulating sensory aspects in pictures was found to increase product liking and purchase intention (Krishna *et al.*, 2016).

We did not observe a similar mediation of state mental imagery on salivation levels, in contrast to previous research showing that self-reported mental imagery vividness influences salivary control (White, 1978), and that imagining a food odour (in combination with the image of a food) increases salivary responses (Krishna *et al.*, 2014). However, we did find that state (gustatory) mental imagery was associated with one’s trait mental imagery, in the sense that the ability to experience imagery, in different sensory modalities, is a trait that varies across individuals (Zeman *et al*., 2020). An individual’s trait gustatory and olfactory imagery were both positively related to state mental imagery, stressing that baseline imagery ability can be a relevant moderator of the effectiveness of VR applications in the food domain. Indeed, studies have revealed that people with higher (trait) mental imagery ability tend to imagine a product’s scent spontaneously upon seeing an image (Sharma & Estes, 2024), need less elaborate descriptions of products than low imagers to experience the same level of craving (Croijmans & Wang, 2021), and report higher levels of craving after exposure to smell alone (Krishna, 2014). Our results are therefore compatible with these earlier observations, and importantly, demonstrate that mental imagery strength (whether state or trait) can be intrinsic to effects of multisensory food cue exposure in a VR setting.

It is worth noting that mental imagery vividness has been positively linked to the sense of presence in VR environments (Iachini *et al.,* 2018), yet our data show that presence was not correlated with any FCR outcomes. Presence captures the extent to which a user suspends (physical) reality and feels part of the (virtual) environment (Slater & Wilbur, 1997). As a central conceptual mediator of various VR applications, a greater sense of presence is widely anticipated to generate results that more accurately reflect measurements obtained in real physical settings. For example, liking ratings obtained in a multisensory VR coffeehouse was more predictive of future coffee liking than ratings obtained from traditional sensory booths in a laboratory (Bangcuyo *et al.*, 2015). The majority of work in VR thus focuses on how to enhance presence, by increasing technological immersion (e.g., through delivering a multisensory experience), or by creating opportunities for natural interaction (Bowman & McMahan, 2007). While it is well-documented that higher technological immersion enhances feelings of presence (Cummings & Bailenson, 2014; Yildirim *et al.*, 2025), establishing a connection between higher levels of presence and a plethora of (cognitive) outcomes such as learning has proven challenging (Makransky *et al.*, 2017).

Our results therefore reflect the current mixed state of evidence in that we indeed found systematic improvements in presence with additional sensory (olfactory) information, but the subsequent impact of presence on FCRs did not manifest. For example, van der Waal et al. (2021) similarly reported that presence was not correlated with craving, yet in another study higher object presence did positively influence craving (Jahn et al., 2022). To better unpack this null finding, we explored scores attached to the different presence subscales. This analysis (see Table S1) revealed that in comparison to ratings on Involvement and Spatial

Presence, the Experienced Realism subscale scored relatively low (2.87 on a five-point scale) across virtual conditions. As such, potential mediating effects of presence might have been diluted as the VR environment may not have been sufficiently consistent with the real-world experience of grocery shopping. This suggests that regardless of how well constructed a virtual environment is, individuals do need to accept the (real-world) premise of the virtual experience for it to be sufficiently effective. We require more empirical studies on not only the role of presence as a mediator, but also a refined theoretical framework for explaining and predicting the effects of higher levels of presence (Barranco Merino *et al.*, 2023).

This study is not without its methodological limitations. First, a subset of participants (N = 13; 19%) did not adhere to pre-test fasting instructions, which was also echoed in failed manipulation checks for hunger. This may have dampened an individual's overall reactivity to food (versus non-food) cues and unintendedly introduced floor effects on craving and salivation. Indeed, if we did not perform exploratory corrections for hunger ratings, we would not have uncovered the further difference in food-specific salivary responses between unisensory VR and multisensory VR exposure. That said, it is worth noting that while hunger ratings were not significantly higher than the neutral (midpoint) value, liking ratings for the food stimulus (i.e., chocolate) were. Collectively, we can therefore assume that individuals perceived food cues to be sufficiently rewarding (Berridge, 2009). Likewise, debriefing checks revealed that 20 (29%) participants correctly guessed the purpose of the research, which could have triggered a tendency for these respondents to report socially desirable craving ratings (Orne, 2017). However, to mitigate this we performed robustness checks (i.e., debriefing and adherence-based exclusions) on our main confirmatory models, and awareness of study aims was in any case less problematic for our physiological (salivation) outcome, whose activity is much less subject to conscious control (Dawes, 1996).

