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Review

Getting started with virtual reality for sensory and consumer science: Current practices and future perspectives

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ABSTRACT

While virtual reality (VR) has become increasingly popular in food-related research, there has been a lack of clarity, precision, and guidelines regarding what exactly constitutes a virtual reality study, as well as the options available to the researcher for designing and implementing it. This review provides a practical guide for sensory and consumer scientists interested in exploring the emerging opportunities offered by VR. We take a deep dive into the components that make up a VR study, including hardware, software, and response measurement methods, all the while being grounded in immersion and presence theory. We then review how these building blocks are put together to create two major categories of research scenarios: product selection, which can be entirely created in VR, and food evaluation, which involve tasting products in real life. For each category, we review current literature with a focus on experimental design, then highlight future avenues and technical development opportunities within sensory and consumer research. Finally, we evaluate limitations and ethical issues in VR food research, and offer future perspectives which go above and beyond ensuring ecological validity in product testing.

1. Introduction

In the seminal science fiction TV series Star Trek: The Next Generation, crew members on the starship USS Enterprise often enjoyed their time off on the Holodeck, a perfectly simulated version of reality that included food amongst other comforts. Not so far from science fiction, immersive technologies have begun to be incorporated into sensory and consumer studies in recent years, in order to improve their ecological validity ((Dacremont and Sester, 2019; Hehn et al., 2019; Jaeger & Porcherot, 2017). Instead of sitting in a silent white sensory booth, participants can be exposed to a variety of visual and auditory stimuli to help them feel as if they were evaluating the product in a situation in which they are likely to make those decisions. These have included videos presented on computer screens, immersive video walls, head-mounted displays (HMDs), and augmented reality interfaces (Crofton et al., 2019).

While the use of immersive technologies is becoming ever more popular (Flavián et al., 2019), it can also seem intimidating for the sensory and consumer scientist. Faced with this profusion of novel technologies, how can researchers and practitioners get started? To make matters more challenging, virtual reality (VR) is a term that is commonly used to include a variety of scenarios ranging from videos presented on computer screens to immersive rooms. As an example, out of the seven articles included in the recent special issue on “Virtual reality and food: Application in sensory and consumer science” in Food Research International, four articles induced VR via HMDs, two involved immersive rooms, and one addressed electric taste augmentation with no VR elements. In this article, we aim to address this issue by presenting a first point of contact for any sensory and consumer scientist interested in VR and how it can be used in research in said fields.

To make sense of the variety of immersive technologies available today, we present the model of reality-virtuality continuum (Milgram et al., 1995), which offers a framework for classifying the wide range of immersive technologies available to the researcher today (Fig. 1).

To understand the continuum, let us consider an example in sensory and consumer science. Going from left to right, a real environment could be consumer testing of a beer in a pub or in the lab, without the aid of any digital technology. In an augmented reality scenario, digital information is overlaid on top of physical reality, which can be either viewed via a screen (e.g., via a smartphone screen like in *Pokémon Go*) or special

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glasses (e.g., Microsoft HoloLens). In our example, consumer testing in a pub can be augmented with information overlaid on top of the beer, telling the consumer about how the beer was produced or showing nutritional information (see Javornik, 2016, for a review on augmented reality). In augmented virtuality, one is immersed in a virtual/digital environment, but can still interact with elements in the real world, which are augmented in the virtual environment. In our example, an augmented virtuality setup could be if a consumer is wearing a HMD showing a virtual pub, while they drink a beer in real life. Augmented virtuality could also involve sitting in an immersive room with video walls showing scenes from a pub, while consumers evaluate a real glass of beer. Finally, and most relevant to the present research, a fully virtual environment is completely separate from physical reality; this might be a food choice study where the consumer is ordering a beer in a virtual pub with a virtual bartender. It could also be a consumer evaluating their expectations of a virtual beer in a virtual pub, without any actual tasting. More often than not, when it comes to VR, sensory and consumer research have relied on the full virtual environment, where what is experienced exists only in the virtual world (Table 2). That said, there has been increasing development in the augmented virtuality spaces, where participants actually consume products while visually immersed in the virtual world (Table 3).

1.1. Scope and method

The current review provides an overview of literature related to VR studies in the domain of sensory and consumer science, with an eye towards how different technologies have been used in combination to create different levels of testing scenarios. After a review of the theoretical foundations of VR experiences (Section 1.2), we take a deep dive into the components that comprise a typical study, including hardware, software, and measurement methodologies (Section 2). Next, we describe scenarios for both product choice and food evaluation research, with overviews of current setups and directions for future development (Section 3). Finally, we evaluate limitations and ethical issues in VR research and offer future perspectives to expand the use of VR beyond contextual food testing (Section 4). It is worth noting at the outset that this review does not discuss the generalisability of VR findings, since it is generally accepted that consumer behaviour in VR is comparable to that observed in the real world (see Hartmann & Siegrist, 2019, for a review).

To get an overview of the state-of-the-art design of VR studies in sensory and consumer science, we conducted a literature search in January 2021 on the Web of Science and Scopus databases, as well as IEEE (Institute of Electrical and Electronics Engineers) and ACM (Association for Computing Machinery) libraries. We included full-length articles, conference proceedings, and conference abstracts. We focused the search on studies in the areas of consumer and sensory science involving selection or consumption of foodstuffs, and where participants were from a healthy (non-clinical) population. Furthermore, we were only interested in studies which implemented VR via commercially available HMDs, therefore excluding those studies which used computer- or room-based VR methodologies or augmented reality. Moreover, we limited the search to studies published from 2015 onwards up to those available online as of January 31st, 2021. The search was based on combinations of the keyword "virtual reality" AND the keywords "Head-mounted display", "food", "eat*", "drink*". The search led to a total of 41 studies, 21 of which involved food selection (Table 2) and 20 involved actual food consumption (Table 3).

Table 1
Potential hardware and software options for setting up specific research scenarios.

Research Scenario	Example	Hardware	Software	Experiment stimuli
See context, then make product selection	See virtual pub, then remove headset before selecting a beer in real life	Smartphone Self-standing Tethered	No programming required if responses collected verbally	Virtual environment + virtual product model
Select and interact with product in context	Select and interact with virtual beer in virtual pub	Self-standing Tethered	Programming required	Virtual environment + product
See context, then evaluate product in real life	See virtual pub, then remove headset before taste beer	Smartphone Self-standing Tethered	No programming required	Virtual environment
Taste and evaluate product in context	See virtual beer while tasting beer, but do not see beer	Smartphone Self-standing Tethered	No programming required if responses collected verbally	Virtual environment + real food sample
Taste and evaluate product in context	See virtual pub while tasting beer, also see virtual beer	Tethered	Programming required	Virtual environment + virtual food model + real food sample

1.2. Theoretical underpinning: Factors governing degree of immersion and presence in VR

Before moving onto the various technologies underpinning VR experiences, it is important to consider the cognitive mechanisms making such experiences feel real/believable to a given participant. After all, we are fully aware that what we see (and sometimes hear, smell, or touch, see Section 2.1.3) is coming from the headset itself, so how can we have a sense of being somewhere else even when we know we are not there

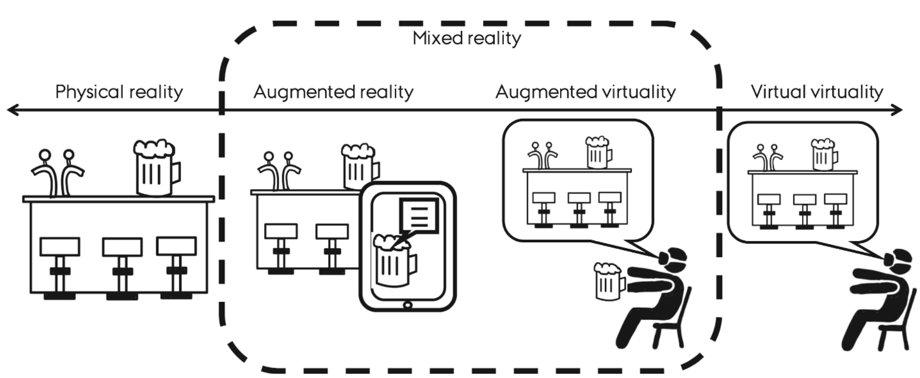

Fig. 1. The reality-virtuality continuum (adapted from Milgram et al., 1995).

Table 2
Literature review of published studies of VR studies involving food choice.

Study	Studied response	Studied factor	Product	VR context	Headset	Tethered	Position tracking	Software platform	VR stimuli designer	Additional sensors
Gouton et al. (2021)	Visual description	Virtual vs. real cookies	Cookies	Replica of booth in VR	HTC Vive	Yes	Yes	Unity	Authors	Vive controller to manipulate models
Huang et al. (2021)	Visual search response time and accuracy	Colour-flavour (in) congruency	Crisps (packaging)	Store shelf	NVIS nVisor SX60	Yes	Yes	Vizard	Authors	Logitech F710 gamepad
Xu et al. (2021)	Food-related information seeking behaviour	Virtual environment vs. real life	Cereal	Replica of real tables	HTC Vive Pro	Yes	Yes	Unity, Recap Photo	Authors	
Cheah et al. (2020)	Food choice	Virtual environment vs. real world	Various	Buffet	HTC Vive Pro	Yes	Yes	Unreal Engine	Authors	
Fang et al. (2020)	Food choice (hypothetical bias)	Virtual environment	Yogurt	Supermarket	Oculus Rift	Yes	Yes	Unity	Authors	Xbox controller
Goedegebure et al. (2020)	Food choice	Healthier vs. regular products	Various	Supermarket	Smartphone-powered	No	No	VR Deck	Authors	
Isgin-Atici et al. (2020)	Usability of virtual environments	Virtual environment	Various	Cafeteria	HTC Vive	Yes	Yes	N/A	Authors	
Lombart et al. (2020)	Product perception	Environment (immersiveness): 360° video vs. 3D model vs. real world booth	Fruits and vegetables	Supermarket	Oculus Rift DK2	Yes	Yes	N/A	Authors	Xbox controller
Persky and Dolwick (2020)	Food choice	Background odour	Various	Buffet	HTC Vive	Yes	Yes	WorldViz	Authors	
Verhulst et al. (2020)	Smell awareness	Food odour visualizations and real odour	Cake and pizza	Tables	HTC Vive Pro	Yes	Yes	Unity	Authors	BITalino Respiration Belt
Allman-Farinelli et al. (2019)	Virtual food choice	Sense of presence	Various (food court shops)	Food court	HTC Vive	Yes	Yes	Unity	Authors	
Lombart et al. (2019)	Product perception and purchase behaviour	Food appearance (shape normality)	Fruits and vegetables	Supermarket	Oculus Rift DK2	Yes	Yes	N/A	Authors	Xbox controller
Sinesio, et al. (2019)	Liking, intention to retaste	Environment (immersiveness): 360° video vs. 3D model vs. real world booth	Beer	Pub	Trust Urban VR (360° video), Oculus Rift (3D Model)	Both	No	N/A	Authors	Intel Real Sense SR300, joystick
Andersen et al. (2019)	Drink desire, product choice after exposure	Virtual environment vs. photo-enhanced imaginative condition	Coffee, tea, juice, soda, beer	Beach	Samsung Gear VR	No	No	N/A	Authors	Sennheiser HD 428
Celikcan et al. (2018)	Food portion size perception	Virtual environment	Various	Cafeteria	HTC Vive	Yes	Yes	Unity	Authors	
Ouellet et al. (2018)	Memory	Feasibility and ecological validity	Various	Small shop	nVisor ST50	Yes	Yes	N/A	Authors in collaboration with Cliniques et Développement In Virtuo	WorldViz PPT-X motion tracker
Persky et al. (2018).	Food choice	Virtual vs. real buffet in physical reality	Various (and pasta)	Buffet	NVIS nVisor SX60	Yes	Yes	N/A	Authors	WorldViz Precision Point Tracker
Schnack et al. (2019)	Telepresence, usability of virtual environment	Telepresence and usability of virtual environment vs. desktop computer setup	Various	Supermarket	HTC Vive	Yes	Yes	N/A	Authors	
Siegrist et al. (2019)	Food choice, information-seeking behaviour	Virtual environment vs. real world	Cereals	Shelves	Oculus Rift DK2	Yes	Yes	Unity, 3ds Max	Authors	iViewXTM, HED4 eyetracker
Ung et al. (2018)	Food choice	Virtual vs. real world mockup buffet	Chicken breast strips,	Replica of mockup buffet	Oculus Rift	Yes	Yes	Unity	Authors	Custom hand

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Table 2 (*continued*)

Study	Studied response	Studied factor	Product	VR context	Headset	Tethered	Position tracking	Software platform	VR stimuli designer	Additional sensors
			pasta, carrot sticks							tracking system
Higuera-Trujillo et al. (2017)	Psychological and physiological responses	Photograph vs. 360° panorama vs. computer generated virtual product shelves	Beer	Shelves	Samsung Gear VR	No	No	Unity, SketchUp	Authors	

physically? The concepts of immersion and presence have been used to approach this phenomenon.

One recent definition of immersion claims that “immersion is a phenomenon experienced by an individual when they are in a state of deep mental involvement in which their cognitive processes (with or without sensory stimulation) cause a shift in their attentional state such that one may experience disassociation from the awareness of the physical world.” (Agrawal et al., 2020, pp. 407). In other words, VR delivers an immersive experience when the individual is completely surrounded by sensory stimuli coming from the virtual world and when they are psychologically engaged in the narratives happening in this world. Using an example from consumer science, an immersive virtual supermarket scenario happens when the participant can see (and hear) a supermarket, and when they believe that they are really engaging in a shopping task. Following theories of situated action (Barsalou, 2008), it is when both criteria are met, that VR is the most effective in the study of how people think and behave in different contexts.

This division between what is available for the participant to experience, and how the participant makes sense of their experience, lies at the heart of immersive VR research. According to classic VR literature, *immersion* refers to an objective description of the technology, whereas the psychological sense of being in the virtual environment is defined by *presence* (Slater & Wilbur, 1997; Schuemie et al., 2001). By this standard, an *immersive* system should ideally deliver inclusive, extensive, surrounding, and vivid imagery with real-time matching between one's bodily action (proprioceptive feedback) and the information generated on the VR display. The more immersive the system, the greater sense of presence is likely to be experienced by the participant, and the more likely they are to behave in a similar way in the virtual environment as in a corresponding physical environment.

Given that the participants' sense of presence underlies the success of research involving VR, there are several factors to consider in the overall design of virtual scenarios, which determine the extent to which participants feel engaged with the virtual world.

First, immersion can be measured by the extent to which physical reality is shut out (inclusive), how much the technology offers a panoramic audiovisual experience similar to that experienced by the human eye/ear (surrounding), the spectrum of sensory modalities presented (extensive), the fidelity of the sensory representation (vivid), how well one's actions can trigger corresponding changes in the VR display (matching), and the extent to which the virtual system contains its own story-line (plot) (Slater & Wilbur, 1997). By limiting the scope of this review to HMDs, we can ensure some degree of inclusivity compared to video walls and immersive rooms, which are alternative VR systems (although one can imagine that heavier headsets and tethered headsets would be harder for the participant to ignore). Surrounding is another feature of HMDs that is limited by the speed of processing and rendering capabilities. In terms of extensiveness, while humans sense the world with all the senses, VR technology has traditionally focused on vision. While all modern HMDs offer sound playback, with advanced HMDs supporting spatialised sound, only very few studies in consumer research have even used sound as part of the virtual environment, not to mention smell and touch (see Section 2.1.3). That said, the one area where consumer research has excelled in comparison to classic VR research is in the realm of mixed-reality food evaluation scenarios (see Section 3.2), where not only the taste, but also the smell and haptic feedback of food from the real world is sometimes represented in VR as well.

In terms of vividness, it is unclear to what extent true photo-realism, or proximity to the real world, is required in order to induce a sense of presence (Van Kerrebroeck et al., 2017). While video game research literature would suggest that people seem to get used to low-resolution environments (Kozlov & Johansen, 2010), since the brain automatically fills in missing details (Slater & Sanchez-Vives, 2016), consumer research has thus far tried to remain true to the real world. And while photo-realism is aimed for, it is not always achieved, especially when it comes to modelling food products in VR (see Section 2.2). While all HMDs automatically support *matching* between head movement and updated visual stimuli (3 degrees of rotational freedom), not all HMDs support translational movement for a full 6 degrees of freedom (3 rotational plus three translational), and additional sensors are required to support haptic feedback (see Section 2.1.1). Finally, compared to other areas of VR research such as gaming or therapy, consumer studies tend to have simplistic plots where the consumer is engaged in either a shopping or food evaluation task.

In terms of enhancing the psychological feeling of presence, it is important that the participant feels natural, to some extent, while interacting in the virtual world. This means that they can either navigate the virtual world according to the same rules as the physical world, or that they feel comfortable interacting with the virtual world according to its own set of rules. This has led some researchers to suggest that participants should always have a practice session to become familiar with the virtual environment before data collection is started (Hartmann & Siegrist, 2019). Otherwise, participants might be too distracted in learning how to navigate the space (or even get accustomed to the headset) to be fully attentive/immersed in the experimental task at hand. Obviously, this depends on the complexity of the experimental task.

In many of the consumer research studies surveyed, participants only looked at the virtual context, and their interaction with the environment was limited to moving their gaze (e.g., Barbosa Escobar, Petit, & Velasco, 2021; Kong et al., 2020). This interaction model is easy for the participants to get used to, but the lack of interaction with the environment also limits the depth of immersion. On the other hand, studies in which the participant can actually interact with objects in the virtual world should theoretically lead to a greater sense of immersion (Slater, 2009), with the caveat that the participant gets to learn to familiarise themselves with mechanisms of interaction. As will be addressed later, any experimental setup that utilises natural interaction, such as hand tracking, will be easier for the participant compared to, say, game controllers, especially when the participant is not used to them.

Having addressed both objective immersion and subjective presence, it is worth noting that mixed reality scenarios in which food evaluation occurs is a very special instance of augmented virtuality (Fig. 1). The combination of visual and (potentially) auditory information coming digitally, together with smell, taste, and tactile properties of the food, should heighten the sense of presence in the VR environment, since the act of eating unifies both virtual and physical sensory cues via oral

Table 3
Literature review of published VR studies involving food evaluation.

Study	Studied response	Studied factor	Product	User interaction with product	Response registration	Headset	Tethered	Position Tracking	Software platform	VR stimuli designer	Additional sensors
Barbosa Escobar et al. (2021)	Taste, premiumness	Coffee farm vs. city vs. white room	Coffee	None	HMD removed during evaluation	Oculus Go	No	Yes	YouTube	YouTube	
Oliver and Hollis (2021)	Food intake, eating parameters, sensory evaluation, biometrics	Restaurant vs. empty room	Pizza rolls	See + touch	HMD removed during evaluation	HTC Vive	Yes	Yes	Unity	Authors	Vive tracker to locate furniture and objects, LeapMotion to track hand motion, empatica E4 wristband (GSR, HR), Biopac mp36r (EMG)
Wen and Leung (2021)	Product sensory perception and purchase behaviour	VR video vs. traditional video of winery tour	Wine	None	Wine tasted after watching video	Oculus Go	No	No	YouTube	YouTube video recorded by wine producer	
Ammann, Stucki, et al. (2020)	Accept/reject chocolate consumption, chocolate liking/ disgust	Chocolate source (come from table or dog)	Chocolate drop	See + touch	Verbal, recorded by experimenter	HTC Vive	Yes	Yes	Unity	Authors	L Motion for hand tracking
Ammann, Stucki, et al. (2020)	Flavour identification	Product colour	Juice and cake slices	See + touch	Verbal, recorded by experimenter	HTC Vive	Yes	Yes	Unity	Authors	Leap Motion for hand tracking
Chen et al. (2020)	Taste and liking	Sweet vs. bitter vs. neutral VR environment	Grenadine beverage	None	HMD removed during evaluation	Galaxy S7 + Samsung Gear headset	No	Yes	Unity	Authors	EEG (ABM B-Alert X10)
Huang et al. (2019)	Colour selection	Tea type	Tea (red vs. green)	None	Use wireless mouse to adjust colour (RGB, hue, saturation, brightness)	NVIS nVisor SX60 HMD	Yes	Yes	Vizard	Authors	Wireless mouse
Kong et al. (2020)	Taste and liking	Sensory booth vs. VR (sightseeing tour, live concert)	Chocolate (milk, white, dark)	None	HMD removed during evaluation	Oculus Go All-in-One	No	Yes	Veer VR	Veer VR	
Nivedhan et al. (2020)	Taste and liking	VR environment colour + sound	Coldbrew coffee	See + touch	Verbal, recorded by experimenter	HTC Vive Pro Eye	Yes	Yes	Unity	Authors	Vive tracker on cup
Torrico et al. (2020)	Taste and liking	Environment (sensory booth + bright/dim restaurant/VR restaurant)	Wine	None	HMD removed during evaluation	Oculus Go	No	No	Youtube	Youtube	
Torrico et al. (2020)	Taste and liking	Sensory booth vs. VR (pos, neg)	Chocolate (full sugar, no sugar)	None	HMD removed during evaluation	Dell visor mixed reality headset	Yes	No	Gala360	Gala360 app	
van der Waal et al. (2020)	Salivation	VR vs. real life, food vs. nonfood stimuli	Chocolate	See	N/A	HTC Vive	Yes	Yes	Unity3D	VR Owl company	
Wang et al. (2020)	Taste and liking	Product colour	Coldbrew coffee	See + touch	Verbal, recorded by experimenter	HTC Vive Pro	Yes	Yes	Unity	Authors	Vive tracker on cup
Worch et al. (2020)	Emotion profile of products	360° video vs. 3D model vs. sensory booth	Beer	None	Joystick to answer questionnaires in VR environment	Trust Urban VR (360° video),	Yes (Oculus Rift)	Yes (Oculus Rift)		Authors	Intel Real Sense SR300 camera to track hands and body in foreground

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Table 3 (*continued*)

Study	Studied response	Studied factor	Product	User interaction with product	Response registration	Headset	Tethered	Position Tracking	Software platform	VR stimuli designer	Additional sensors
Huang et al. (2019)	Taste and liking	Product colour	Tea (chinese red or green)	See	Gamepad to answer questions in VR environment	Oculus Rift (3D Model) NVIS nVisor SX60	Yes	Yes	Vizard 4.0	Authors	Logitech F710 wireless gamepad to respond to questions
Picket and Dando (2019)	Taste and liking	Bar vs. winery	Beer and sparkling wine	None	Participants moved cursor in VR by turning their heads, then pressed a button on the controller to take a screenshot	Samsung Gear	No	No	Samsung Galaxy S6	Authors	
Korsgaard et al. (2019)	Food intake	Real vs. VR environment	Mini muffins, coconut macaroons, frangipane cake, apple slices, boxed juice	See + touch	N/A	Oculus Rift CV1	Yes	Yes	Unity	Authors	Intel RealSense SR300 depth sensor, Nvidia Shadowplay
Harley et al. (2018)	Part of workshop	Mixed reality environments (beach, forest		See + touch	N/A	Oculus DK2 (beach), Gear VR (forest)	No	No	Unity 3D	Authors	
Stelick et al. (2018)	Taste and liking	Sensory booth vs. park bench vs. cow barn	Blue cheese	None	Presented in VR, panellists pressed key on Bluetooth keyboard which was connected to smartphone	Samsung Gear VR	No	No	Samsung Gear 360 Action Director and Adobe Premiere Pro	Authors	
Li and Bailenson (2017)	Subsequent food intake	Empty room vs. restaurant	Donut	See + touch	N/A	HTC Vive	Yes	Yes	Vizard 5	Authors	Vive controller strapped to participant's hand for handtracking

referral (Spence, 2016). The few studies which have researched the impact of altering visual food appearance on taste/flavour evaluation have shown that multisensory integration is in fact possible across the reality-virtuality continuum (Ammann, Stucki & Siegrist, 2020; Wang, Meyer, Waters, & Zendle, 2020).

2. Putting a VR study together - component overview (2020)

Which factors do researchers need to consider before they design a VR study? In the sections below, we offer an overview of current equipment options for hardware and software, as well as considerations for how participant responses can be collected. Fig. 2 illustrates how these factors come together in an actual food evaluation scenario.

2.1. Hardware

2.1.1. Head mounted displays

VR technology has experienced rapid technological advancements in the last few years, especially after 2012, when more corporate resources became allocated to the development of VR (Berkman, 2018; Bown et al., 2017). The release of different tiers of consumer and professional grade commercially available stereoscopic head mounted displays in the last five years has facilitated the use of VR technology in sensory and consumer science. To date, more than 40 studies have used commercially available HMDs in these academic fields (see Tables 1 and 2).

A general taxonomy of VR HMDs is useful to understand the capabilities and potential uses of the different headsets in research. HMDs can be broadly classified into tethered, standalone, and mobile-powered devices (Angelov et al., 2020). Tethered devices are those that need to be connected to external computing hardware, whereas standalone devices are those that have integrated computing power. Mobile-powered devices are headsets that allow the participant to view content from smartphones in VR.

2.1.1.1. Quality and performance. Tethered devices provide the highest quality and richest experiences given that their computing capabilities depend on the computer they are connected to (Crofton et al., 2019). Tethered devices are generally programmatic and allow for the development of complex content. Additionally, they can be connected to a myriad of external sensors (Anthes et al., 2016). The quality and capabilities of standalone headsets are lower than tethered ones, but they vary widely across devices. Nevertheless, in the last couple of years, the performance and quality of standalone devices has increased significantly (Crofton et al., 2019). However, the ability to develop content for standalone devices is limited, thus studies using standalone devices generally depend on prebuilt content. Mobile-powered headsets generally consist of plastic or cardboard contraptions with lenses that allow the visualization of VR content from smartphones, and they provide the lowest quality.

2.1.1.2. Costs and mobility. Naturally, the use of tethered devices requires a higher investment than standalone ones, since the headsets have higher prices, and the technical requirements of the computers needed are highly demanding. Tethered headsets also have limited mobility, as they need to be connected to a computer (generally a high-end desktop), and they may require base stations to track user movements. Hence, their use tends to be limited to laboratories (de Regt et al., 2020). On the other hand, standalone devices are virtually out-of-the-box solutions that provide good mobility and ease of use. Therefore, they can be used outside the laboratory, which allows researchers to use them in more naturalistic settings, such as companies, stores, and events. However, the battery capacity of stand-alone headsets poses some limitations (Angelov et al., 2020). On the lowest side of the spectrum, smartphone-powered devices have the lowest investment requirements, and highest portability. However, the high mobility comes at the expense of content's quality, variety, and complexity.

2.1.1.3. HMDs in the literature. The academic literature in sensory and consumer science experienced a sharp increase in the number of published articles involving VR HMDs in 2018, after only a few studies published in 2017 (see Tables 2 and 3). This increase is likely due to the release of the HTC Vive and Oculus Rift headsets, both in 2016, which represented an effective and relatively easy way to use VR in research. A few studies using smartphone-powered headsets (i.e., Samsung Gear VR) were also published in 2018. In 2020, the number of studies using VR stereoscopic HMDs rose significantly. The most prominent headsets in the literature in the 2015–2020 period were the tethered headsets HTC Vive ($n = 15$) and Oculus Rift ($n = 10$). The NVIS nVisor SX60 was also used in a few studies ($n = 4$), and the Dell Visor ($n = 1$) was used earlier in the period. As for standalone devices, the Oculus Go—released in 2018—was the only headset used ($n = 4$). Smartphone-powered headsets were also used in various studies, Samsung Gear VR ($n = 6$) being the most common headset.

2.1.1.4. Quality of the virtual experience. Given the rapid advances in VR technology, hardware can quickly become outdated. It is, therefore, more useful to examine key factors that determine the quality of virtual experiences and apply it to the current and future hardware. Some of the

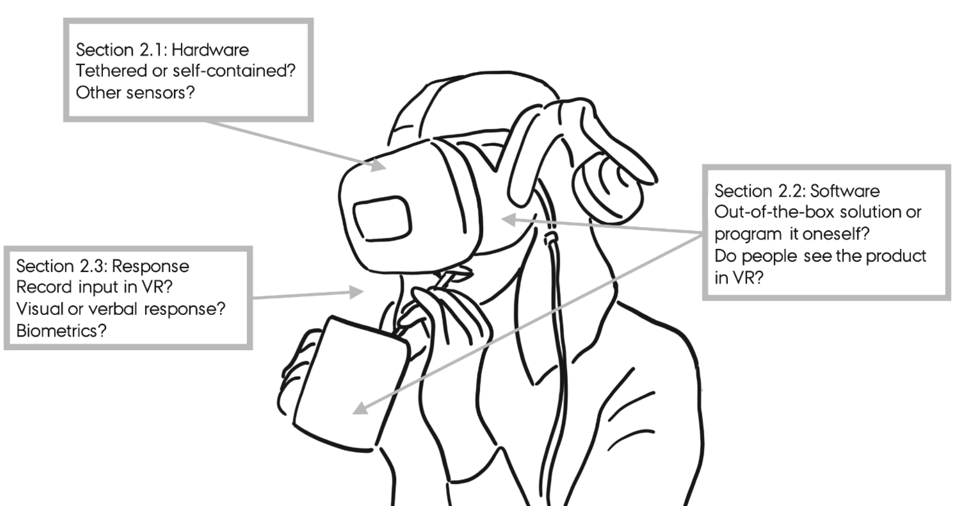

Fig. 2. Factors to consider when designing a VR study.

key concepts previous literature has posed as critical in driving the quality of virtual experiences relate to the concepts of presence and immersion (Section 1.2).

One of the most important concepts that determines the quality of virtual experiences is the sense of presence (Sanchez-Vives & Slater, 2005; Steuer, 1992), which relates to the sense of being in the virtual environment rather than the actual physical location. Another important characteristic of virtual experiences is that they trigger realistic responses to situations in the virtual environment, which in addition to the sense of presence is mainly affected by transference—behavioural similarity between real and virtual world (Alcañiz et al., 2019). Naturally, the high-end HMDs will generate a higher sense of immersion, given their higher image and audio quality, wider visual field, and lower latency. Furthermore, headsets with more degrees of freedom and that allow interactions with the virtual world will trigger higher levels of transference since actions in the real world will have a better correspondence to those in the virtual world. Finally, the quality of the virtual experience is also linked with the phenomenon of motion, or cyber sickness (Chang et al., 2020), for instance, when the HMD cannot produce a high-quality image, or when the computing power available cannot meet the demands of a high-end HMD.

2.1.2. Motion tracking

A critical differentiating factor of VR HMDs is their tracking system, given its large effect on the quality of the experience. VR HMDs can be further classified, based on their tracking systems, into orientational and positional (Angelov et al., 2020). Devices in the former category can only determine the orientation of the headset and controllers (if any) in the 3D environment. Devices with positional tracking can additionally determine the position of the user in space (6D). Headsets with positional tracking systems can establish the user's position either with base stations (or markers) placed in the physical space, or they can use cameras in the headset. Positional tracking HMDs, therefore, can provide more immersive experiences.

From the most prominent HMDs used in the literature so far, the HTC Vive Pro uses a marker-based tracking system that uses two external laser emitters ("Lighthouses") that send light sweeps to the headset. The headset tracks and measures the light pulses timing to estimate its horizontal and vertical positioning (Niehorster et al., 2017). On the other hand, the Oculus Rift S (2019) uses five cameras embedded in the headset, together with an AI algorithm to determine the user's position.

In addition to tracking the movement of the users' head and body, some VR devices use additional sensors to track hand motions and gestures, as well as the movement of external objects. The most common type of hand tracking devices in the literature to date are the integrated handheld controllers. For instance, the HTC Vive handheld controllers, which are used in several studies (e.g., Celikcan et al., 2018; Cheah et al., 2020; Gouton, Dacremont, Trystram, & Blumenthal, 2021; Isgin-Atici et al., 2020; Li & Bailenson, 2017; Schnack, Wright, & Holdershaw, 2019; Xu et al., 2021), allow users to grasp and manipulate objects in the virtual environment. For instance, in Gouton et al. (2021), participants used the HTC Vive controllers to interact with virtual cookies inside a virtual sensory booth environment. Additionally, the HTC Vive provides an external tracking device ("HTC Vive tracker") that can be attached to objects to track their global position and orientation (see Ammann, Hartmann, Peterhans, Ropelato, & Siegrist, 2020; Nivedhan et al., 2020; Oliver & Hollis, 2021; Wang et al., 2020). This device creates the possibility to map and manipulate real objects in VR, thereby creating mixed virtuality scenarios (Fig. 1). For example, Wang et al. (2020) and Nivedhan et al. (2020) attached the Vive tracker to a real cup, which was mapped into the virtual environment. This way, participants' actions in the real world had an effect in the virtual environment. Other studies have used third-party optical tracking devices like Leap Motion (Ammann, Hartmann, et al., 2020; Ammann, Stucki, et al., 2020; Oliver & Hollis, 2021; Tuanquin, 2017) and the Intel RealSense SR300 camera (Korsgaard et al. 2019; Sinesio et al., 2019; Worch et al., 2020). Less immersive options have also been used. Some studies have used gamepads and controllers from gaming platforms, such as Xbox controllers (Lombart et al., 2019, 2020; Verhulst et al., 2017) or the Logitech F710 wireless gamepad (Huang, Huang, & Wan, 2019, 2021).

An important aspect to consider is the extent of motion tracking that is necessary, but also ideal, in food-related scenarios. Tracking hand and finger motions can add a high degree of immersiveness and agency to virtual experiences, such as those involving product evaluations, and even more so to those dealing with packaging and label information. Regarding the need for 6D positional tracking, the design of most studies do not involve people moving. While the ability to walk in room-scale VR environments has been shown to increase immersion (Shewaga et al., 2020), it is imperative to evaluate how much it would add to the sense of presence, immersion, and realism of shopping or eating experiences. In addition, poor implementation of motion tracking systems can be detrimental for the VR experience. For instance, high levels of latency between users' actions—including head and hand movements—in the real world and their response in the virtual environment can hinder the sense of presence and agency, and they can negatively impact comfort (Pritchard et al., 2016; Sanchez-Vives & Slater, 2005).

2.1.3. Other senses

Sound is a relatively simple element to work with, in terms of parametric manipulations and equipment, and almost all VR HMDs have immersive audio capabilities, either as embedded or external headphones. Nevertheless, only a few food-related studies have incorporated sound, be it environmental or product-related. Moreover, the use of fully spatial audio is even scarcer despite the suitability and usability of this type of audio in VR, as well as the availability of commercial recording devices for spatial audio. This could reflect the need to validate VR as a tool for research before moving on to more complex scenarios. Hence, there are plenty of untapped opportunities for research in this space, considering the importance of sound in the consumer shopping or eating experience (Spence et al., 2019). That said, it is important to consider the trade-off between added value and technical requirements of including immersive auditory stimuli in VR. As Jiang et al. (2018) found, more sound sources are necessary to create realistic soundscapes in VR, which demands more rendering power.

Smell can increase the sense of presence in virtual experiences (Munyan et al., 2016), and it is a critical sense when it comes to food. Additionally, smell brings opportunities for the development of experiences based on chemical, emotional, spatial, and temporal features, such as enhancing story narratives and directing users' attention in VR (Maggioni et al., 2020). That said, smell is complex and hard to control given its molecular nature and the impossibility to create primary odours (Kerruish, 2019), which are some of the main reasons why it remains understudied, especially in VR. Only a limited number of studies we surveyed incorporated smells, and all of them have used custom-made solutions, which are rarely digitized. For example, Verhulst et al. (2020) used real food to induce smell sensations of virtual foods, and Harley et al. (2018) used various real objects to recreate odours of different environments. Moreover, Li and Bailenson (2017) attached a cotton swab, soaked in scented aromatic oil, to the VR headset to simulate the aroma of a donut. Persky and Dolwick (2020) used nebulizing scent diffusers with french fries scented oil to recreate the smell of a buffet. Nevertheless, a myriad of commercially available solutions with different capabilities and price levels for implementing odours in VR have become available in the last five years (see Flavián et al., 2021 for a review on smell in VR), including FeelReal (2015), Noslus Rift (2016), Vaqso (2017), OWidgets (Maggioni et al., 2019), Olorama (2020), Aroma Shooter (2020), Ohroma (forthcoming).

The sense of touch can also increase the immersiveness and interactivity of virtual experiences. However, the studies so far have not fully capitalized on this sense, and almost all of them have only used simple controllers native to the VR headsets or external console-like ones to move in the virtual environments or manipulate objects. Nevertheless, multiple commercially available haptic devices have been developed in recent years. For instance, haptic gloves from companies such as haptx, VRgluv, SenseGlove, and Manus are now available. These gloves have various capabilities including hand and finger tracking, haptic feedback, and force feedback, among others. For example, the Manus Prime II Haptic (2020) allows users to manipulate objects, interact with the environment, and feel textures. Another type of commercially available haptic device, based on ultrasound, has been developed by Ultaleap. For example, the Ultraleap STRATOS Inspire is a programmable haptic module that uses focused ultrasound to reproduce haptic sensations with which users can interact.

2.2. Software

There are two major approaches when it comes to the choice of software for designing VR studies; researchers have used either an out-of-the-box solution (e.g., 360° videos), or a custom VR environment that was built by themselves or outsourced to a third-party company. Multiple companies offer VR study design/setup services for researchers (e.g., van der Waal et al., 2020) but a review of these is out of scope for this paper.

2.2.1. Low user-interactivity solutions

For researchers designing a study themselves, the easiest option is to record or find an existing 360° video. Existing platforms hosting 360° videos include Youtube (Barbosa Escobar et al., 2021; Torrico et al., 2020), Veer VR (Kong et al., 2020), Trust Urban VR (Worch et al 2020), and Gala360 (Torrico et al., 2020). Besides looking for pre-existing 360° videos, the rising popularity and affordability of 360° cameras makes it easier than ever for researchers to produce their own 360° videos (e.g. Picket and Dando, 2019; Wen and Leung, 2021). Scanning software such as Recap Photo or Apple's Lidar technology can also be used to scan a physical environment (Xu et al., 2021) to produce a similar 3D model. However, while easy to implement, a 360° video does not offer the possibility of user interactivity with the environment.

2.2.2. High user-interactivity solutions

In order to have more control over the VR environment and to enable interactivity, researchers need to design the environment themselves. In terms of designing and programming the environments, the majority of studies we surveyed ($n = 19$) used Unity. Unity is a real-time development platform that was originally designed as a video game engine, but has since been adopted in a wide range of industries including film, architecture, and construction (https://unity.com/). Unity is the most common platform for designing VR experiences (Marvin, 2018) and is compatible with all commercially available HMDs, and it can also be integrated with other sensors. However, in exchange for a great degree of flexibility, it also requires some knowledge of game programming, which may be intimidating for those with no prior 3D modelling or game development experience.

For those researchers who are a bit more comfortable with coding, Vizard (WorldViz, Inc.) is a VR engine and software development platform that allows researchers to build experiments via Python scripts. Vizard supports connectivity with headsets, trackers, and sensors while also making it easy to script user interactions and data collection (WorldViz 2020). In our literature search, several studies used Vizard, especially when questionnaires were presented in the virtual environment (Huang et al., 2019; Huang, Zhao, & Wan, 2021; Li & Bailenson, 2017; Persky & Dolwick, 2020).

2.2.3. 3D models

An additional challenge in making a custom VR study is to find/produce appropriate models, food and otherwise, with which to populate the virtual environment. Custom models can be produced using 3D modelling software such as Rhino (Huang et al., 2019), 3ds max (Siegrist et al., 2019), or Sketchup (Higuera-Trujillo et al., 2017), but also involves additional know-how. Fortunately, it is becoming increasingly easier to find high quality 3D models in online databases/stores such as SketchFab. Of special interest to sensory and consumer science research is 3D models of food products with a high degree of realism. Research so far has relied on relatively low-resolution simulations of foodstuffs, such as chocolate pieces (Ammann, Hartmann, et al., 2020; Torrico et al., 2020; van der Waal et al., 2020), beverages served in mugs or narrow glasses (Ammann, Hartmann, et al., 2020; Wang et al., 2020), fruits and vegetables (Lombart et al., 2019, 2020), and buffet with geometric chicken strips, carrot sticks, and pasta (Ung et al., 2018). Fig. 3 shows a collection of virtual food products used in previous research.

2.3. Response measurement

The easiest way to measure responses is to ask participants to take off the VR headset and make their evaluations in physical reality. This has the benefit of ease of study implementation, since only the context needs to be presented without any additional user interaction. It is also suitable for studies where there is a complex evaluation process (e.g., Chen et al., 2020; Lombart et al., 2020). However, it takes participants out of the virtual experience.

Another alternative is to have the experimenter verbally ask participants questions while the participants are in the virtual experience. The experimenter then records the responses of the participants, such as flavour identification (Ammann, Hartmann, et al., 2020), or taste intensity (Wang et al., 2020). This has the benefit of minimising programming while keeping participants immersed in the scenario. Going one step further, Morotti, Donatiello, and Marfia (2020) used a smart speaker avatar powered by Alexa voice service to engage with the consumer in a virtual shopping scenario. Smart speakers present a natural integration in VR studies to capture natural evaluation of products especially when it comes to food, since consumers are more used to describing their eating experience in words rather than via scales.

There are different ways to present questionnaires in the VR environment itself. Questionnaires can pop up in the environment, and participants can either use a hand-held VR controller (e.g., Worch et al., 2020), a mouse (e.g., Huang et al., 2019), or their head movement/gaze (e.g., Picket & Dando, 2019) to choose the correct answer. Programming questionnaires in the VR environment obviously raises the technical difficulty of the task, which is perhaps why some researchers choose to present questions verbally, or do the assessment outside of the virtual environment.

Besides explicit questions, it is also possible to combine biometric sensors with a VR study. One can measure respiration (Verhulst et al., 2020), skin conductance and heart rate (Oliver & Hollis, 2021), electromyography (EMG) (Oliver & Hollis, 2021), or even electroencephalography (EEG) (Chen et al., 2020). Eye tracking is also possible with built-in eye trackers in the HMD (Siegrist et al., 2019)

Moreover, current sensors already attached in VR as part of the experience can be used to record behavioural data. For example, hand movement is already tracked with devices like Leap Motion (Ammann, Hartmann, et al., 2020; Ammann, Stucki, et al., 2020; Oliver & Hollis, 2021) to help participants interact with virtual objects, but it can also be potentially used as a measure of emotional response to objects (Cervera-Torres et al., 2021; Shafir et al., 2016).

3. VR in action - building research scenarios

In the following section, we combine hardware, software, and response measurement options discussed previously to examine two major scenarios relevant to sensory and consumer research: product selection and food evaluation. We categorised these two scenarios because they represent a major split in research implementation: while product selection scenarios can be implemented entirely in VR, food evaluation scenarios involving participants tasting a product in physical reality. For each research scenario, we first review current literature to

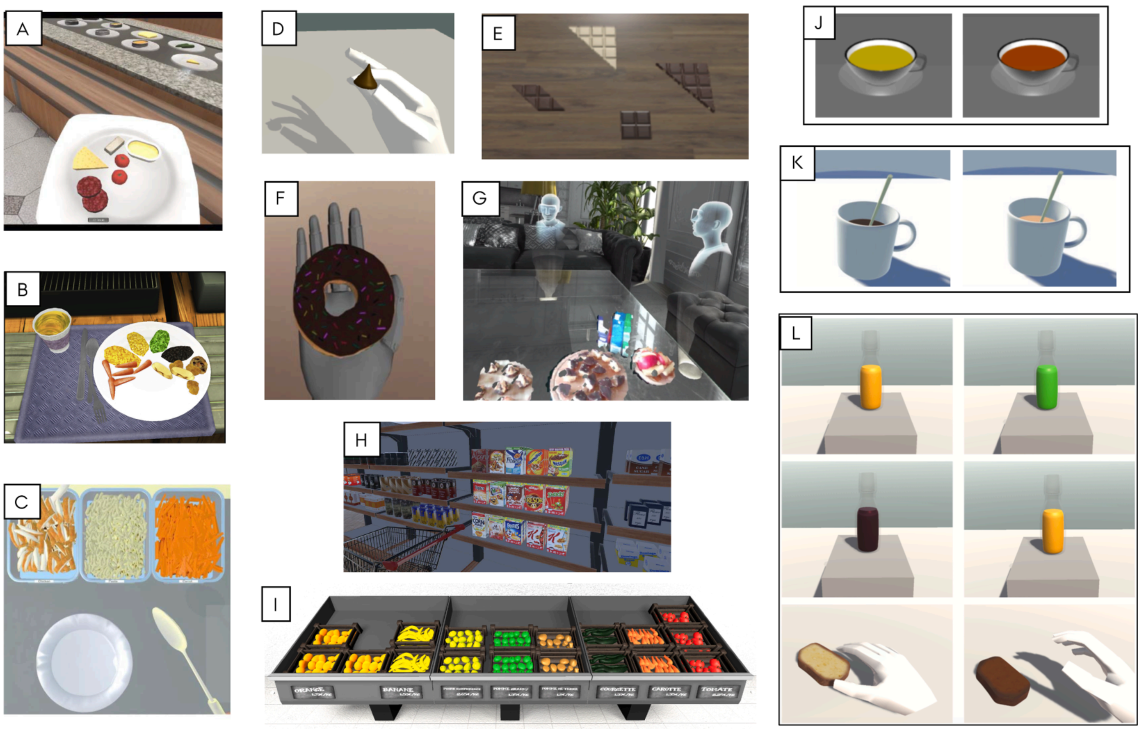

Fig. 3. Examples of 3D models of food products used in previous VR studies: Buffets - (A) Celikcan et al., 2018, figure 5, (B), Persky et al., 2018, Fig. 2, (C) Ung et al., 2018, Fig. 1; Simple geometric food shapes - (D) (Ammann, Hartmann, et al., 2020), Fig. 3, (E) van der Waal et al., 2020, Fig. 3, (F) (Li & Bailenson, 2017), Fig. 2; Depth-sensor capture of physical food - (G) Korsgaard et al., 2019, Fig. 3; Supermarket shopping scenarios - (H) (Siegrist et al., 2019), Fig. 2, (I) Lombart et al., 2019, Fig. 2; Food colour manipulation studies - (J) Huang et al., 2019, Fig. 1, (K) Wang et al., 2020, Fig. 1, (L) (Ammann, Stucki, et al., 2020), Fig. 1.

outline the myriad of technical possibilities to fit specific experiment designs. Next, we highlight future research avenues and technical development opportunities in each scenario. Table 1 summarises the equipment and experiment setup options for specific research scenarios.

3.1. Food choice scenarios

3.1.1. Current literature

Research on food choice scenarios involving VR where food is not consumed is still in its infancy. It has mostly explored the feasibility and validity of VR, or it has compared VR environments or food to other media or the real world. These studies became popular in 2018 and experienced a steep increase again in 2020 (see Table 2). This literature has mainly explored product perception (Lombart et al., 2019, 2020; Sinesio et al., 2019), food choice (Allman-Farinelli et al., 2019; Andersen et al., 2019; Celikcan et al., 2018; Cheah et al., 2020; Fang et al., 2020; Goedegebure et al., 2020; Persky et al., 2018; Persky & Dolwick, 2020; Ung et al., 2018), purchase behavior (Higuera-Trujillo et al., 2017; Xu et al., 2021). Moreover, these studies can be broadly divided into two categories, depending on whether it is the feasibility and effectiveness of the virtual environment (compared to other media or the real world) that is being studied, or whether it is the product that is manipulated and studied.

To the best of our knowledge, except for one study (Persky & Dolwick, 2020), all the studies in the first category explore either the feasibility or validity of VR environments (Allman-Farinelli et al., 2019; Celikcan et al., 2018; Isgin-Atici et al., 2020; Ouellet et al., 2018), or they compare them to other media or the real world. On the other hand, Persky & Dolwick (2020) evaluated the effect of background smell (i.e., French fries) in a virtual buffet on food choice. The studies in this category have used multiple environments including buffets (Cheah et al., 2020; Persky et al., 2018), cafeterias or food courts (Allman-Farinelli et al., 2019; Celikcan et al., 2018; Isgin-Atici et al., 2020) supermarkets (Fang et al., 2020; Lombart et al., 2020; Ouellet et al., 2018; Schnack et al., 2019), isolated shelves (Higuera-Trujillo et al., 2017; Siegrist et al., 2019), as well as pubs (Sinesio et al., 2019) and beaches (Andersen et al., 2019). The complexity and immersiveness of these environments vary widely, but mobility and the integration of other senses is limited.

The studies that explore food choice or purchase behaviour—especially those that involve grocery and meal shopping—may require a high degree of interactivity since they need to make it possible for participants to interact with products and select or purchase them in real time. These studies require a relatively high degree of custom programming, whether it is the environment or the products, which also demands high-end VR headsets (e.g., HTC Vive, Oculus Rift). However, this type of study could also be relatively simple, if the goal is to evaluate people's food choice and behaviour after being exposed to a predesigned or pre-recorded VR environment (e.g., Andersen et al., 2019) without any interaction, which does not require high-end headsets. In this latter case, less expensive headsets such as standalones and even smartphone-powered devices can be used.

Studies in the second category, where the product itself is the object of study, are more limited in number. In contrast to the first category, most of these studies do not compare VR with other media. Instead, these studies manipulate features of the food and evaluate different responses entirely in VR (Goedegebure et al., 2020; Huang et al., 2021; Lombart et al., 2019; Verhulst et al., 2020). For instance, Lombart et al. (2019) studied the effect of shape abnormality of fruits and vegetables in VR on consumer perception, and Verhulst et al. (2020) investigated the effect of different types of odours visualizations in VR on odour awareness. Only one study has compared VR with real world food (Gouton et al., 2021). Here, the authors compared participants' visual descriptions of real-world commercial cookies with those of their virtual versions.

Research involving food in VR tends to be more complex than studying context since it requires creating new 3D food models and manipulating their features, which can vary in complexity and difficulty.

For instance, these food models can be simple like the crisps packaging in (Huang et al., 2021), or they can require more programming, such as the semi-automatic generation process used in the fruits and vegetables in (Lombart et al., 2019) or the smell visual representations in (Verhulst et al., 2020). Furthermore, more realistic food stimuli may require the virtualization of real food with methods such as photogrammetry as in (Gouton et al., 2021).

3.1.2. Future perspectives in food choice scenarios

As the present literature on food choice involving VR shows, this area of research is still relatively new, and it is still exploring the validity and potential uses of the technology. The studies so far have shown promising results in the usability of VR. However, there are key aspects that could help advance this field further, in terms of studies focusing on contexts, as well as products; these aspects are mainly related to the manipulation of environments, incorporation of other senses, and use of biometric measures. Additionally, this field presents a unique opportunity for multidisciplinary collaboration.

First, given that multiple studies have shown that VR environments elicit similar emotional and behavioural responses to real-world scenarios, not to mention higher engagement and immersiveness than 2D contexts, future research should focus on manipulating virtual shopping environments. VR is an effective tool for the manipulation of a plethora of elements in realistic contexts that would be hard, costly, and timely in real life. This is especially relevant for the study of crossmodal effects applied to environmental factors, as well as the creation of complete environmental designs and their potential effects on food choice and purchase behaviour. For instance, VR makes it possible to uncover features more efficiently in realistic contexts that may increase the purchase of healthy products. Moreover, virtual environments can be used to study how multiple variables can induce specific emotions when shopping for food. Going beyond, VR provides the opportunity to develop fictitious worlds and explore their effects on cognition, decision making, food choice, and purchase behaviour. While its relevance may not be apparent at first, the increasing accessibility of VR can make experiences in virtual worlds—including fictitious ones—that include shopping capabilities more common.

Furthermore, there is a great opportunity to leverage multiple senses to increase the immersiveness of virtual environments and potential future areas of study (Cornelio et al., 2021). Incorporating haptic feedback would allow for more in-depth studies, especially on product perception and purchase behaviour. Haptic devices such as the realistic grasping gloves proposed by Oprea et al. (2019) and the inflatable physical props proposed by Teng et al. (2018) could be applied to packaging to make virtual objects more realistic. Such devices would enhance the immersiveness of virtual environments and increase people's sense of agency in the virtual world. At the same time, they could trigger behaviours closer to those in the real world. Moreover, this haptic feedback opens possibilities to study the manipulation of touch (i.e., textures, weight perception, visuo-tactile incongruencies).

Another direction that could advance research on food choice in VR is the additional inclusion of sensors to capture behavioural and biometric data. Similar to Ergan et al. (2019) who investigated the influence of architectural designs in VR using a set of sensors (i.e., EEG, galvanic skin response [GSR], photoplethysmogram [PPG]), future studies could use multiple measures such as body temperature, skin conductance, heart activity, brain activity, as well as head and body movement to analyse people's responses to products and contexts. Such studies could then more accurately reveal the hedonic evaluations and emotions triggered by products and environments. Consequently, the insights resulting from these studies would serve to guide the development of food products and food-related spaces.

This field of research would substantially benefit from closer collaboration between the areas of human–computer interaction, psychology, sensory science, and marketing to capitalize on their expertise. As Velasco et al. (2018) suggested, increased crossed awareness of the different technologies stemming from the human- and food-interaction fields shed light on further applications that can lead to higher returns. This multidisciplinary collaboration can lead to a more accelerated and impactful advancement of the field (see also Velasco, Wang, Obrist, and Nijholt (2021)). For instance, interfaces that create virtual multisensory environments can be used to study human behaviour and decision making to prompt change in different areas, from sustainable food choice to healthier diets. Moreover, these changes can lead to more efficient allocation of financial resources.

3.2. Food evaluation scenarios

3.2.1. Current literature

Compared to food choice scenarios, research involving VR and eating has developed later, and become increasingly popular only in the last two years (note the explosion of papers in 2020, Table 3). When it comes to actually tasting the food in VR, studies generally fall into two categories. First, there are studies where VR is used just to induce context, and the food is not represented in VR (Barbosa Escobar et al., 2021; Chen, Huang, Faber, Makransky, & Perez-Cueto, 2020; Kong et al., 2020; Picket and Dando, 2019; Torrico, Han, et al., 2020; Torrico, Sharma, et al., 2020; Worch et al., 2020; Wen & Leung, 2021). Often, responses are collected after the headset is taken off.

The benefits of such studies is that programming is fairly simple, and this can be done with a wide variety of HMDs. It is especially suitable for lightweight and cheaper mobile solutions such as smartphone-powered headsets (e.g., Google Cardboard, Samsung Gear VR), and studies can be conducted relatively easily with multiple participants at a time. To make getting started even easier, contexts can be recorded (e.g., Picket and Dando, 2019), designed (e.g., Chen et al., 2020), or simply selected on a 360-video platform such as YouTube (e.g., Torrico, Han, et al., 2020; Torrico, Sharma, et al., 2020).

However, the challenge with context-only eating scenarios is that eating instructions need to be very carefully given to consumers, if eating is to be done while headsets are worn. For example, in Torrico et al. (2020), participants tasted 15 mL of wine from small 215 mL ISO wine tasting glasses while wearing a VR headset, but the wine glasses themselves were not visible in VR. In this case, there needed to be an experimenter in the room to help the participants taste the (invisible) wine in VR. The difficulty involved in having participants taste food while wearing a headset is perhaps why some researchers have used HMDs only to introduce a context, then had participants evaluate the food outside of the virtual context (e.g., in the context of a winery tour, Wen & Leung, 2021). Obviously, the problem with this approach is that exposure to the virtual context is separated from actual food evaluation, so we cannot effectively measure the true influence of context on product evaluation.

Secondly, there are studies where the participant can interact with the food itself in VR. These studies face more programmatic challenges, with the trade-off of achieving greater immersion and reality. It is possible to alter the visual appearance of food in VR (Ammann, Hartmann, et al., 2020; Wang et al., 2020), leading to rapid product development possibilities but also novel ways of studying multisensory integration. In order to represent food in VR, experimenters need to find 3D models representing the food to be consumed, then figure out how to set up interaction with the food. This *augmented virtuality* setting represents an interesting design challenge. One way is to use VR trackers, which can be mapped in VR. These can be attached to objects to help anchor the physical and virtual worlds (Oliver and Hollis, 2021), or they can be attached to servingware to enable foods to move simultaneously in physical and virtual reality, as was done with coffee mugs (Nivedhan et al., 2020; Wang et al., 2020). In this case, participants were told to reach out and grab the virtual mug, where a physical mug was also located. This way, participants were able to manipulate the mug and drink the coffee in a natural way; however, participants could not see their own hands. The other approach is to use hand trackers such as

LeapMotion (Ammann, Hartmann, et al., 2020; Ammann, Stucki, et al., 2020; Oliver and Hollis, 2021) so that participants could see their own hands in VR and use it to pick up food items. This requires more programming skills to integrate LeapMotion with Unity and to implement collision detection properly, so that any contact between the hand and food can be registered and processed further in VR. For instance, if the user picks up a piece of food in physical reality, then the virtual food model also needs to track with the virtual hand in VR. A hybrid method was employed by Korsgaard et al. (2019), whereby an Intel Realsense SR300 depth sensor was mounted on top of the HMD, so that food and hands were projected into the virtual environment as textured geometry. Participants in the meal saw a blended mixed-reality scenario with real food in the virtual environment.

One challenge with eating in VR is - what happens to the food after the participant eats it? For example, in Oliver and Hollis (2021), participants were given ten mini pizza rolls to eat. Since the pizza rolls could be eaten in one bite, the researchers did not have to worry about modelling half-eaten food. However, the pizza rolls that were eaten had to be deleted manually by the experimenter to maintain equivalence between the number of pizza rolls in virtual and physical reality. Therefore, a technical challenge still remains to implement a seamless eating experience in VR. Note that the mixed reality approach used by Korsgaard et al. (2019) would take care of the eaten food approach, since the physical food is always dynamically modelled in VR using the additional depth sensor; however, this approach has additional technical complexity.

One additional challenge is to ensure that the food in question can be comfortably and easily consumed while wearing a large HMD. Just try drinking a large glass of wine or normal mug of coffee while wearing a HTC Vive or Oculus Rift (see Fig. 2)! So far, researchers have gotten away with this challenge by using finger foods (Gorini et al., 2010; Ammann, Hartmann, et al., 2020), narrow glasses (Ammann, Stucki, et al., 2020) and the use of straws (Nivedhan et al., 2020; Wang et al., 2020).

3.2.2. *Future perspectives in food evaluation scenarios*

How can we develop more seamless experiences entirely in VR? While introducing a virtual immersive context (without food) can already make a difference to food evaluation (e.g., Chen et al., 2020), looking at the food is an important part of the eating experience (Simmons et al., 2005; van der Laan et al., 2011). For product development, there is as of yet no study comparing the influence of using VR only to induce context, versus experiencing the product—seeing and touching it—in the virtual world. Going forward, we suggest there are three areas of future development which can capitalise on key digital transformations (mixed reality, internet of things, and AI-powered technologies) taking place in consumer experiences (Hoyer et al., 2020): expanding the range of foods, improving response collection via automation and synchronised sensors, and coupling virtual and physical worlds in mixed-reality scenarios where the food takes centre stage.

First, it is important to consider limitations on the kind of food that can be eaten while wearing a HMD. As mentioned previously, so far researchers have been limited to relatively small pieces of food, or drinks in small containers. The smartphone-headset options have smaller fingerprints, which also makes it easier to accommodate a wider range of servingware. We are probably still somewhat away from a knife and fork scenario, since that depends on development in hand tracking and food tracking technology, although the use of front-of-HMD cameras (such as those found in the HTC Vive pro Eye) is making it easier to program mixed reality scenarios. Luckily, much of sensory testing involves one-bite or one-sip samples, which makes it easier to implement in VR.

To develop a seamless experience, data collection should happen in-situ as naturally as possible, without participants having to answer a questionnaire that pops up in VR or having to take off the headset to answer questions. Having experimenters verbally ask participants is one way to go, although automation, either via smart speaker technology as demonstrated in Morotti et al. (2020), or even service robots (Wirtz et al., 2018), seem like a promising direction. One benefit of voice interaction is the possibility to record and transcribe participant experiences as they express it naturally, as they might describe it to another person, rather than having to translate their experiences into numerical scales, as is so often the case with consumer research. This also enables the possibility of having take-home or remote testing, without the experimenter having to be there. Another possibility is to collect biometric information, such as demonstrated by Oliver and Hollis (2021) with the use of a wristband to measure skin conductance and heart rate, and EMG electrodes to measure chewing detection. While hooking up participants with electrodes might be time-consuming, simple biometric measurements such as the wristband can be an easy addition, keeping in mind the motion constraints with biometric sensors. Another possibility is to use sensors already part of the HMD ecosystem, like the HTC Vive Pro Eye with built-in eye trackers, or measuring hand movement with LeapMotion trackers.

The ultimate challenge, however, is to integrate the food itself into the VR experience. One direction is to model the food in VR, which requires knowing precisely what the participant will be eating ahead of time. While the food items used in studies so far have been for the most part simplistic 3D representations rather than life-like models, with the advent of 3D scanner capabilities (e.g., in the latest generation of iPhones and iPad Pros), it should become ever easier for researchers to make realistic 3D models of experimental stimuli that can be added into the experiment. However, given the difficulty of dynamically following deformations in the food as it is eaten, the method of producing a virtual model is limited to beverages or one-bite foods. In contrast, another direction is to use cameras built into the HMDs, or depth sensors (e.g., Korsgaard et al 2019) to create true mixed-reality worlds where the food eaten can be automatically detected and depicted in the virtual world. This technology enables dynamic scenarios where the participant can visualise how much of the food has been eaten. However, this also requires considerable computational know-how and is currently used in AR research using specialised software (Nishizawa et al., 2016; Ueda et al., 2020; Ueda & Okajima, 2019). Beyond the food itself, in order to create greater interactivity in VR, the participant, or at least the hands and if applicable, utensils, should be tracked. Hand-tracking technology is relatively mature (e.g., LeapMotion), but being able to track both hands and utensils is still a challenge without using sophisticated computer vision algorithms.

4. Limitations and future applications

4.1. *Limitations of HMDs*

While VR is becoming an ever more accessible and versatile technology, it is not necessarily suitable for all food-related scenarios. Fundamentally, VR faces the issue of immersion; first, people know that they are wearing a headset. Second, while technology is improving, it is still difficult to have close-to photorealistic experiences in VR, especially when interactivity with food or other people are involved. From this perspective, two major challengers to VR are immersive rooms, where the sense of immersion is provided by large projections or video walls; and AR, where virtual information is imposed on top of the physical world.

While relatively more expensive, the greatest advantage of immersive rooms compared to VR is the ease of incorporating social interactions with others. So far, it has been difficult to study social eating scenarios in VR due to technical limitations. Moreover, it is the most seamless (at least, from the perspective of food interaction) and natural of all the immersive technologies since the participant doesn’t have to wear any additional equipment. In an immersive room, one can interact with the food as well as fellow diners naturally, and it is possible to include additional sensory stimuli such as surround sound, aromas, wind, and temperature control for an even more realistic experience.

That said, immersive rooms do have the drawback of not allowing participants to interact with the virtual environment, in contrast to the possibilities offered by a programmable environment via HMD.

Compared to VR, AR has the benefit of automatically "tracking" participant hands, utensils, the food itself, and fellow diners, which also represents valuable data. This also means AR is also more suitable for social eating or shopping situations since the participant can interact with others with ease. What is more difficult in AR is to change the appearance of the food, which typically requires advanced computer vision algorithms (e.g., Ueda et al., 2020) to overlay the desired visual input on top of the food in the real world. Where AR excels is to introduce additional information about the food, in a shopping or dining context. AR can also provide entertainment to make the meal more enjoyable, such as Le Petit Chef (https://lepetitchef.com/), a projective mapping story-telling dining experience where a miniature chef narrates the meal while "cooking" virtual food on diners' plates.

That said, how can ecological validity in VR be improved? As mentioned previously, incorporating more sensory modalities in the VR experience as well as replacing intrusive questionnaires with behavioural and biometric measurements will contribute to create a more seamless user experience. For the most part, the combination of biometric sensors with VR should not detract from the user's immersive experience, especially if the sensors are already built into the HMD (e.g., eye-tracker in the Vive Pro Eye), or if they have lightweight formats (e.g., wristband-format skin conductance sensors or EEG headbands).

Moreover, ecological validity may be achieved even without full immersion, if the goal is to measure the influence of context on product evaluation, where the focus is on the product itself rather than on the user truly believing that they are in another place. After all, previous literature has shown that context-induced differences in product evaluation can be achieved even with less than full fidelity attempts at context replication (Jaeger & Porcherot, 2017; Plaza et al., 2019).

Finally, one important issue with VR is VR-induced or cyber sickness (Chang et al., 2020). VR-induced sickness occurs when visual information, as presented to the eyes, does not track with dynamic vestibular experience, and this sensory discrepancy, which can be also caused by ingesting poisonous substances, therefore triggers the body's most innate defense mechanism - to throw up what was most recently eaten (Spence, 2021). Cyber sickness can be induced by a myriad of factors, including hardware, such as when there is a greater degree of latency in the system; content, such as when a person experiences dynamic content while sitting still (a potential issue with showing 360 videos); and human factors, such as the participants' previous experience with VR (Chang et al., 2020). To minimise cyber sickness, researchers should carefully consider their choice of hardware and software to optimise for smooth graphical rendering, or, if using a 360 video, making sure that any movements in the video happen smoothly (i.e., avoid jerky or rapid motion). Moreover, researchers should ensure that participants get the opportunity to familiarise themselves with the VR environment before data collection. The degree of cyber sickness experienced by each participant should also be measured, in order to control for its effects in experimental results. That said, it is worth pointing out that typical VR tasks in sensory and consumer science do not involve much movement, especially when the participant is sitting still, so the risk of cyber sickness is relatively low.

4.2. Ethical issues in VR

Typically, as with any other research, VR studies should comply with local regulations, as well as ethical guidelines laid out for research (e.g., The Declaration of Helsinki). However, there are certain specific ethical issues and challenges associated with VR in sensory and consumer science that may be worth considering, in particular realism. For example, it is possible to recreate stressful, dangerous, or other emotionally intense events, either real or imaginary (e.g., just imagine yourself eating with a virtual replica of your own self), in VR (e.g., eating in a context of fear), which feel real to the participants. Considering the increasing realism of the VR environments, the opportunities of recreating and experimenting with real and imaginary scenarios, as well as the corresponding effects of study manipulations on participants, can be significant, and in some cases even more than in traditional studies, e.g., say, imagery scenario-based research relative to VR scenario-based research (Pan & Hamilton, 2018; Slater et al., 2020). This issue, of course, becomes even more salient when it comes to vulnerable participants (e.g., participants with a specific food disorder, Kellmeyer, Biller-Adorno, Maynen, 2019).

Velasco and Obrist (2020) introduced certain questions that researchers and practitioners designing multisensory experiences may consider in order to evaluate the full impact of the experience on users. These questions, which are also applicable here, include: why (the rationale/reason for the VR experience), what (the impression that wants to be created in the VR environment), when (the VR event), how (the sensory elements in VR), who (the someone who conducts the experiment), and whom (the participant). Following the answers to these questions, one may consider the three laws of multisensory experiences to delimit whether a VR experience is ethically problematic or not: 1) It should be used for good and must not harm others, 2) the participants should be treated fairly, and 3) the researcher and the sensory elements must be known to the participants. Although this is not an exhaustive framework, it can guide the thinking process about the possible implications of a VR study.

4.3. Future applications of VR in sensory and consumer science

Beyond food selection and consumption scenarios already covered above, we believe that, with inspiration from other disciplines such as clinical research or human–computer interaction, VR can be used in new ways in the area of consumer research, with the aim of altering people's behaviour in order to improve population and planetary health.

4.3.1. Appetite regulation

Obesity is a chronic and progressive disease with high morbidity and mortality due to its comorbidities, social problems, and poor quality of life (Demir & Bektas, 2017). It is a major public health problem in the world, even considered as the "epidemic of the 21st century" (Ajejas Bazán et al., 2018). Unfortunately, obesity prevalence is expected to be even higher by 2026 (Janssen et al., 2020). Traditional weight-management programs, which are time and cost consuming, are effective in the short-term but have been reported as ineffective one year after treatment (Coons et al., 2011). Some researchers and clinicians have started to explore and implement how VR environments can be used to treat (or complement treatment for) obesity and eating disorders. A recent review (Rumbo-Rodríguez et al., 2020) showed evidence that the use of digital technology, such as smartphones, websites, and VR, in patients with obesity allows improvement in treatment and greatest weight loss. Furthermore, there is evidence that exposure to food stimuli in VR and VR-body image treatments are effective (Gutiérrez-Maldonado et al., 2021). For example, it has been shown that craving experienced during VR was consistent with craving assessed with questionnaires in non-VR environments (Ferrer-Garcia et al., 2014). Another study showed that when comparing virtual food with the corresponding real food and food photographs, virtual food was as effective as a real food (and even more effective than photographs of food) in triggering psychological and physiological responses in patients with eating disorders (Gorini et al., 2010).

Despite the fact that VR as an embodied technology can simulate environments, people, and objects to trigger cravings in patients with eating disorders and obesity, there is a lack of research on how virtual contexts, with or without virtual foods, affect human appetite (Spence et al., 2016). Larson et al (2014) showed that repeated evaluation of food pictures has a similar effect as actual food consumption. An experimental study showed that when touch or smell cues were added to the virtual environment, people tended to feel more satiated than when they were just exposed to the virtual food (Li & Bailenson, 2017). There is a need for further research on this topic, but if satiation takes place when seeing, smelling, and touching virtual food, then VR could be an extremely helpful technology for the prevention of obesity. In fact, Project Nourished (https://projectnourished.com/) has just one such aim, to deliver the sensory aspects of eating through the combination of a VR headset, scent diffusers, gyroscopic utensils, and bone-conducting headphones, without the user consuming any calories.

4.3.2. Eating experience enhancement

One exciting potential for VR is to improve eating experiences in extreme situations. Space food is a vivid example that comes immediately to mind. While in space, astronauts habitually consume only 80% of their recommended daily calories (Taylor et al., 2020). While this may not seem like a big issue, consequences of chronic undernutrition can be critical for long-term space travel, e.g., to Mars. Efforts are underway to make space food more appealing. Considering that space food is usually served in clinical shrink-wrapped plastic tubes or bags and eaten in tight quarters full of other technical equipment, VR could help to make both the context and the food appear more comforting and natural for the astronauts, leading to greater food acceptance (e.g., Meiselman et al., 2000). While eating with a VR headset might seem like technology overload at home on earth, VR might be easily integrated into a spaceship environment or on the space suit itself (Obrist, Tu, Yao, & Velasco, 2019).

Closer to home, VR technology can potentially help those in danger of chronic undernourishment, such as recovering hospital patients (Sánchez-Lara et al., 2010) or the elderly (Divert et al., 2015). While the jury is still out on whether virtual environments can create a comforting eating environment, thereby alleviating boredom and/or induce appetite, previous research on atmosphere in hospitals and nursing homes indicate that this could be a promising direction (Justesen et al., 2016; Schweitzer et al., 2004). After all, meal satisfaction with hospital food is linked to features of the immediate eating environment (Hartwell et al., 2016), and there is evidence that the hospital eating environment can potentially be a meaningful source of emotional healing for patients (Beck et al., 2019). Background noise levels and music, for instance, can be used to improve mealtime atmosphere in hospitals (Mathiesen et al., 2020) and also has the potential to calm patients and enhance specific flavours in the food (Spence & Keller, 2019).

4.3.3. Consumer attitude change

Beyond physiological benefits, VR, with its potential for storytelling and empathy-building (e.g. https://www.treeofficial.com/), can be used to affect consumer attitude change towards a healthier, more sustainable food ecosystem. As previously mentioned, researchers have used VR to understand consumer food choices (Table 2), demonstrating that consumer behavior in a VR store is more comparable with the behaviour in a physical store than with a 2D store (van Herpen et al., 2016). With COVID-19 and its consequent sharp increase in online food shopping, including groceries (Alaimo et al., 2020), VR could help supermarkets and consumers in sensing the shopping experience as much "real" as possible. Online supermarkets could add a feature of healthy dishes suggestion and dishes preparation (by a known local chef) based on the consumer's products purchase to promote healthy eating habits and remove the link between boredom and healthy food.

Another area in which VR can be leveraged relates to the development of strategies to induce more sustainable behaviours through virtual experiences. For example, VR opens the possibility to create immersive and interactive game-like experiences in which users must eat unfamiliar (think of extraterrestrial) foods as part of the gameplay, which in the real world are alternative sustainable sources of food. Through play and repeated exposure, these experiences can introduce people from different ages to novel, sustainable foods, which could later translate into increased acceptance and liking. These experiences could be implemented in research-based institutions, but they could also be implemented as part of the business models of new ventures, such as VR arcades. As Chittaro and Buttussi (2019) found, games with arcade elements can increase knowledge and trigger attitude change related to aviation safety. Additionally, given the positive correlation between immersion and motivation the authors found, VR may heighten these effects on food-related attitudes and behaviours.

5. Conclusion

This paper provides a practical guide for sensory and consumer scientists interested in exploring the emerging opportunities offered by VR. While VR has been a much-used term in research, there has been a lack of clarity and precision regarding what exactly constitutes a VR study, and how different types of research setup might result in levels of immersion and presence. Beyond just offering an abstract research overview, we take a deep dive into the components that make up a VR study, including hardware, software, and response measurement methods, all the while being grounded in immersion and presence theory. These building blocks can be put together to create VR scenarios which are purely virtual (e.g., product choice) or mixed reality (e.g., food evaluation). Current research has mostly involved product choice scenarios, due to the additional technical complexity that could accompany a mixed reality setup. That said, our review has highlighted the wide scope of VR solutions already implemented, ranging from fully customised tethered scenarios to lightweight "out of the box" smartphone setups, which demonstrates both the rapid technical development in the field and the ingenuity of researchers involved.

As VR technologies continue evolving, greater degrees of immersion, the increased use of multisensory stimuli, and more subtle integrated measurement methods will combine to create more seamless experiences for the user. Going beyond using VR to achieve ecological validity in product testing, future opportunities in sensory and consumer science lies in altering consumer behaviour to help people create healthier, more sustainable lifestyles. With the ever-expanding availability and accessibility of equipment and software, it is an exciting time for food-related VR research!

Declaration of Competing Interest

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

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