A second methodological consideration is the study population, which consists of young adult students, who generally have stronger digital skills and experience with immersive VR and games, and may be more likely to adopt these types of technologies (İşgin-Atıcı et al., 2020). Although young adults are a relevant target population for VR interventions, the scarcity of studies involving other populations is problematic. The limited research on older adults and non-student populations leaves the effectiveness of immersive VR interventions in these groups uncertain. Specifically, no studies have directly compared responses to virtual food cues in younger and older adults or adolescents; a relevant avenue for future research given that differences in non-VR food cue reactivity have been reported pertaining to age (e.g., adults versus adolescents; van Meer et al., 2025). The latter could become an increasingly feasible research line in light of the growing availability of mobile VR headsets that can be deployed remotely to diverse participant pools (e.g., Sajjadi *et al.*, 2022).

Finally, a major limitation that should be highlighted is that the "real-life condition" in this study was a replicated promotional product set-up in a controlled lab setting. So, although this portion of the experiment was conducted in a physical setting without VR, it was still within the confines of an artificial scenario. This design choice was necessary to prioritize internal validity for this "proof-of-concept" study, which primarily focused on detecting and comparing fundamental differences in FCRs induced specifically by the gradual introduction of multisensory (olfactory) food cues. Besides having a limited generalizability to real-world contexts, another drawback of our lab-based approach concerns potential inaccuracies in estimating the "true" magnitude of effects within and between exposure modes. Specifically, we would expect less pronounced FCRs in the "real-life" condition with exposure to a real-world supermarket, due to the added presence of salient (non-target) products that can compete for one's attentional resources (Gidlöf *et al.*, 2017).

Furthermore, odours naturally diffuse across space from their source (Jacobs, 2012), which would likely lead to the mixing of olfactory input from (non)food stimulus types in an actual supermarket. Consequently, our results may have similarly overestimated true differences in FCRs *between* exposure modes, as a real-world supermarket would also have exhibited stronger (visual and semantic) correspondences with the VR supermarket environment. Indeed, studies employing better matched "real-life" counterparts appear to have reported smaller (yet significant) discrepancies in both explicit (e.g., self-reported product perceptions; Pizzi *et al.*, 2019) and implicit (e.g., eye-tracking; Pfeiffer *et al.*, 2020) outcomes. Therefore, while these preliminary results are encouraging, follow-up studies are required to more robustly benchmark the performance of multisensory VR against real-world scenarios.

A few unresolved questions warrant further investigation. As multisensory VR environments become a frontier topic in the development of next generation immersive technologies (Melo *et al.*, 2020), it would be worthwhile to explore its promises for domains that traditionally proved difficult for virtual experiences, such as (public) health research. For instance, future studies could investigate the utility of such a multisensory VR supermarket for measuring other physiological (e.g., salivary enzyme activity; Morquecho-Campos *et al.*, 2019) and behavioural markers (e.g., food spatial memory and grocery purchases; de Vries *et al.*, 2021) of dietary relevance – especially if such a VR infrastructure can incorporate additional sources of data from emerging components like heart rate monitors and eye-tracking (Halbig & Latoschik, 2021). If the latter were achieved, we could use the multisensory VR set-up to model the impact of potential health interventions, such as simulating how structural (policy) changes to the physical food environment (e.g., nudging) can impact dietary choices (Blom *et al.*, 2021; Larson & Story, 2009), across different socioeconomic groups (Mizdrak *et al.*, 2017). The merits of a multisensory VR set-up for non-food purposes can likewise be assessed, such as for cue exposure addiction therapy and smell training in clinical populations (Hone-Blanchet *et al*., 2014; Hwang *et al*., 2023). In both instances, an exciting possibility for methodological advancement would be to implement a parametric version of odour administration, such that odour intensity is automatically tailored to the distance or movement trajectory of the associated virtual object, thereby mimicking the real-world behaviour of odours (e.g., Yildirim *et al.*, 2025).

In conclusion, this pre-registered lab experiment highlights that an immersive multisensory VR food environment with olfactory cues can credibly model psychological (craving) responses to foods, albeit to a weaker degree than experienced in real-life. The added value of such a technology over unisensory (vision-only) VR infrastructures may lie in enhancing conceptual mediators (i.e., presence and consumption mental imagery) and in approaching physiological (salivary) responses to foods as in real-life. However, important boundary conditions (e.g., hunger state, trait mental imagery) should be taken into account to maximize these benefits.

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Author Contributions

RdV, NvdL, TvL, MV, and SB conceptualized the theoretical framework and study design, as well as acquired funding for the research. RdV and NvdL developed study materials. KV assisted with data collection and data curation, under the supervision of RdV.

MV analysed and visualized the data. All authors interpreted study data, contributed to writing and editing of the manuscript, and approved the final article.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: