DOCTORAL (PhD) DISSERTATION

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Budapest
2025

Hungarian University of Agriculture and Life Sciences

APPLICATION OF IMMERSIVE METHODS IN CONSUMER SENSORY SCIENCE

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2025

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ABBREVIATIONS

AI	Artificial Intelligence
ANOVA	Analysis of Variance
AOIs	Area of Interests
AR	Augmented Reality
AV	Augmented Virtuality
CATA	Check-All-That-Apply
ET	Eye Tracking
Exp.	Experiment
HMD	Head Mounted Display
JAR	Just-About-Right Scale
MFA	Multiple Factor Analysis
P	Participant
PANAS	Positive and Negative Affect Schedule
PCA	Principal Component Analysis
SB	Sensory Booth
SDK	Software Development Kit
SSQ	Simulator Sickness Questionnaire
UI	User Interface
VR	Virtual Reality
VRNQ	Virtual Reality Neuroscience Questionnaire
VRSQ	Virtual Reality Sickness Questionnaire
XR	Extended Reality
XRSQ	Extended Reality Sickness Questionnaire

1. INTRODUCTION

Consumer sensory science is a rapidly evolving field that plays a central role in shaping food innovation, market competitiveness, and product development strategies. As global food systems respond to rising consumer expectations for healthier, more sustainable, and emotionally engaging food experiences, understanding how individuals perceive and interact with food products has become more important than ever. The need to capture consumer responses with greater accuracy, relevance, and realism is accelerating the shift towards advanced sensory evaluation methods. Reflecting this momentum, the global sensory testing market was valued at approximately USD 26.63 billion in 2024 and is projected to grow to USD 47.5 billion by 2033 (Business Research Insight, 2024), highlighting the rising demand for high-quality and innovative sensory research.

The discipline of sensory science is evolving in response to increasing demands for more realistic, context-rich, and predictive methods of consumer evaluation (Low et al., 2024). As the food industry shifts towards personalised experiences and sensory-driven innovation, there is a growing need to understand how consumers perceive products beyond traditional laboratory environments (Zulkarnain, Kókai, et al., 2024a). Conventional sensory evaluation methods typically rely on controlled booths and standardised questionnaires, offering high internal validity but limited ecological realism. These artificial settings do not represent the diverse, dynamic environments in which food consumption occurs. As a result, the ability of these methods to predict real-world consumer behaviour remains restricted. To address these limitations, researchers are turning to immersive and data-driven technologies that can replicate naturalistic contexts and provide deeper insight into how perception, attention, and emotion influence sensory experiences.

Virtual Reality (VR) is at the forefront of this transformation. It enables the creation of immersive, interactive environments in which participants can evaluate food products in conditions that closely resemble real-life scenarios (Gere, Zulkarnain, et al., 2021). Unlike static sensory booths, VR allows for the flexible manipulation of environmental cues such as setting, lighting, background noise, and social context. These elements have a significant impact on how individuals perceive taste, smell, texture, and overall product acceptability. By integrating such variables into the testing process, VR offers a means to improve ecological validity without sacrificing experimental control. In sensory science, this opens new possibilities for studying context-dependent responses, emotional associations, and behavioural outcomes linked to food consumption.

At the same time, the rapid growth of the sensory testing market signals a need to modernise existing methodologies and incorporate technologies that can support large-scale testing while capturing more authentic consumer behaviour (Business Research Insight, 2024). VR offers advantages in scalability, cost-efficiency, and standardisation, particularly when used to simulate multiple environments without the need for physical reconstruction. These benefits position VR as a promising tool not only for academic research but also for practical applications in industry and policy.

This research focuses on the development, validation, and application of a Virtual Sensory Laboratory. The central aim is to establish VR as a scientifically sound and practically feasible methodology for consumer sensory testing. A sequence of structured experiments was conducted to evaluate various aspects of VR-based testing, including participant acceptability, methodological accuracy, cross-context comparability, and technological usability. These studies include direct comparisons between traditional and VR sensory evaluations, assessments of participant behaviour across different virtual environments, and the impact of immersive design elements on sensory outcomes. In addition to basic environmental simulation, the research also investigates Augmented Virtuality (AV), which blends physical food stimuli with virtual backdrops, offering an enhanced level of immersion that may further align testing environments with real-world eating situations.

As immersive technology becomes increasingly accessible and cost-effective, its integration into consumer research is expected to grow. However, rigorous scientific validation is essential before VR can be widely adopted as a replacement or enhancement for conventional sensory methods. This thesis contributes to that effort by systematically testing the reliability, usability, and outcome quality of VR-based sensory evaluations under multiple conditions. Each experiment builds towards a comprehensive framework for virtual sensory analysis that prioritises reproducibility, participant engagement, and ecological realism. In addition to VR, this research applies Eye Tracking (ET) to explore how visual attention influences consumer perception in sensory testing. ET provides objective, high-resolution data on gaze patterns, fixation duration, and visual focus areas. This allows researchers to examine how consumers interact visually with food products, packaging, and digital environments during sensory tasks. The use of ET supports the measurement of cognitive processes that underlie perception and preference formation. By applying this tool in one of the experiments, the research captures attention dynamics in both traditional and immersive settings, offering a more complete picture of how visual behaviour intersects with sensory evaluation outcomes.

The application of ET also contributes to a better understanding of how consumers respond to visual elements such as sustainability labels, product claims, and environmental cues that are often overlooked in standard testing formats. While VR focuses on simulating the environment and capturing behavioural responses, ET provides a layer of objective measurement that reveals how these environments influence visual and cognitive engagement. Together, these approaches allow for more holistic and nuanced analyses of the sensory experience, considering not only sensory inputs but also psychological processes involved in consumer decision-making.

This research addresses critical methodological gaps in current sensory science literature. Most previous studies have relied heavily on self-report instruments and lab-based settings, which may not fully capture the complexity of food-related behaviour. There remains a lack of validated tools that combine realistic simulation with objective data capture, particularly for large-scale or industry-relevant testing. By demonstrating the scientific potential of immersive environments and attention-based measurement tools, this research contributes to the advancement of sensory science in both theoretical and applied contexts. The findings reflect a broader shift in methodology that moves beyond controlled booths and paper ballots towards more context-aware, engaging, and evidence-based approaches. As immersive technologies become more accessible and accepted, their thoughtful application in consumer research will play a crucial role in shaping the future of sensory evaluation.

2. OBJECTIVES

The aim of this doctoral research was to evaluate the application of immersive technologies (VR and AV) and visual behaviour tracking (ET) in consumer sensory evaluation. The research sought to enhance ecological validity, predictive accuracy, and methodological reliability. Five main research objectives were formulated based on the experimental framework. Each objective is supported by a structured set of tasks aligned with the corresponding experimental phases.

I. Assessing the acceptability and feasibility of a Virtual Sensory Laboratory
   - To explore the development and practical integration of immersive VR environments in consumer sensory testing, focusing on usability, participant comfort, and overall viability.

II. Comparing consumer responses between traditional and virtual sensory settings
   - To examine differences in sensory perception and acceptance across conventional laboratory and immersive VR contexts.

III. Evaluating the impact of immersive methods and contextual cues on perception
   - To determine how environmental immersion and sensory cues influence consumer behaviour and sensory outcomes.

IV. Exploring the role of Eye Tracking (ET) in immersive contexts
   - To analyse visual attention and cognitive processing patterns using ET data within VR sensory tasks.

V. Investigating the use of Augmented Virtuality (AV) for integrated food-virtual testing
   - To assess how real food stimuli can be effectively combined with virtual settings for enhanced sensory realism and ecological validity.

3. LITERATURE OVERVIEW

3.1. Fundamentals of Sensory Analysis

Sensory analysis is a scientific discipline that systematically evaluates attributes of products through human senses including sight, smell, taste, touch and hearing (Jaeger et al., 2025). This evaluation approach provides robust and quantitative data crucial in product development, quality assurance and consumer research. The primary aim of sensory analysis lies in understanding sensory perceptions and preferences of consumers, allowing manufacturers and researchers to optimize products effectively. The discipline is critical in identifying product differences, assessing consumer acceptance, and predicting potential market success based on sensory attributes (Lawless, 2013).

Effective sensory analysis requires a structured methodological approach following rigorous standards. Controlled test environments, standardized protocols and meticulous panel selection are foundational requirements to ensure the reliability and validity of sensory data. Panellists are individuals carefully selected based on specific criteria including sensory acuity, reliability and ability to communicate sensory experiences clearly. Panellists within sensory analysis can be broadly categorized into two distinct groups: trained panellists and consumer panellists, as outlined in ISO 8586:2023 (International Organization for Standardization, 2023). These two groups serve different roles depending on the objectives of the sensory study. Trained panellists, also referred to as sensory experts, are individuals who undergo substantial training to accurately detect, describe and quantify product attributes consistently over repeated assessments. This training process involves the development of precise sensory vocabularies, the use of standardized scoring scales and familiarisation with a wide range of product stimuli (Djekic et al., 2021). The aim of a trained panel is to provide objective, reproducible, and accurate data that supports detailed product profiling and quality control (Ciccone et al., 2021).

In contrast, consumer panellists represent typical consumers whose evaluations reflect real market scenarios (Álvarez-Pato et al., 2020). Unlike trained panellists, consumers do not undergo formal training in sensory evaluation methods. Instead, their responses primarily indicate subjective preferences, likes and dislikes and acceptance of products (Ares & Varela, 2017). Consumer panellists are generally recruited based on demographic criteria such as age, gender, geographic location and frequency of product usage (Shi et al., 2021). Insights from consumer panels offer valuable information concerning overall product acceptance, purchasing intent and potential market success. These results guide strategic decision-making regarding product formulation, packaging and positioning in the market (Rawat & Sahni, 2023).

Sensory evaluation methods can be categorized into three main groups (Stone & Sidel, 2004). Discrimination testing determines whether perceivable differences exist between samples. Affective testing evaluates the degree of liking or acceptance among consumers. Lastly, descriptive analysis employs trained panels to accurately identify and quantify specific sensory attributes. The choice of method largely depends on the research objectives and the information sought by researchers. For instance, descriptive methods are ideal for in depth profiling of products while affective tests directly inform product acceptance and marketability (Delarue & Lawlor, 2023).

Sensory data analysis necessitates rigorous statistical methods to interpret and validate findings reliably. Statistical analyses typically employed include analysis of variance, principal component analysis, cluster analysis and regression analysis (Pinheiro et al., 2023). These methods effectively identify significant differences, highlight sensory attributes driving consumer preferences and elucidate complex relationships among sensory variables. Advances in computational tools facilitate deeper insights from sensory data, enabling researchers to visualize complex interactions and predict consumer responses accurately (Ambroze & Niedziela, 2023).

Recent developments in sensory analysis increasingly incorporate innovative technological solutions include ET and VR. Integrating these technologies offers enhanced ecological validity and deeper insights into consumer behaviour (Gere, Zulkarnain, et al., 2021). ET facilitates understanding consumer attention and engagement during sensory evaluations (Vu et al., 2016), whereas VR provides realistic contextual scenarios otherwise challenging to replicate (E. Crofton & Botinestean, 2023). Employing these tools in sensory science broadens the capability to investigate consumer perceptions dynamically, enriching sensory data interpretation substantially (Gere, Zulkarnain, et al., 2021).

The clear distinction between trained and consumer panels remains crucial in sensory research. While trained panels provide reliable and objective sensory characterization, consumer panels contribute authentic insights about product acceptance and market potential. Combining data from both panel types allows comprehensive understanding of product sensory performance alongside consumer preferences. Given the PhD research scope focused on consumer sensory evaluations, particular emphasis is placed on accurately capturing and interpreting consumer responses. Such an approach ensures practical relevance and actionable outcomes applicable directly to consumer-focused product innovation and market strategies (Stone et al., 2012).

3.2. Theoretical Frameworks in Sensory Science

Theoretical frameworks in sensory science provide structured approaches that facilitate systematic understanding and interpretation of sensory perception and consumer behaviour. These frameworks serve as foundations for sensory research, enabling coherent integration of methodological choices, data interpretation and scientific communication. Among notable theories used within sensory science include Signal Detection Theory, Multisensory Integration Theory, Expectation Confirmation Theory and Attention Theories, each contributing uniquely toward understanding consumer responses during sensory evaluations (Lawless & Heymann, 2010).

Signal Detection Theory fundamentally contributes to understanding sensory perception by distinguishing true sensory signals from noise (Alves-Pinto et al., 2012). It provides a basis for interpreting variability in sensory detection and consumer decision processes, highlighting that sensory judgments are influenced not only by physical properties of stimuli but also by psychological processes. This theory aids in assessing panellist sensitivity, bias in responses and evaluating threshold levels in detection tasks (Alves-Pinto et al., 2012).

Multisensory Integration Theory further advances sensory science by explaining how simultaneous sensory inputs interact and influence perception. Sensory attributes are rarely perceived in isolation. Rather, consumer perception involves integrated sensory experiences shaped by multiple modalities, creating complex sensory profiles. Thus, product perception and acceptance depend strongly upon interactions among visual, olfactory, gustatory and tactile inputs, emphasizing the necessity of considering cross modal effects during sensory analysis (Ohla et al., 2012).

Expectation Confirmation Theory addresses the cognitive dimension of sensory evaluation, emphasizing how consumer expectations shape sensory perceptions and acceptance (Lee et al., 2021). Consumers inherently possess prior expectations regarding product attributes, which subsequently influence their sensory judgments and satisfaction. Discrepancies between expected and actual sensory experiences can significantly impact product evaluations, either positively or negatively (King et al., 2024). Understanding these expectation biases assists researchers and manufacturers to strategically manage product presentations and optimize consumer acceptance (Mehta et al., 2022).

Attention Theories elucidate how attentional processes guide sensory perception by selectively allocating cognitive resources toward specific stimuli. Attention directly influences sensory perception through modulating awareness and sensory thresholds (Sherman & Turk-Browne, 2024). Employing methods like ET provides direct measurement of consumer attention allocation, allowing researchers to objectively assess how visual attention guides sensory perception and influences consumer choice behaviour (Agost & Bayarri-Porcar, 2024).

3.3. Consumer Sensory Evaluation Methods

Consumer sensory evaluation methods systematically capture consumer perceptions, preferences, and attitudes toward sensory attributes of products. These methods directly engage consumer panels, allowing researchers to gain insights critical for product development and market success prediction (Yadav et al., 2024). Unlike evaluations conducted by trained panellists, consumer assessments provide subjective feedback rooted in everyday experiences and expectations. Depending on the specific research objectives, consumer sensory evaluation methods can broadly be categorized into affective tests, discrimination tests, and descriptive tests, each providing unique perspectives into consumer perception (Varela & Ares, 2012).

Affective tests directly measure consumer liking, acceptance, or preferences toward products (King & Meiselman, 2010). These tests assess consumer hedonic responses, reflecting subjective and emotional reactions to sensory characteristics. Methods within affective testing include Hedonic Scale tests, Preference tests, Ranking tests, and Purchase Intent assessments (King & Meiselman, 2010). The Hedonic Scale is the most widely used affective method, typically employing a 9-point structured scale ranging from extremely dislike to extremely like, quantifying overall acceptance clearly and consistently across diverse product types (Gamba et al., 2020). Preference tests complement hedonic evaluations, specifically assessing consumer preference by directly comparing two or more products or product formulations (Booth, 2016). Ranking tests extend preference testing by requiring consumers to rank multiple samples according to preference, thus efficiently determining relative product appeal (Carabante & Prinyawiwatkul, 2018). Affective tests are critically important as they explicitly quantify consumer acceptance, directly linking sensory characteristics to consumer satisfaction, market success, and product viability (Drake et al., 2023).

Discrimination tests investigate the ability of consumers to perceive sensory differences between similar products (Rogers et al., 2024). These tests identify whether consumers can detect sensory differences among samples rather than assessing overall liking or acceptance. Common discrimination tests include Triangle tests, Duo Trio tests, Paired Comparison tests, and Difference From Control tests (Rogers et al., 2024). The Triangle test presents three samples, two identical and one different, requiring consumers to identify the unique sample, measuring their sensory discrimination capabilities (McClure & Lawless, 2010). Duo Trio tests provide a reference sample and require consumers to select the matching sample from two alternatives, evaluating the consumers' discrimination sensitivity (Lee & Kim, 2008). Paired comparison tests directly assess perceived sensory differences between two samples, making them ideal for rapid product comparisons or optimization (Vietoris, 2017). Discrimination tests are particularly valuable in identifying whether subtle sensory differences are perceivable to consumers, aiding product development by determining noticeable formulation differences, sensory thresholds, and ingredient substitutions (Rogers et al., 2024).

Descriptive tests conducted with consumer panels aim to gather detailed consumer-generated descriptions of sensory experiences, effectively capturing qualitative and quantitative data on sensory characteristics from a consumer perspective (Stone & Sidel, 2004). Methods frequently used include Check All That Apply (CATA), Free Choice Profiling (FCP), and Flash Profiling (Lazo et al., 2016). CATA methods allow consumers to freely select applicable attributes from a predefined list, rapidly generating sensory profiles directly reflecting consumer language (Ares et al., 2017). FCP empowers consumers to generate their own descriptors without predefined attribute lists, thereby providing richer qualitative data directly representing authentic sensory experiences (Varela & Ares, 2014). Flash profiling similarly allows rapid, consumer-generated profiling with minimal training, capturing immediate and spontaneous sensory perceptions (H. Wang et al., 2022). Descriptive tests are valuable because they directly incorporate consumer-driven language, enhancing understanding of how consumers perceive and describe sensory characteristics. These methods enable researchers to efficiently capture detailed sensory descriptions for meaningful product differentiation and sensory optimization (Alcantara & Freitas-Sá, 2018).

3.3.1. Hedonic Scale and Preference Testing

Hedonic Scale testing measures consumer acceptance and liking of products using standardized rating scales. The widely adopted 9-point hedonic scale ranges from extremely dislike to extremely like, enabling clear quantification of overall consumer acceptance (Villanueva et al., 2005). Preference testing directly assesses consumer preference among multiple products or variations. Participants explicitly indicate their preferred product, providing straightforward information useful in product screening, optimization, and marketing strategies (O'Mahony & Wichchukit, 2017).

Hedonic testing is crucial in consumer research as it directly quantifies consumer satisfaction, facilitating clear product acceptance assessment. Its importance lies in simplicity and effective communication of consumer attitudes toward sensory attributes, directly guiding decisions about formulation and market positioning. Preference testing further complements hedonic evaluations by clearly identifying superior products from consumer perspectives, thus significantly influencing strategic product development decisions (Crichton-Fock et al., 2023).

3.3.2. Just-About-Right (JAR)

Just About Right (JAR) scaling evaluates the appropriateness of specific sensory attributes from the consumer viewpoint (Rothman & Parker, 2009). Consumers indicate if a product attribute such as sweetness, aroma intensity, or texture is at an optimal level or deviates from their ideal. The JAR scale typically consists of 5 points ranging from too weak to too strong, with the midpoint indicating the attribute is just about right (Rothman & Parker, 2009).

JAR scaling is particularly important due to its practical relevance in product optimization. It provides explicit diagnostic information highlighting attributes requiring adjustment to align with consumer ideals (Li et al., 2014). By directly identifying sensory attributes that deviate from consumer preferences, researchers can effectively guide targeted product adjustments, improving consumer acceptance and satisfaction. Hence, JAR scales are valuable in strategically refining products toward ideal sensory profiles (Paries et al., 2022).

3.3.3. Check-All-That-Apply (CATA)

Check All That Apply (CATA) methodology gathers consumer perceptions by having participants select all attributes applicable to a product from a predefined attribute list (Ares et al., 2017). Consumers freely select terms accurately describing their perceptions, such as sweet, creamy, bitter, or fresh, enabling rapid characterization of consumer sensory profiles.

The importance of CATA lies in its simplicity, speed, and ability to capture rich descriptive information directly from consumers. It effectively captures consumer perceptions without requiring extensive training, providing immediate insights into consumer-defined product profiles. CATA data supports efficient product profiling, comparison of sensory characteristics, and identification of consumer-defined attributes associated with liking or disliking (Vigneau et al., 2022). Thus, it is extensively used to quickly gather robust sensory data, directly informing product formulation, consumer segmentation, and market positioning (Ares & Jaeger, 2023).

3.3.4. Package Design Analysis

Package design analysis examines how visual and structural packaging elements influence consumer sensory expectations, perception, and purchase behaviour (Shirai, 2025). As packaging serves as the first point of interaction between a product and the consumer, its design significantly shapes consumer assumptions regarding product quality, flavour, and overall sensory experience before consumption (Ghorbani & Westermann, 2025; Srivastava et al., 2022). This method involves systematically evaluating how various packaging cues such as colour, shape, texture, graphics, and typography impact consumer interpretation and hedonic response.

Consumer-based package design testing typically integrates methods such as conjoint analysis, visual preference mapping, and eye tracking, often in combination with sensory and emotional profiling (Ye et al., 2020). Eye tracking is particularly valuable in capturing real-time visual attention and identifying which packaging elements consumers focus on, providing objective data on decision-making processes (Motoki et al., 2021).

The importance of package design analysis lies in its direct influence on consumer expectations and purchase intent. Effective packaging aligns consumer expectations with the actual sensory attributes of the product, reducing disconfirmation and enhancing satisfaction. In highly competitive markets, optimizing package design not only supports brand differentiation but also reinforces product identity and improves overall consumer experience (Álvarez-González et al., 2024; Poslon et al., 2021). Consequently, packaging design analysis is an essential component in sensory-driven product development and marketing strategy.

3.4. Reality-Virtuality continuum and Virtual Reality (VR)

The Reality Virtuality continuum (Figure 1) represents a theoretical concept introduced by Milgram & Kishino (1994) to systematically categorize immersive experiences spanning between fully real and entirely virtual environments. According to this continuum, experiences can be arranged on a linear spectrum starting from Reality, progressing through various forms of Mixed Reality, and ultimately culminating in complete Virtuality. Reality involves the purely physical environment, directly perceived through human senses without technological mediation. Mixed Reality occupies intermediate points on this continuum, incorporating varying degrees of real and virtual elements. Augmented Reality, situated closer to reality, integrates digital enhancements onto real environments. Conversely, Augmented Virtuality primarily consists of virtual environments supplemented by real-world inputs. At the far end of the spectrum lies complete Virtuality, entirely computer-generated and isolated from physical sensory cues. Understanding this continuum assists researchers in clearly defining methodological choices and situating experimental setups precisely within the broader framework of immersive technologies.

VR refers specifically to immersive digital environments created using computer graphics and interactive technologies. It is characterized by real-time interaction, sensory immersion, and presence within digitally generated scenarios (Rubio-Tamayo et al., 2017). Presence describes users feeling psychologically immersed and spatially located within virtual environments, perceiving and interacting realistically despite being physically elsewhere (Velichkovsky, 2017). VR typically employs specialized hardware such as head mounted displays to visually isolate users from external environments, controllers for interaction, and spatial audio systems to enhance immersion (Oyedokun et al., 2024). Essential attributes distinguishing VR from other technologies include total sensory immersion, spatial interactivity, and user-centred design, ensuring environments respond dynamically to user actions and behaviours (Oyedokun et al., 2024).

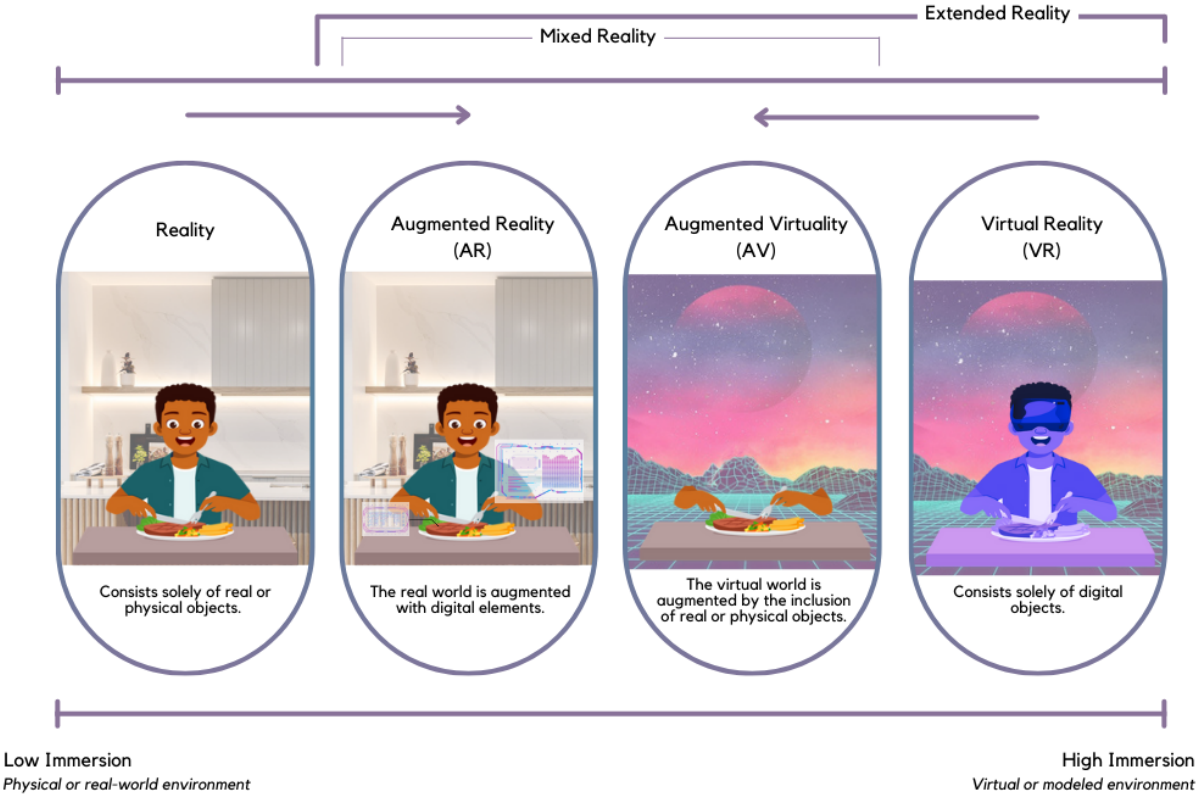


Figure 1: Illustration of Reality-Virtuality Continuum in a concept of sensory and consumer science inspired by Milgram & Kishino (1994).

VR technology offers significant advantages within research contexts, providing controlled yet realistic environments previously challenging or impossible to replicate physically. Researchers can systematically manipulate virtual scenarios, enabling precise control over experimental variables such as context, stimuli presentation, and environmental conditions (Radianti et al., 2020). Moreover, VR facilitates repeated exposure to standardized sensory experiences across different participants, improving reproducibility and reliability in sensory testing (Gere, Zulkarnain, et al., 2021). Consequently, the use of VR technology considerably enhances ecological validity in sensory and consumer research, bridging gaps between laboratory findings and real-world consumer experiences.

3.5. Virtual Reality (VR) in Sensory Analysis

VR is increasingly recognized as a valuable methodological advancement within sensory analysis, enhancing realism, control and ecological validity of consumer sensory studies (Zulkarnain, Kókai, et al., 2024a). Traditional sensory research often struggles to replicate realistic consumption contexts, which can significantly influence consumer perceptions and preferences. Incorporating VR directly addresses this limitation by allowing researchers to create immersive virtual environments closely resembling authentic consumer experiences (Zulkarnain, Kókai, et al., 2024b). Consequently, sensory data obtained through VR provide greater external validity, improving the predictive accuracy of consumer responses toward products in real market conditions.

The primary importance of VR in sensory analysis lies in its ability to deliver consistent yet contextually realistic experimental scenarios. Conventional sensory evaluations frequently occur in sterile laboratory settings devoid of contextual cues, diminishing the representativeness of obtained results. VR facilitates accurate simulation of contextual details such as visual atmosphere, auditory cues and situational dynamics influencing sensory perception. These immersive scenarios can influence psychological and emotional states, significantly altering product evaluations by activating associative memory and contextual expectations. As a result, sensory responses captured in VR are more indicative of genuine consumer experiences compared to traditional evaluations (Kamal et al., 2024; Zulkarnain, Cao, et al., 2024).

Moreover, VR technology affords researchers the capacity to precisely manipulate experimental variables, ensuring rigorous methodological control without compromising environmental authenticity. Adjustments of contextual factors including lighting, ambient sounds, product placement and virtual social interactions become easily manageable within VR settings (Maymon et al., 2023). Such flexibility enables systematic exploration of contextual influences on sensory perception, facilitating deeper understanding of consumer behaviour mechanisms. Researchers can methodically examine how specific environmental conditions modify product perceptions, hedonic liking, and ultimately influence consumer decision making processes (Motoki et al., 2019).

Integration of VR further expands possibilities in cross modal sensory research, effectively capturing interactions among various sensory modalities in realistic contexts (Wu et al., 2022). Multisensory interactions fundamentally shape consumer perception and preference, with visual, auditory and tactile stimuli dynamically influencing taste and aroma perceptions. Through immersive VR, researchers systematically introduce controlled multisensory stimuli alongside products, reliably observing changes in sensory perception triggered by specific environmental cues. Consequently, sensory studies utilizing VR become capable of accurately quantifying multisensory integration effects previously challenging to assess systematically in conventional laboratory conditions (Melo et al., 2022).

VR additionally contributes toward improving consumer engagement and attention during sensory evaluations. Compared to traditional environments, immersive virtual scenarios increase participant motivation, attentiveness and involvement through heightened cognitive engagement (Man et al., 2024). Improved participant immersion reduces external distractions, allowing more accurate and consistent sensory judgments. Enhanced engagement directly translates into higher quality sensory data with reduced variability attributable to participant inattention or fatigue (Man et al., 2025).

Beyond methodological improvements, VR fundamentally shifts the analytical scope of sensory studies, generating novel data streams complementing traditional sensory ratings. Combining VR with advanced biometric technologies, such as ET, further enriches sensory evaluations, capturing physiological and behavioural indicators alongside subjective sensory responses (Crofton et al., 2019a). Such multidimensional data collection provides comprehensive insight into consumer cognitive and emotional states during sensory assessments. Hence, VR facilitates development of innovative sensory methodologies, encompassing novel data analytical approaches capable of extracting deeper consumer behaviour insights (Zulkarnain, Kókai, et al., 2024a).

VR significantly enhances traditional sensory analysis methodologies by delivering controlled yet realistic sensory environments, improving ecological validity, increasing consumer engagement, enabling systematic multisensory integration studies, and broadening analytical potential through novel biometric data integration (Schouteten et al., 2024). Consequently, VR technology emerges as a critically important methodological innovation within sensory science, transforming contemporary understanding of consumer sensory perception and evaluation (Crofton & Botinestean, 2023).

3.6. Applications of VR in Sensory Research

VR technology offers diverse applications in sensory research by providing realistic and immersive environments that closely replicate real-world experiences. Researchers can precisely manipulate contextual variables, systematically examine consumer behaviours, and capture authentic sensory responses, which enhances the validity and reliability of sensory data (Table 1). The flexibility and interactivity provided by VR significantly improves the predictive accuracy of consumer evaluations, offering novel insights previously challenging to achieve using traditional sensory analysis approaches (Bhavadharini et al., 2023).

Table 1: VR application in sensory analysis practices.

	Findings	References
Investigating the impact of context	VR can simulate different eating environments, such as restaurants or home settings, to study how contextual factors influence sensory perception and consumer behaviour	Oliver & Hollis (2021)
	The emergence of virtual and augmented reality technologies has presented new opportunities to enhance sensory marketing efforts in the food industry. VR can provide immersive and interactive user experiences, highlighting its potential to influence consumer sensory experiences.	Crofton et al. (2019)
	The use of multi-sensory cues in VR contexts can enhance presence and engagement, potentially affecting sensory perception of food.	Song et al. (2022)
Cross-modal correspondence	This study shows that VR enhances food liking when the eating environment matches the product, such as watermelon in summer or chocolate truffle in winter. While emotions remained stable, high engagement was reported. VR offers a realistic, controlled tool to study contextual influences in sensory food evaluation.	Schouteten et al. (2024)

Assessing product acceptability	VR settings impacted on consumers' wine tasting encounters, approval, and emotional reactions is explored in this study. The research underscores the development of a simulated virtual environment within a controlled laboratory arrangement for the sensory assessment of wine offerings, highlighting the prospect for VR to shape both the acceptance of products and the overall experiences of consumers.	Torrico et al. (2020)
	VR environments give an impact on the sensory perception of beef steaks and chocolate. It underscores the significant interest among researchers in exploring methods to replicate consumption contexts in the sensory evaluation of foods, with the goal of enhancing the ecological validity of consumer data. The findings suggest that VR holds the potential to affect product acceptability by generating immersive sensory experiences.	Crofton et al. (2021)
	Level of environmental immersion affects hedonics, perceived appropriateness, and willingness to pay in alcoholic beverages. It underscores the capability of VR in sensory evaluation to engage participants in a real-world scenario while maintaining a controlled environment. This highlights the potential of VR to influence both product acceptability and consumer preferences.	Picket & Dando (2019)
Enhancing sensory training	The potential of VR for the enhancement of emotion regulation, emphasizing the opportunity to manipulate sensory stimuli and provide exposure to multiple contexts, suggesting the potential for VR to enhance sensory training by providing exposure to diverse sensory contexts.	Colombo et al. (2021)
Investigating sensory disorders	VR can be employed to study sensory disorders and their impact on food perception. For instance, VR has been used to assess sensory and motor functions in children with developmental disorders.	Lestari et al. (2022)
Exploring novel food experiences	VR can create immersive and interactive experiences that allow individuals to explore novel food sensations and flavours. It has been used to simulate unique food experiences, such as tasting virtual chocolates or exotic cuisines	Kong et al. (2020)

	Explores a novel VR food choice task, demonstrating the potential for VR to create novel sensory experiences and assess basic valuation processes in food choice.	Van Der Laan et al. (2022)
Understanding consumer preferences	Explores the impact of technology interface and product type on consumer responses, emphasizing the preference for a novel, vivid, and visually rich sensory environment that offers a multisensory shopping experience and enhances cognitive and affective responses. This highlights the importance of creating immersive and visually appealing experiences to influence consumer preferences and responses.	Mishra et al. (2021)
	Explores consumer perceptions and purchase behaviour toward imperfect fruits and vegetables in an immersive VR grocery store, indicating the potential for VR to influence consumer behaviour and preferences in the context of food choices. This highlights the applicability of VR in studying consumer preferences and purchase behaviour in virtual environments.	Lombart et al. (2019)
	Effectiveness of VR as a tool for promoting pro-environmental dietary change, indicating the potential for VR to influence consumer behaviour and food preferences. This suggests that VR can be used to shape consumer preferences and behaviours in the context of food choices and consumption.	Plechatá et al. (2022)
Understanding consumer emotions	The impact of VR sensory evaluation on participants' emotional states is notable, showcasing a significant influence on their assessments. The findings indicate a rise in the overall positive effects and a reduction in the negative ones.	Zulkarnain et al. (2024)
Assessment of the VR environment	VR sensory laboratory can serve as a useful resource for sensory scientist and consumer intrigued in investigating the emerging opportunities provided by VR. The virtual laboratory had demonstrated its potential application in the food industry, particularly in sensory science.	Zulkarnain, Kókai, et al. (2024a)

The versatility of VR technology substantially extends the boundaries of traditional sensory research, allowing deeper exploration into complex sensory and consumer behavioural dynamics. As VR applications evolve, their integration within sensory studies is anticipated to continue growing, unlocking new methodological possibilities and enhancing both the depth and scope of sensory science research (Zulkarnain & Gere, 2025).

3.7. Augmented Virtuality (AV) and its Possible Role in Sensory Analysis

Augmented Virtuality (AV) represents an intermediate state within the Reality Virtuality continuum, characterized by embedding real world sensory stimuli into predominantly virtual environments (Zulkarnain et al., 2024). Unlike Augmented Reality, which introduces virtual components into real environments, AV incorporates real objects or sensory elements into computer generated virtual scenarios. This integration provides controlled yet realistic sensory experiences, enabling researchers to maintain precise experimental manipulation while achieving higher sensory realism and ecological validity in sensory evaluations (Zulkarnain et al., 2024).

In sensory science, AV allows for controlled exposure to authentic sensory stimuli, such as actual food samples or real aromas, within immersive virtual settings. Researchers can systematically manipulate virtual context conditions while directly engaging consumer senses with tangible, real products. This approach accurately captures consumer perceptions and preferences under realistic consumption contexts, offering valuable insights unattainable through purely virtual or traditional sensory evaluation techniques (Ribeiro et al., 2024).

AV holds value in studying multisensory integration by facilitating simultaneous control and realistic representation of multiple sensory modalities. Researchers can investigate precisely how sensory interactions between real and virtual stimuli shape consumer perceptions, attention patterns and acceptance. This capability is particularly beneficial in examining sensory dominance, cross modal effects and the influence of contextual stimuli on consumer sensory processing. The flexibility provided by AV thus significantly enhances the exploration of complex sensory mechanisms driving consumer responses (Gonzalez et al., 2021).

The technology further promotes participant engagement and reduces sensory fatigue commonly observed in traditional evaluations, as realistic interactions with actual sensory stimuli embedded in virtual contexts encourage active consumer participation. By improving immersion and authenticity, AV effectively addresses traditional sensory evaluation challenges, increasing data reliability and enhancing consumer response accuracy (Long et al., 2023).

AV presents substantial methodological opportunities within sensory research, allowing deeper understanding of consumer sensory perceptions, multisensory integration and contextual influences, through realistic yet precisely controlled experimental environments (Chai et al., 2022). Despite its potential, AV faces challenges related to seamless real-virtual integration, latency issues, and the need for advanced haptic and olfactory feedback systems (Long et al., 2023; Ribeiro et al., 2024). However, as technology advances, AV is expected to become a powerful tool in sensory science, bridging the gap between traditional sensory evaluation and fully immersive VR-based research, offering realistic yet controlled sensory experiences for food science, consumer psychology, and market research applications (Zulkarnain et al., 2024).

3.7.1. Conceptual Introduction of Augmented Virtuality (AV) in Sensory Analysis

3.7.1.1. Concept and Key Components of Augmented Virtuality

Creating an augmented virtuality (AV) study involves looking at its key parts (Figure 2), which are System Development, Response Measurement, and Environment and Test Samples. These parts are like building blocks that help researchers get a better understanding of the components needed as shown in the concept in Figures 2 and 3.

Zulkarnain, Kókai, et al. (2024b) have developed an application on Virtual Reality (VR) that can potentially transformed into an AV application. They suggest that VR Sensory booths can be utilized to create immersive experiences by incorporating different sensory methods in various environments. The place of measurement AV can easily be an empty table with a white or green background, so it masks the test samples or objects in the virtual environment. This approach can significantly enhance the development of AV applications, paving the way for more realistic and engaging user experiences.

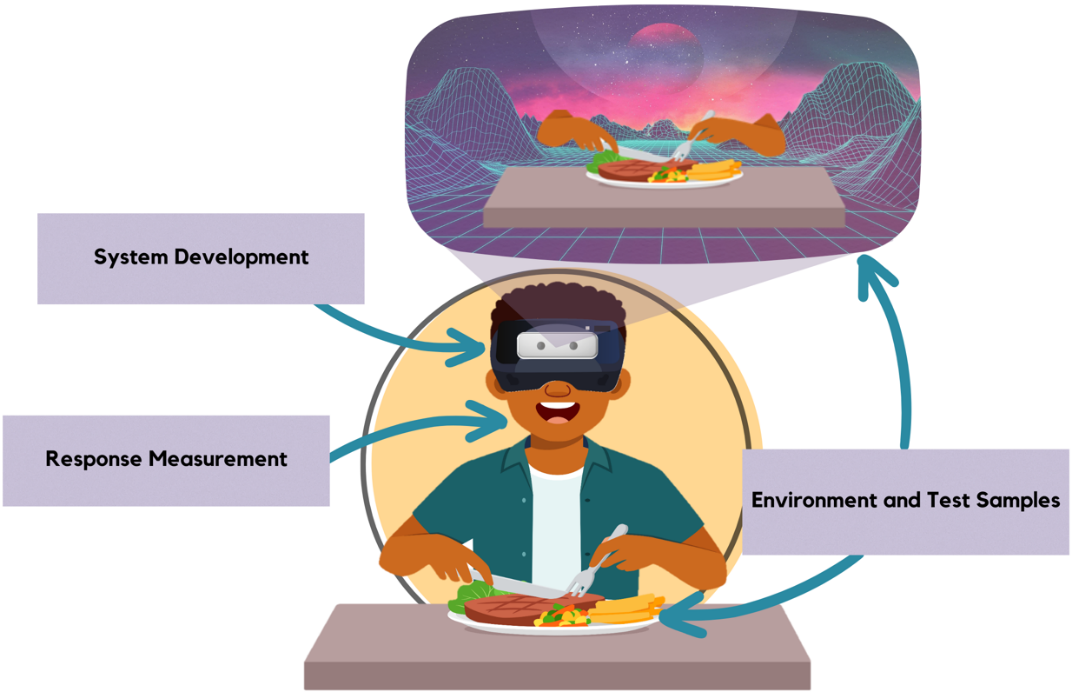


Figure 2: Augmented Virtuality key components that should be considered.

3.7.1.2. AV System Development: Hardware, Software, and Sensor Integration

In the comprehensive system development of AV, a various approach is adopted with some examples of picture or graphical representation in Figure 3, intertwining hardware components, and software applications, and integrating tracking devices or sensors into the framework to enable precise spatial mapping and interaction, thereby constructing a seamless and immersive virtual environment for users to engage with.

Head Mounted Displays (HMDs) are wearable devices resembling glasses that are utilized in Virtual Reality (VR) and Augmented Reality (AR) applications. These devices offer immersive experiences by displaying virtual content or introducing additional elements into the real world (Ukai et al., 2021). Examples include HTC Corporation (Xindian, New Taipei, Taiwan), Meta

Platforms Technologies (Menlo Park, California, U.S.), and Pico Immersive Pte. Ltd. (Tokyo, Japan). Head-mounted displays (HMDs) are highly suitable for Augmented Virtuality (AV) as they enable users to perceive and engage with virtual and real elements concurrently. When conducting AV research that emphasizes sensory experiences with actual products, the main objective is typically not to sustain an uninterrupted perception of the physical environment. Instead, the focus is on controlling or enhancing the perception of the actual product within a virtual environment. Immersive virtual reality head-mounted displays (HMDs) can effectively accomplish this by providing precise manipulation of both auditory and visual stimuli. This capability allows researchers to isolate and study specific sensory elements of the product. While Mixed Reality (MR) cameras are also crucial in AV. They blend real-life scenes with computer-generated images, making augmented reality more realistic (Khatib et al., 2021). Examples include Stereolabs Inc. (San Francisco, U.S.) and Intel RealSense Technology (Santa Clara, California, U.S.). However, nowadays, most HMDs come with MR cameras already integrated.

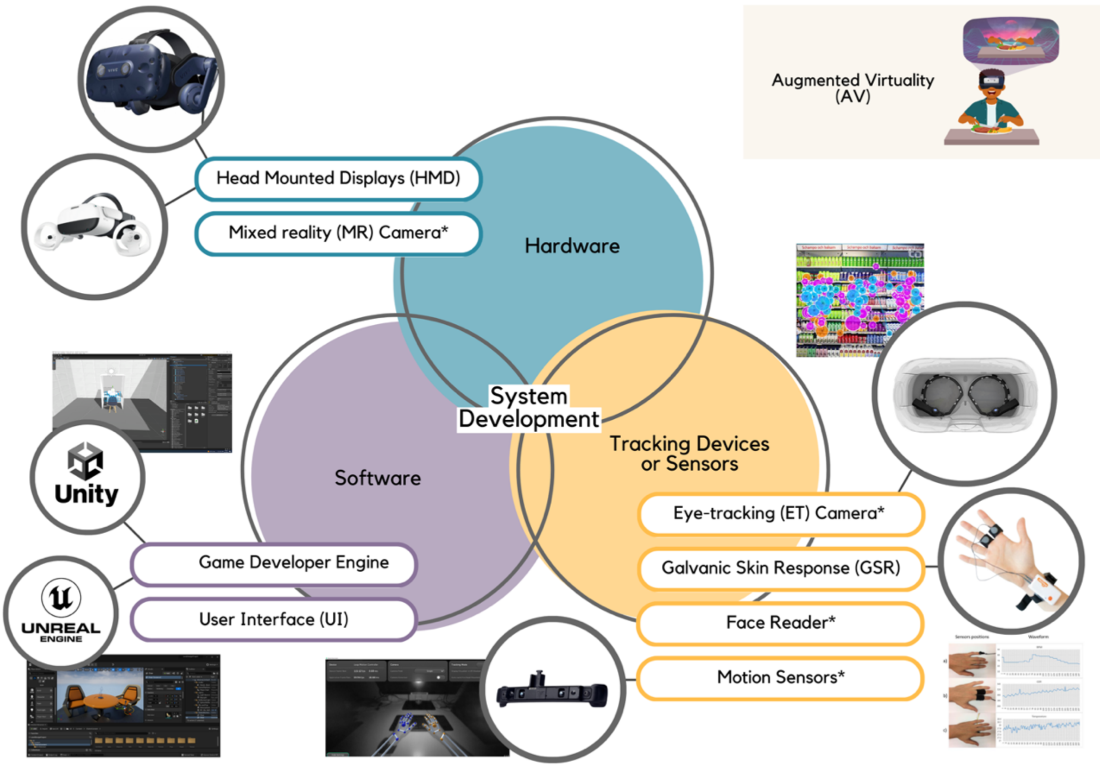


Figure 3: The system development on hardware components, software applications and integrating tracking devices or sensors with some examples of picture or graphical representation. (*Not necessary to have as they are built into some of the Head Mounted Displays)

Software, especially game development engines, is crucial in making AV experiences. These tools help make video games by coding, designing graphics, adding sound, and managing game parts (Chia et al., 2020). Unreal Engine, developed by Epic Games, Inc. (Cary, North Carolina, U.S.), and Unity from Unity Technologies (San Francisco, California, U.S.) are some examples of software for VR. These engines have strengths and weaknesses for AV development. Based on the studies (Zulkarnain, Kókai, et al., 2024a, 2024b), Unreal Engine excels in delivering photorealistic graphics and immersive experiences, making it ideal for projects that require high visual fidelity and realism. However, its steep learning curve may pose challenges for beginners. Unity, on the other hand, prioritizes accessibility and rapid development, making it a popular choice for indie developers and small teams. Its user-friendly interface and extensive documentation make it easier for newcomers to get started with AV development. While Unity may not offer the same level of graphical fidelity as Unreal Engine out of the box, its flexibility and ease of use make it a compelling choice for projects where time-to-market and iteration speed are crucial factors.

Tracking Devices or Sensors are tools used to gather data about how people interact with things in AV. Eye-tracking cameras follow where people look at, helping understand how people choose food or products (Gere, Héberger, et al., 2021). Examples include Tobii AB (Danderyd Municipality, Sweden) and iMotions A/S (Copenhagen, Denmark). Another sensor are Galvanic Skin Response (GSR) sensors which measure electrical changes in skin to understand emotions or reactions to food (Tonacci et al., 2019), such as, Shimmer Research Ltd (Dublin, Ireland), Maxim Integrated Products Inc (San Jose, California, U.S.), and Mindfield Biosystems Ltd (Gronau, Germany). Face readers interpret facial expressions to discern emotions or traits, utilizing facial expression analysis technology such as facial electromyograms and facial gesture recognition, to enable hands-free user interfaces and immersive social interactions within virtual reality environments (Cha & Im, 2022). Most HMDs have a built-in face reader that tracks lip movement. Last but not least, motion sensors, track the movements of the user's body and head to translate them into corresponding actions within the virtual environment, enhancing immersion and interaction (Liliana et al., 2020). Examples include Magic Leap, Inc (Plantation, Florida, U.S.) and most HMDs also have a built-in front camera that tracks hand gestures. Tracking Devices or Sensors are essential components of AV development, enabling developers to gather valuable data on user interactions, physiological responses, and expressions. By leveraging this data, developers can create more engaging, personalized, and immersive AV experiences that effectively respond to user actions and emotions.

3.7.1.3. Response Measurement in AV Environments

Response Measurement, especially in food sensory analysis using AV technology, is crucial for advancing AV experiences. By accurately capturing and analysing participants' responses to virtual food stimuli, developers can improve the realism, effectiveness, and reliability of AV applications in food research and product development. AV technology transforms traditional evaluation methods by allowing virtual elicitation of responses from participants. Response Measurement is essential for enhancing the depth, accuracy, and reliability of sensory evaluation in AV development for food research and product development. By effectively capturing and analysing participants' responses, developers can create more immersive, engaging, and personalized AV experiences that drive innovation in the food industry and offer tailored sensory experiences to consumers.

Using VR headsets or immersive displays, individuals can interact with virtual food items, providing feedback on taste, aroma, texture, and appearance (Gagaoua et al., 2022). This method breaks geographical barriers, enabling data collection from diverse populations under controlled experimental conditions. Biometric technology, like measuring autonomic nervous system reactions, captures subconscious sensory and emotional responses to food stimuli, offering reliable assessments beyond conscious control (Biju et al., 2021).

Moreover, AV can revolutionize sensory analysis tests such as preference tests, triangle tests, just-about-right, check-all-that-apply (Ares & Jaeger, 2015), or rate-all-that-apply methods (Ares et al., 2014) by simulating real-world environments. Through interactive virtual platforms, participants can evaluate food attributes authentically, enhancing engagement and flexibility in experimental design (Zulkarnain, Kókai, et al., 2024b). Statistical analysis techniques, like multivariate analysis methods, help uncover patterns and correlations in participants' responses, providing a comprehensive understanding of sensory perception and interaction with virtual food stimuli (Crofton et al., 2019).

Motion sickness and system development questionnaires in AV can be essential for understanding issues like simulator sickness, system faulty and the environment. Some examples of questionnaires like SSQ (Simulator Sickness Questionnaire) (Kennedy et al., 1993), ARSQ (Augmented Reality Sickness Questionnaire) (Hussain et al., 2023), VRSQ (Virtual Reality Sickness Questionnaire) (Kim et al., 2018), and PANAS (Positive and Negative Affect Schedule) (Watson et al., 1988) measure participants' comfort levels and overall experiences. These tools help assess how comfortable people feel when using AV technology, which is crucial for ensuring a positive user experience. By collecting responses through these questionnaires, researchers can identify factors that contribute to discomfort and make improvements to enhance comfort and usability. Studies on VR have shown that comfort plays a significant role in how people perceive and interact with virtual environments (Zulkarnain, Cao, et al., 2024; Zulkarnain, Kókai, et al., 2024a, 2024b). By measuring responses through questionnaires like SSQ, ARSQ, VRSQ, and PANAS, researchers can gain valuable insights into the importance of comfortability in AV experiences. This understanding can guide the development of more user-friendly and enjoyable AV applications in the future.

Overall, AV technology, combined with biometric and statistical analysis, enhances the depth and accuracy of sensory evaluation in food research, leading to innovative product development and personalized sensory experiences.

3.7.1.4. Perceptual Differences and User Expectations in AV.

In exploring augmented virtuality (AV) for food sensory evaluation, both real and virtual environments are crucial. Real settings provide tangible sensory cues like texture, aroma, and appearance, adding authenticity to food assessment. Virtual environments offer flexibility and control, allowing researchers to simulate different scenarios and manipulate sensory factors. Combining both realms optimizes sensory testing by blending the realism of physical settings with the adaptability of virtual simulations. Since AR technologies have been used in gastronomy to compare visual expectations of real and virtual food products (Çöl et al., 2023), it is also can be used in AV.

Sound and real products (refer as object) are key in AV food sensory evaluation. Sound influences perception, affecting taste, texture, and overall sensory experience. Adding ambient sounds from real or simulated environments enriches sensory testing, enhancing immersion and authenticity. Objects contribute to the touch and the feel of presence aspects of food evaluation, influencing perceptions through interactions and sight. Integrating these elements in AV environments helps capture comprehensive sensory assessments, reflecting diverse responses and preferences (Wang et al., 2021). Additionally, nanowire-based soft wearable interfaces have been developed to enhance the sensory experience in virtual and augmented reality applications (Wang et al., 2021).

Regarding food products, AV sensory testing covers a range from beverages and snacks to complex dishes. Each product has unique sensory traits, allowing researchers to explore taste, aroma, appearance, and texture. By selecting various food items, researchers can assess the versatility of AV technology across culinary experiences, enriching sensory science and consumer insights. Virtual and augmented reality technologies show potential in sensory science, especially in studying meal choices and testing usability in a virtual reality food court (Lombart et al., 2019). Moreover, these technologies relate to consumer consciousness in multisensory extended reality, emphasizing their impact on perception and psychology (Petit et al., 2022).

In AV food sensory evaluation, test samples span various food products, from beverages and snacks to complex dishes. Each product offers distinct sensory features, enabling researchers to investigate into taste, aroma, appearance, and texture. By including a diverse array of test samples, researchers can gauge the versatility of AV technology across culinary experiences, enhancing sensory science and consumer understanding.

3.8. Eye-Tracking (ET) in Sensory Research

ET technology is increasingly recognized as a valuable and innovative approach within sensory research, offering objective insights into consumer visual attention, cognitive processes and decision-making behaviours (Orquin & Loose, 2013; Yüce, 2024). ET technology involves capturing and recording eye movements, including fixation, gaze duration, saccades and pupil dilation. These measurements provide reliable indicators of attention allocation, cognitive load and emotional engagement during sensory evaluation tasks (Motoki et al., 2021). By accurately quantifying visual attention, ET contributes significantly toward understanding the mechanisms driving sensory perception, expectation biases and product acceptance among consumers (Guo et al., 2016).

In sensory analysis, visual cues often strongly influence consumer perceptions, expectations and product acceptance. ET is particularly effective for measuring these visual influences objectively by quantifying the exact points where consumers visually focus during product evaluations. ET captures subtle visual behaviours, offering deeper understanding into how consumers perceive and process product labels, packaging designs and overall product presentation (Szakál, Fekete-Frojimovics, et al., 2023). This understanding allows researchers to better interpret consumer sensory data and effectively identify visual factors that significantly impact consumer responses (Motoki et al., 2021).

The fundamental parameters recorded in ET studies typically include fixations, saccades and gaze duration (Danner et al., 2016). Fixation refers to the maintenance of visual attention on a specific area or object, measured by fixation count and duration. Areas receiving more or longer fixations generally indicate greater visual interest or higher cognitive involvement. Gaze duration captures the total time a consumer visually engages with stimuli or areas, providing insights into sensory or visual complexity. Longer gaze durations commonly correlate with greater cognitive processing or difficulty during decision making (Szakál, Zulkarnain, et al., 2023). ET metrics thus objectively reflect underlying cognitive processes associated with sensory evaluation, facilitating precise interpretation of consumer attention patterns toward visual product characteristics such as packaging, colour, and labelling details (Motoki et al., 2021).

ET in sensory research provides robust evidence regarding expectation biases triggered by visual stimuli. Consumers inherently possess preexisting expectations about products based on visual cues including packaging, branding, colour and presentation style. These visual expectations significantly shape sensory perceptions, hedonic evaluations and ultimate product acceptance (Szakál, Fekete-Frojimovics, et al., 2023). ET allows precise measurement of how visual attention patterns form and influence expectation biases, providing objective evidence for understanding and managing consumer expectations strategically. Researchers can then leverage this information to optimize packaging design, labelling strategies or product presentations to enhance consumer perceptions and satisfaction (Modi & Singh, 2024).

Furthermore, ET contributes substantially to understanding the cognitive processes underlying sensory evaluations. Consumer attention patterns directly reflect cognitive involvement, decision making strategies and sensory processing. The ET data reveal cognitive load, indicating areas or stimuli requiring greater cognitive effort or information processing (Sun et al., 2022). Increased fixation counts or longer gaze durations typically correspond to higher cognitive load or interest, signifying areas particularly influential for consumer decisions. Understanding cognitive load through ET metrics helps researchers optimize product presentations, streamline sensory attributes and improve consumer experiences, resulting in more positive product evaluations (Mormann et al., 2020).

In addition to visual attention measurement, ET also serves as a predictive tool for consumer choice behaviour. Research demonstrates strong correlations between visual attention patterns and subsequent purchase decisions, indicating that eye movement data effectively predict consumer choice (Agost & Bayarri-Porcar, 2024). Specific visual metrics including first fixation location, gaze duration and revisit frequencies reliably forecast consumer preferences and choices (Van Der Laan et al., 2015; Van Loon et al., 2022). Thus, integrating ET metrics into sensory studies improves predictive accuracy regarding consumer purchasing behaviours, directly linking visual engagement patterns with product acceptance and market performance (Szakál, Zulkarnain, et al., 2023).

The integration of ET with VR significantly expands possibilities within sensory research by providing precise measurement of consumer visual behaviours in realistic, immersive contexts (Gere, Zulkarnain, et al., 2021). ET embedded within VR headsets captures natural visual attention patterns, offering detailed data on how consumers visually explore and interact with virtual product presentations and immersive environments (Adhanom et al., 2023). The immersive nature of VR influences visual attention uniquely compared to traditional sensory settings, affecting cognitive load, sensory perceptions, and consumer expectations (Zulkarnain, Kókai, et al., 2024b). Combining ET with VR enables researchers to systematically examine these influences, providing enriched data linking visual attention directly to sensory ratings, decision making, and product acceptance under realistic contextual conditions. This methodological integration generates novel insights, strengthening ecological validity, and significantly advancing sensory evaluation techniques (Josupeit, 2023).

3.9. Questionnaires Used in Sensory and Immersive Research

Questionnaires represent essential tools in sensory and immersive research, systematically capturing subjective experiences, attitudes, perceptions, and physiological symptoms from participants (Putze et al., 2020). Questionnaires provide structured, standardized methods to quantify complex subjective phenomena, ensuring reliable, valid, and interpretable data (Hahn-Klimroth et al., 2024). Within sensory research involving VR, specialized questionnaires evaluate diverse factors including sensory perception, immersion, presence, emotional states, cognitive load, and simulator sickness (Zulkarnain et al., 2024). The classification of the following instruments as prominent is based on their frequent application in immersive sensory science studies and repeated citation across leading publications in the field. The VR Sickness Questionnaire (VRSQ), VR Neuroscience Questionnaire (VRNQ), Simulator Sickness Questionnaire (SSQ), and Positive and Negative Affect Schedule (PANAS) are among the most widely adopted and validated tools in recent immersive research. Each targets specific constructs that are critical for the comprehensive analysis of consumer sensory responses, cognitive engagement, and overall user experience in virtual environments.

3.9.1. Virtual Reality Sickness Questionnaire (VRSQ)

The Virtual Reality Sickness Questionnaire (VRSQ) by Kim et al. (2018) measures discomfort symptoms experienced during or after VR exposure, including general discomfort, fatigue, headache, dizziness, eyestrain, and nausea. Symptoms are rated on a scale from "none" to "severe," providing a direct measure of participant susceptibility to VR-induced discomfort. High VRSQ scores indicate increased physiological strain, prompting researchers to modify VR system settings, exposure durations, and task complexity to reduce discomfort. VRSQ is essential for improving VR-based sensory research by enhancing participant comfort and ensuring more reliable sensory data (Kim et al., 2018).

3.9.2. Virtual Reality Neuroscience Questionnaire (VRNQ)

Kourtesis et al. (2019) introduced the Virtual Reality Neuroscience Questionnaire (VRNQ) to assess the suitability and quality of VR software, particularly for research and clinical applications. The VRNQ comprises four main domains: user experience, game mechanics, in-game assistance, and VR-induced symptoms and effects (VRISE). Each domain includes five items rated on a 7-point Likert scale, where higher scores reflect better performance or fewer symptoms. For example, the user experience domain captures immersion, presence, and overall satisfaction, while the VRISE domain evaluates the severity of symptoms such as nausea or dizziness. The questionnaire enables researchers to identify strengths and limitations of VR applications, helping to optimise software design, minimise discomfort, and improve ecological validity in immersive sensory evaluations (Kourtesis et al., 2019).

3.9.3. Simulator Sickness Questionnaire (SSQ)

The Simulator Sickness Questionnaire (SSQ) concept introduced by Kennedy et al. (1993) measures symptoms related to simulator sickness in VR environments, including nausea, oculomotor disturbances, and disorientation. It consists of 16 items rated on a severity scale, quantifying sickness intensity. High SSQ scores correlate with impaired sensory attention, reduced sensory accuracy, and participant discomfort, requiring adjustments in visual fidelity, interaction methods, and environmental settings. SSQ is widely used to improve VR usability and ensure more reliable sensory data by mitigating VR-induced sickness effects (Kennedy et al., 1993).

3.9.4. Positive and Negative Affect Schedule (PANAS)

Watson et al. (1988) developed the Positive and Negative Affect Schedule (PANAS) to measure emotional states across two distinct dimensions: positive affect and negative affect. The questionnaire consists of two 10-item subscales, each representing specific emotional descriptors. Participants are asked to rate how strongly they have experienced each emotion such as excitement, interest, anxiety and distress using a 5-point Likert scale (1 = very slightly or not at all, 5 = extremely). Positive affect reflects emotions that enhance sensory engagement and increase product liking, whereas negative affect includes emotions that may reduce sensory acceptance and distort perception. Incorporating PANAS in sensory and VR evaluations helps researchers better understand and manage emotional contexts, leading to more accurate interpretations of sensory data and improved product optimisation strategies aligned with consumer emotional responses (Watson et al., 1988).

3.10. Critical Evaluation of Previous Studies

The integration of immersive technologies in sensory research has been explored to enhance the ecological validity of sensory evaluations and capture subconscious consumer behaviours. Studies have shown that VR enhances sensory perception by simulating realistic consumption contexts, while ET provides objective insights into consumer attention and decision-making. However, critical analysis of previous research highlights inconsistencies in methodologies, challenges in sensory replication, and gaps in data reliability that need to be addressed to improve the accuracy of VR and ET-based sensory studies.

Several studies have demonstrated that VR increases the contextual relevance of sensory evaluations by simulating realistic environments such as restaurants, supermarkets, and kitchens. Environmental cues like lighting, sound, and spatial settings have been shown to influence sensory perception and consumer preferences (Crofton & Botinestean, 2023). However, a key limitation is the inability of virtual stimuli to replicate real-world sensory inputs accurately. While visual and auditory cues can be simulated effectively, taste, aroma, and texture remain challenging to reproduce. Some studies have combined VR with real food samples to enhance sensory realism, but synchronisation between virtual and physical stimuli remains difficult, often leading to mismatched sensory cues and biased responses (Schouteten et al., 2024; Torrico et al., 2020; Zulkarnain et al., 2024).

ET technology has provided valuable insights into subconscious visual attention patterns during sensory evaluations. Research shows that gaze fixation on specific visual cues, such as product labels, packaging, and colour, influences sensory expectations and consumer preferences (Motoki et al., 2021). However, gaze-tracking accuracy within VR remains a challenge due to head movement, calibration drift, and variations in display resolution, leading to inconsistent data (Qian & Teather, 2017). Differences between VR-based and desktop-based ET studies highlight variability in fixation duration, gaze distribution, and attention patterns, which reduces data reliability and comparability across studies (Adhanom et al., 2023).

Multisensory integration is another area of inconsistency. Studies have explored how visual and auditory cues in VR environments influence flavour perception, with findings showing that warm-coloured lighting enhances sweetness perception and background noise alters taste intensity (Chen et al., 2020; Dawes et al., 2023). However, individual differences in sensory adaptation and cognitive processing introduce variability in responses. Factors such as prior exposure to VR, susceptibility to cybersickness, and visual acuity further complicate the replicability of multisensory findings (Savickaite et al., 2022). The lack of consistency in experimental protocols, including differences in VR exposure duration and stimulus presentation, limits the generalizability of results (Basharat et al., 2023; Sadiq & Barnett-Cowan, 2022).

Research on cognitive load and sensory engagement within VR environments has produced mixed results. Some studies suggest that highly immersive environments enhance sensory perception by increasing emotional engagement and attentional focus, while others argue that excessive immersion leads to cognitive overload and decision fatigue, reducing sensory evaluation reliability (Bernal et al., 2024; Kia et al., 2024; Marucci et al., 2021). Different studies use varied instruments to measure cognitive load, including the Presence Questionnaire (PQ) and the Immersive Tendencies Questionnaire (ITQ), leading to inconsistencies in measuring cognitive engagement across studies. The impact of cognitive fatigue on sensory evaluation results remains poorly understood and requires further investigation (Liu & Zhang, 2024; Minkley et al., 2021; Skulmowski & Rey, 2020).

Standardization of methodologies for integrating VR and ET in sensory analysis remains a significant challenge. Studies vary widely in terms of VR hardware specifications, ET calibration procedures, and experimental designs (Ryabinin & Belousov, 2021). Some studies use high-end VR headsets with built-in gaze-tracking systems, while others rely on external ET devices, creating inconsistencies in data accuracy and reliability (Schuetz & Fiehler, 2022). Differences in frame rate, field of view, and rendering quality also affect participant comfort and sensory response accuracy (Lamb et al., 2022). Lack of uniformity in experimental protocols makes it difficult to compare findings and establish best practices for VR and ET-based sensory research (Hou et al., 2024).

Motion sickness is another critical issue affecting VR-based sensory research. Studies using the Simulator Sickness Questionnaire (SSQ) and the VR Sickness Questionnaire (VRSQ) have identified symptoms such as nausea, dizziness, and disorientation as common side effects of immersive VR exposure (Ng et al., 2020). These symptoms negatively affect sensory evaluation accuracy by altering taste perception and increasing participant discomfort. While some studies have attempted to minimise motion sickness through frame rate optimisation, reduced field of view, and shorter exposure times, individual susceptibility to VR sickness varies widely, complicating standardisation efforts (Zulkarnain, Cao, et al., 2024; Zulkarnain, Kókai, et al., 2024a).

Ethical considerations in VR and ET-based sensory research have received limited attention (Bye et al., 2019). ET technology records involuntary physiological responses such as pupil dilation and saccadic movements, raising concerns about data privacy and participant consent (David-John et al., 2021). The collection and analysis of such data create potential risks of participant discomfort and psychological distress, particularly during prolonged VR exposure (Wilson et al., 2024). Few studies provide clear guidelines on ethical best practices, including protocols for managing cybersickness, cognitive fatigue, and participant withdrawal from VR-based experiments (Thorp et al., 2024).

The use of immersive technologies in sensory research has demonstrated substantial potential in enhancing the ecological validity of sensory evaluations while providing objective insights into consumer behaviour (Zulkarnain et al., 2024). However, several limitations persist, including reduced sensory realism, inconsistencies in data collection methodologies, and challenges in achieving accurate and stable gaze tracking. In addition, concerns about cognitive and physical effects remain significant barriers. These include symptoms such as cybersickness, eye strain, disorientation, cognitive fatigue, and impaired attention, which can negatively impact participant comfort and data quality (Ugwitz et al., 2022). Addressing these challenges requires further refinement of experimental protocols, improved standardisation across studies, and better integration of multisensory inputs to ensure that VR and ET-based sensory evaluations produce reliable, replicable, and ecologically valid results (Bhavadharini et al., 2023; Crofton et al., 2019).

4. MATERIALS AND METHODS

4.1. Study Framework and Rationale

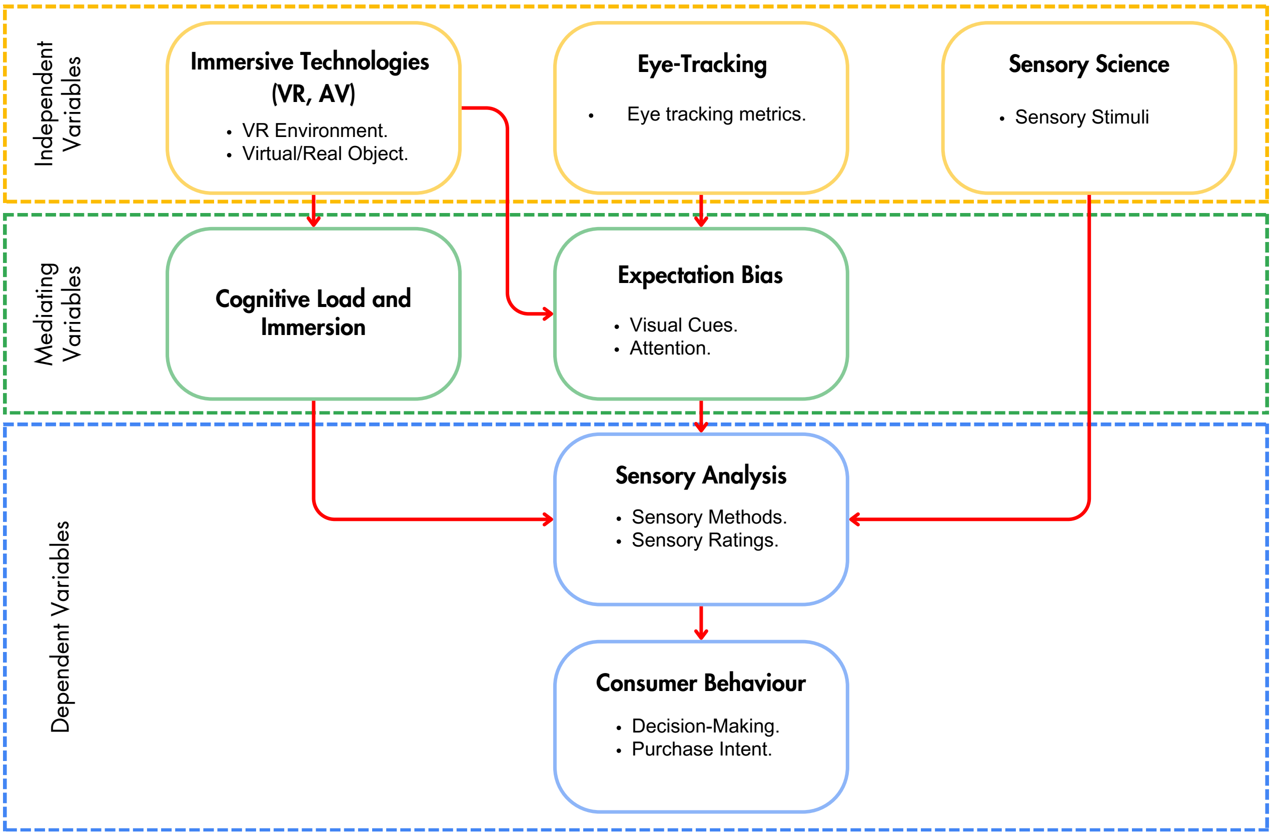


Figure 4: Study Framework and Rationale – The framework illustrates the relationships between independent variables (Immersive Technologies, Eye Tracking, and Sensory Science), mediating variables (Cognitive Load and Immersion and Expectation Bias), and dependent variables (Sensory Analysis and Consumer Behaviour). Immersive Technologies and Eye Tracking influence cognitive and sensory processing, subsequently affecting sensory perception and consumer decision making.

Figure 4 shows the study framework outlining complex interactions among Immersive Technologies, Eye Tracking, and Sensory Science in shaping Sensory Analysis and Consumer Behaviour. The framework comprises three levels of variables: independent, mediating, and dependent, each reflecting distinct aspects of the sensory evaluation process within immersive contexts. The primary aim is to evaluate how integrating Immersive Technologies and Eye Tracking enhances ecological validity in Sensory Analysis and provides deeper insight into consumer decision making and product acceptance.

Independent variables include Immersive Technologies, Eye Tracking, and Sensory Science. Immersive Technologies include Virtual Reality and Augmented Virtuality, utilizing Virtual Reality environments and virtual or real objects to create controlled yet realistic evaluation scenarios. These technologies enable simulation of authentic consumption contexts such as restaurants, markets, and homes, influencing how participants perceive and experience sensory stimuli. Eye Tracking objectively measures gaze behaviour metrics, including fixation duration, fixation count, and saccadic movements. Eye Tracking provides precise data about visual engagement with sensory stimuli and product attributes, capturing subconscious visual attention patterns that significantly influence sensory perception and preference. Sensory Science encompasses the nature and quality of sensory stimuli, such as taste, aroma, texture, and visual presentation, essential to accurately reflecting realistic consumption experiences within immersive testing environments.

Mediating variables, Cognitive Load and Immersion and Expectation Bias, critically mediate the influence of Immersive Technologies, Eye Tracking, and Sensory Science on Sensory Analysis and Consumer Behaviour. Cognitive Load and Immersion reflect mental engagement and demands experienced during sensory evaluations in immersive environments. High immersion levels enhance participant presence and engagement, promoting realistic sensory responses. However, excessive cognitive load resulting from overly complex virtual settings or multitasking scenarios may impair sensory focus and accuracy. Expectation Bias is influenced by visual cues and attention, whereby product packaging, colour, and branding shape participant sensory expectations and subsequent sensory ratings. For example, premium visual cues can result in higher sensory evaluations despite unchanged product attributes.

Dependent variables include Sensory Analysis and Consumer Behaviour. Sensory Analysis evaluates sensory ratings and responses using sensory evaluation methods such as nine-point hedonic scales, just about right scales, and check all that apply approaches. These methodologies offer quantitative and qualitative insights into participant perception of product sensory attributes and overall acceptance. Eye Tracking data often correlates fixations on specific attributes with elevated hedonic scores or altered sensory perceptions, such as perceived sweetness or freshness. Consumer Behaviour encompasses decision making and purchase intent, indicating how sensory perceptions translate directly into consumer choices. Combining Eye Tracking metrics and Sensory Analysis methods identifies clear relationships between visual attention patterns, sensory preference, and consumer product selections.

The framework highlights interactions among independent, mediating, and dependent variables clearly. Immersive Technologies and Eye Tracking directly influence Cognitive Load and Immersion and Expectation Bias, subsequently shaping Sensory Analysis outcomes. Sensory Analysis directly impacts Consumer Behaviour, influencing sensory judgments and product acceptance. The structured, integrated nature of this framework facilitates identifying recurring patterns linking visual attention, sensory perceptions, and consumer behaviours across immersive experimental settings. For instance, using Virtual Reality and Eye Tracking jointly clarifies how visual attention within immersive environments affects taste perception and purchasing decisions.

Overall, this study framework addresses methodological limitations inherent in traditional sensory research by systematically evaluating sensory perception in realistic, immersive environments. It enables deeper understanding of relationships among visual attention, sensory attributes, and contextual factors, significantly influencing consumer decision making. Systematic analysis of these interactions supports targeted product optimization, effective market positioning, and improved consumer targeting strategies. Ultimately, the integrated methodological approach ensures sensory data collected in immersive scenarios accurately represent real world consumption behaviours, significantly enhancing sensory research reliability and ecological validity.

4.2. Research Design and Methodological Approach

This study adopts a structured research design to evaluate the individual and combined effects of VR and ET in consumer sensory evaluations. The methodological approach is divided into two phases: the first phase focuses on the application of VR alone in sensory evaluation, while the second phase investigates the combined use of VR and ET. This design allows for the isolation of the independent effects of VR and ET, while also assessing their interactive influence on sensory perception, visual attention, and consumer decision-making. The study framework includes controlled exposure to VR environments simulating realistic consumption contexts, real-time recording of ET data, and sensory evaluation using established methods such as hedonic scales, JAR scales, and CATA. The design ensures consistency and comparability between phases, allowing direct evaluation of how VR and ET individually and collectively enhance the accuracy and ecological validity of sensory research.

4.2.1. Experimental Overview

4.2.1.1. Experiment 1: Virtual Sensory Laboratory Acceptability

This experiment involved 60 participants and aimed to establish a baseline for VR-based sensory evaluations by examining participant engagement and response accuracy within a controlled virtual environment. Participants performed two tasks: identifying bakery items in a virtual sensory booth and completing an aroma recognition task using five scented sticks (lemon, strawberry, cinnamon, vanilla, and caramel). The study collected product identification accuracy, aroma recognition scores, hedonic ratings using a 9-point scale, and emotion ratings via standardized questionnaires. Simulator sickness symptoms were monitored using the Simulator Sickness Questionnaire (SSQ). This experiment provided feasibility data and highlighted perceptual and technical constraints to refine future VR-based protocols.

4.2.1.2. Experiment 2: Comparison between Traditional and VR Sensory Testing

A total of 42 participants took part in this experiment, which compared sensory responses in traditional laboratory settings and VR environments. Lemonade samples with 10%, 20%, and 30% sugar concentrations were evaluated in both conditions using a 9-point hedonic scale for liking and sweetness perception. Emotional states were assessed using the PANAS questionnaire, while VR-induced discomfort was evaluated using the SSQ. This crossover design ensured that all participants experienced both testing conditions. The collected data included hedonic ratings, emotion scores, and sickness ratings, allowing comparisons of sensory and psychological outcomes between contexts.

4.2.1.3. Experiment 3: Virtual Sensory Testing with Different Methods and Environments

This two-part experiment involved 42 participants in Part One [testing methods (M)] and 45 participants in Part Two [environmental context (E)]. Part One compared the effectiveness of Just-About-Right (JAR) scaling, Check-All-That-Apply (CATA), and Preference Testing when evaluating biscuits and orange juice in a virtual booth. Part Two examined the same evaluations conducted in two immersive environments, a park and a food court. Key data collected included JAR and CATA responses, preference rankings, hedonic ratings, PANAS emotion scores, and SSQ responses. This study contributed to refining VR sensory evaluation procedures by assessing both methodological and contextual effects.

4.2.1.4. Experiment 4: ET and VR ET on Sustainable Labelling

Experiment 4 investigates how sustainable product labelling affects consumer decision-making and visual attention using Eye Tracking (ET) and Virtual Reality Eye Tracking (VR ET). Participants evaluated 20 product packages with various sustainability claims (e.g., eco-friendly, organic, recycled) under two conditions: a desktop-based evaluation with screen-based ET and a VR-based evaluation using Ocumen ET. Including a standalone desktop ET condition allowed assessment of ET's independent effect, separate from VR immersion. A randomized crossover design balanced exposure and minimized order bias. Key ET metrics—fixation duration, count, and saccadic movement—were collected, alongside questionnaire data on sensory acceptance and purchase intent. This setup enabled direct comparisons between traditional and immersive environments, isolating the effects of ET while examining how VR enhances visual and behavioural responses. Statistical analyses including ANOVA, PCA, and cluster analysis were used to evaluate visual attention and decision-making patterns. The results clarify how eye tracking and immersive context shape responses to sustainability labels.

4.2.1.5. Experiment 5: Introductory Use of Augmented Virtuality (AV) for Colour Masking in Sensory Evaluation

This experiment involved 42 participants and explored the application of Augmented Virtuality, or AV, in sensory testing. AV refers to a hybrid immersive environment where real physical elements such as food samples are presented within a predominantly virtual setting. This is different from Virtual Reality, or VR, which involves a fully computer-generated and immersive environment with no real-world sensory input. AV allows participants to interact with actual products while surrounded by controlled virtual visuals, making it possible to isolate and manipulate specific sensory cues such as colour while preserving the real tasting experience.

Participants evaluated red, orange, and yellow cherry tomatoes in a virtual café environment. The study included two phases. In the expectation phase, participants viewed colour images of the tomatoes and rated their expected liking, flavour, sweetness, and sourness. In the tasting phase, real tomato samples were served in greyscale while participants remained in the virtual café using head-mounted displays. This setup masked colour perception while keeping all other sensory dimensions intact. Data collected included expected and preferred sensory ratings, preference rankings, responses to the Simulator Sickness Questionnaire, and a post-AV questionnaire assessing comfort and engagement. Significant differences between expected and preferred ratings demonstrated the influence of visual cues, especially colour, on flavour and sweetness perception. This introductory experiment shows that AV can help reduce perceptual bias and improve control in immersive sensory evaluations.

4.3. Framework–Experiment Alignment

To reinforce the practical relevance of the conceptual framework presented in Figure 4, each experiment in this dissertation has been explicitly mapped to the independent, mediating, and dependent variables of the model. This alignment demonstrates how the theoretical constructs such as visual attention, expectation bias, and cognitive load were operationalised through the experimental phases. Table 2 summarises this alignment, ensuring transparency and methodological coherence.

Table 2: Mapping of Experiments to Conceptual Framework Constructs

Experiment	Independent Variables	Mediating Variables	Dependent Variables	Primary Objective and Framework Linkage
1	Virtual reality (VR), Sensory science	Cognitive load and immersion	Sensory analysis	Examined the feasibility and participant acceptance of a fully immersive VR environment, establishing baseline cognitive responses and engagement.
2	Virtual reality (VR), Sensory science	Expectation bias, Cognitive load	Sensory analysis, Consumer behaviour	Investigated how immersive VR settings alter product perception and decision-making compared to traditional conditions.
3 (Methods)	Virtual reality (VR), Sensory science	Cognitive load	Sensory analysis	Assessed the suitability of different sensory evaluation methods in a VR setting. Focused on method-driven variance in perceptual accuracy.
3 (Environment)	Virtual reality (VR), Sensory science	Expectation bias, Cognitive load	Sensory analysis	Analysed how different immersive virtual environments influence attention, expectation, and sensory judgments.
4	Eye tracking (ET), Virtual reality (VR), Sensory science	Expectation bias, Cognitive load	Consumer behaviour, Sensory analysis	Explored visual attention toward product labels using ET and VR ET. Linked attention metrics to purchase intent and product liking.
5	Augmented virtuality (AV), Sensory science	Expectation bias	Sensory analysis	Applied AV to mask colour cues and isolate taste perception. Focused on reducing expectation-driven bias.

This structured alignment confirms that each experiment directly tests one or more theoretical pathways within the framework. The comprehensive integration of immersive technologies (VR, ET, AV) across these studies supports a holistic evaluation of how consumer sensory experience, attention, and behaviour are shaped under ecologically valid conditions.

4.4. Experimental Setup and Instruments Used

4.4.1. Virtual Reality Hardware and Software

<u>VR Hardware</u>

Three VR headsets will be used for the study to accommodate different experimental settings and optimize participant comfort and performance:

I. HTC VIVE Pro Eye (HTC Corporation, Xindian, New Taipei, Taiwan)

Figure 5: HTC VIVE Pro Eye (HTC Corporation, Xindian, New Taipei, Taiwan) HMDs.

The HTC VIVE Pro Eye (Figure 5) is a high-performance VR headset equipped with integrated ET functionality. It provides a resolution of 1440 x 1600 pixels per eye and a refresh rate of 90 Hz, ensuring high visual clarity and smooth motion. The integrated ET system allows for precise gaze measurement, fixation tracking, and pupil dilation recording. The HTC VIVE Pro Eye will be used for highly immersive sensory tasks where detailed gaze tracking is required.

II. Meta Quest 2 (Reality Labs, Meta Platforms Inc., Menlo Park, California, US)

Figure 6: Meta Quest 2 (Reality Labs, Meta Platforms Inc., Menlo Park, California, US) HMDs.

The Meta Quest 2 (Figure 6) is a standalone VR headset with a resolution of 1832 x 1920 pixels per eye and a refresh rate of 120 Hz. Its wireless design allows for increased mobility and reduced participant fatigue during extended VR sessions. The Meta Quest 2 will be used in experimental setups where mobility and participant comfort are prioritized, such as interactive or exploratory sensory evaluations.

III. Pico Neo 3 Pro Eye (ByteDance Ltd., Haidian, Beijing, China)

Figure 7: Pico Neo 3 Pro Eye (ByteDance Ltd., Haidian, Beijing, China) HMDs.

The Pico Neo 3 Pro Eye (Figure 7) features a resolution of 1832 x 1920 pixels per eye and a refresh rate of 90 Hz. It includes integrated ET and supports high-performance VR rendering. The Pico Neo 3 Pro Eye will be used for experiments that require a balance between mobility and gaze tracking accuracy, particularly in dynamic VR environments with complex stimuli.

Software Platforms

The study will use three major software platforms to create and manage the VR environments, sensory stimuli, and ET data collection:

I. Unreal Engine (Version 4.27.2) – Epic Games, Cary, North Carolina, USA

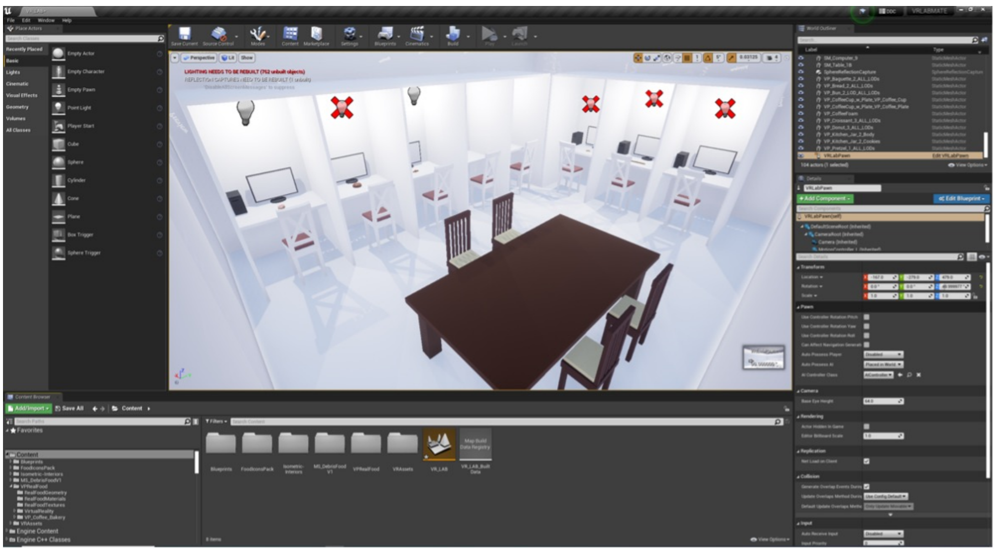


Figure 8: The Unreal Engine Software for the development of VR.

Unreal Engine (Figure 8) is a high-performance game development platform used to create photorealistic VR environments. The software supports real-time rendering, spatial audio integration, and complex lighting models, ensuring that sensory stimuli are presented with high visual fidelity and realistic environmental context. Unreal Engine's compatibility with Tobii Ocumen SDK allows for seamless integration of ET data with VR stimuli.

II. Unity – Unity Technologies, Unity Software Inc., San Francisco, California, USA

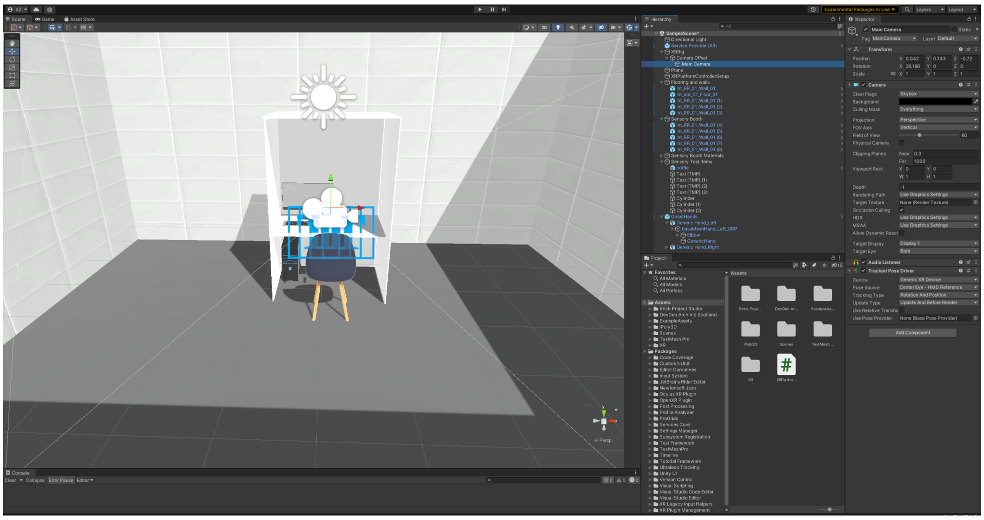


Figure 9: The Unity Software for the development of VR.

Unity (Figure 9) is a widely used game engine for developing interactive VR experiences. It supports a range of VR headsets and provides real-time rendering capabilities, interaction models, and physics-based sensory simulations. Unity's flexibility allows for the development of customized sensory evaluation tasks and adaptive testing scenarios. Unity's compatibility with Tobii Ocumen SDK facilitates real-time ET data collection and analysis within the VR environment.

III. Tobii Ocumen SDK – Tobii Technology, Danderyd, Sweden

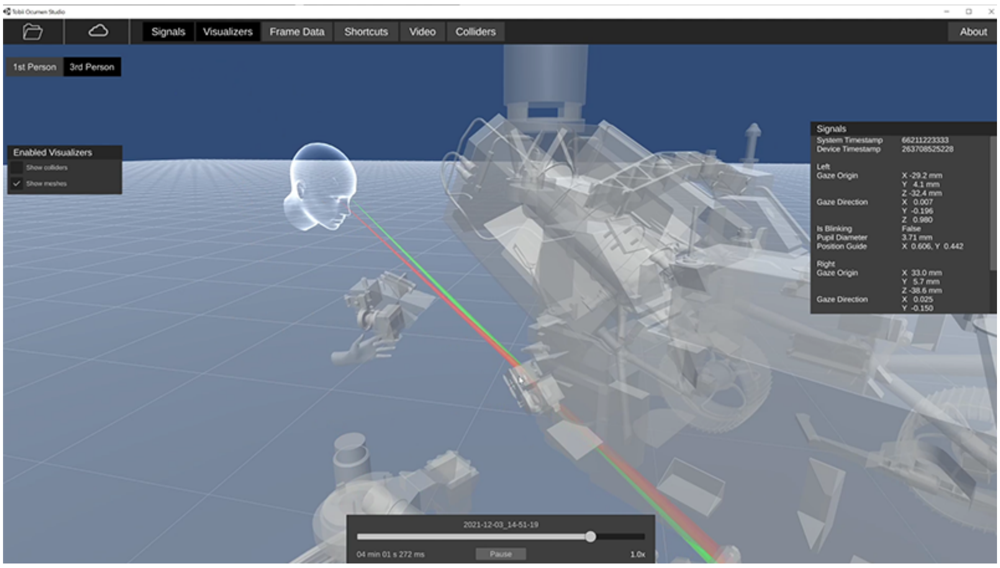


Figure 10: Ocumen Studio for ET data.

Tobii Ocumen SDK provides a development framework for integrating ET data into VR applications. It allows for real-time extraction of gaze metrics (fixation, saccades, and pupil dilation) and supports gaze-based interaction models. Ocumen SDK's compatibility with both Unreal Engine and Unity enables consistent and accurate ET data collection across different VR headsets and experimental conditions. The data collected using Ocumen Studio (Figure 10) will be processed using Python-based scripts for advanced analysis and visualization.

Rationale for Hardware and Software Selection

The selection of VR headsets was based on the specific requirements of each experimental task, prioritizing visual fidelity, mobility, participant comfort, and gaze-tracking precision.

- HTC VIVE Pro Eye was chosen for experiments requiring high gaze-tracking accuracy and visual detail, such as Experiment 4 involving product label analysis. Its integrated ET and high-resolution display enabled fine-grained capture of gaze metrics in immersive retail simulations.

- Meta Quest 2 was used in exploratory and mobility-focused evaluations (e.g., Experiments 1 and 3(E)), where participant freedom of movement and comfort were essential. Its standalone design minimized tethering-related restrictions, making it ideal for more naturalistic interaction.

- Pico Neo 3 Pro Eye offered a balance between mobility and integrated ET, making it suitable for complex virtual environments where moderate gaze-tracking fidelity and participant comfort were both required. It was applied in Experiment 3(M) to examine participant responses under varied virtual contexts.

Software platforms were selected to support flexible development of immersive environments and seamless integration of eye-tracking data:

- Unreal Engine was employed in high-fidelity visual simulations due to its superior graphics rendering and environmental realism, especially in tasks requiring detailed visual stimuli and lighting effects.

- Unity provided flexibility and was preferred for interactive and adaptive sensory evaluation tasks. It supported rapid prototyping and real-time adjustments during pilot testing phases.

- Tobii Ocumen SDK enabled precise integration of ET metrics within VR scenes, ensuring consistent gaze data capture across headsets. Its compatibility with both Unity and Unreal allowed for methodological consistency across experiments.

This tailored selection strategy ensured that each experiment leveraged the optimal technological configuration to balance immersion, data accuracy, and participant experience.

4.4.2. Eye-Tracking Equipment and Calibration Procedures

ET data will be collected using two different Tobii platforms to measure gaze behaviour, visual attention, and cognitive load during sensory evaluations under both controlled and immersive conditions. All devices were calibrated using a consistent nine-point calibration process, ensuring accuracy and reliability of the recorded data across different experimental setups. This approach allowed for consistent measurement standards and supported the integration of eye tracking data into both traditional and virtual environments.

Tobii Screen-Based Eye Tracker

Figure 11: Screen-Based Eye Tracker Tobii Pro Nano.

A Tobii screen-based eye tracker (Figure 11) will be used for controlled laboratory settings where environmental variables can be tightly controlled. The desktop eye-tracker records gaze data at a high sampling rate of 60 Hz and provides detailed data on micro-fixations, gaze shifts, and pupil dilation. It requires participants to sit in a fixed position, ensuring consistent head positioning and stable gaze tracking.

The following data will be extracted from the desktop eye-tracker:

- Fixation duration – how long participants focus on a specific product attribute
- Fixation count – how frequently a specific attribute is fixated on
- Gaze path – sequence and direction of gaze shifts between different elements
- Saccadic movement – rapid gaze shifts between two points of interest
- Pupil dilation – changes in pupil size indicating cognitive load and emotional engagement

4.5. Selection of Participants

The study will employ a purposive sampling strategy to recruit participants who represent the target consumer population for sensory evaluation of food products. A sample size of 20 to 60 participants will be selected, consistent with established sensory research guidelines for achieving statistically reliable data while maintaining practical feasibility. Participants will be recruited through targeted advertisements and university research databases to ensure a diverse sample in terms of age, gender, and sensory sensitivity. Inclusion criteria will require participants to have normal or corrected-to-normal vision, no known sensory deficits (e.g., anosmia or ageusia), and no history of severe motion sickness or neurological disorders that may interfere with VR exposure. Participants with prior VR experience will not be excluded but will be required to disclose their experience level to assess potential bias in immersion and sensory perception.

The age range for participant selection will be set between 18 and 45 years to control for age-related differences in sensory sensitivity and cognitive processing. A balanced gender distribution will be maintained to capture potential gender-based differences in sensory perception and visual attention patterns. To minimize variability, participants will be instructed to refrain from consuming strong-flavoured food, caffeinated beverages, or alcohol at least two hours before the session, as these factors may alter taste perception and cognitive performance. Screening questionnaires will be administered to confirm eligibility and identify potential confounding variables, such as smoking habits, medication use, and dietary restrictions.

A within-subject design will be used, where all participants will be exposed to both VR-only and VR ET conditions to reduce inter-individual variability and enhance statistical power. Participants will be randomly assigned to different session orders to counterbalance potential order effects and control for learning or fatigue. Ethical approval will be obtained from the university's research ethics board, and participants will provide informed consent before participation. Participants will receive compensation for their time to enhance recruitment and reduce dropout rates. The sampling strategy is designed to ensure that the study findings are statistically reliable, generalizable to the target consumer population, and methodologically rigorous. Table 3 shows the average of participants gender and age for each experiment. Throughout the experiment each participant will be given a code which starts with P and the number (e.g., P00).

Table 3: Mean of participants gender and age.

Experiment	Gender	Number of participants (*n*)	Percentage (%)	Age				
				Mean ± SD			Min	Max
1	Male	18	30	24.23	±	4.16	19	45
	Female	42	70	23.74	±	2.55	20	36
	Total	60	100	24.46	±	3.65	19	45
2	Male	16	38	25.19	±	3.10	21	33
	Female	26	62	25.50	±	2.97	21	32
	Total	42	100	25.31	±	2.98	21	33
3 (Methods)	Male	10	24	26.20	±	5.87	20	34
	Female	32	76	24.84	±	3.31	21	40
	Total	42	100	25.17	±	4.02	20	40
3 (Environment)	Male	14	31	26.36	±	4.96	20	40
	Female	31	69	24.71	±	3.16	21	31
	Total	45	100	25.22	±	3.83	20	40
4	Male	14	33	24.14	±	2.14	21	29
	Female	28	67	24.43	±	2.69	20	30
	Total	42	100	24.33	±	2.50	20	30
5	Male	14	33	22.79	±	1.42	20	24
	Female	28	67	24.89	±	2.59	20	30
	Total	42	100	24.19	±	2.46	20	30

4.6. Environmental Setups and Experimental Procedures for Sensory Evaluations

4.6.1. Environmental Setup

An empty and quiet classroom (3 m × 4 m × 2.8 m) at the Hungarian University of Agriculture and Life Sciences (MATE) was designated for the VR experiments. The controlled environment ensures minimal external influences, including noise, lighting, and temperature, which could otherwise affect sensory perception and participant behaviour. The VR environment was implemented using Unreal Engine version 4.27.2 (Epic Games, Cary, North Carolina, US) and Unity (Unity Technologies, Unity Software Inc., San Francisco, California, US), depending on the experimental requirements.

Three VR headsets were used to create and present the virtual environments, including the HTC VIVE Pro Eye for high-fidelity immersive experiences, Meta Quest 2 for wireless and interactive sensory testing, and Pico Neo 3 Pro Eye for experiments requiring integrated ET and high resolution. Two student assistants were recruited to assist in setting up the system and guiding participants through the experiments.

Virtual Environment Setup

Five main virtual environments were developed (Table 4) to simulate realistic consumption settings and support the ecological validity of sensory evaluations. Each environment was selected based on its alignment with specific experimental goals and its relevance to real-world consumer contexts.

1. Sensory Laboratory

   This environment was based on ISO 6658:2017 standards (International Organization for Standardization, 2017) for sensory testing to create a scientifically controlled baseline. The virtual lab included neutral grey walls, standardized lighting (6500 K), and isolated booths, allowing for minimal external interference. It was used primarily in Experiment 1 to evaluate participants' interaction with a virtual sensory space while ensuring consistency with traditional lab protocols.

2. Sensory Booth

   The sensory booth environment simulated an isolated test chamber, optimized for reducing noise, visual clutter, and social influence. This setup provided a simplified but highly controlled visual context to measure subtle differences in participant attention and perception. It was suitable for comparison against more immersive or dynamic environments, especially in Experiments 1, 2 and 3(M).

3. Park and Food Court

   These dynamic environments were created using 360-degree video footage captured in public, naturalistic locations in Budapest. Their purpose was to replicate everyday consumption scenarios, such as outdoor snacking or food court dining, to examine contextual influences on sensory responses. These scenes supported Experiment 3(E) by allowing the exploration of environmental congruency and distraction effects on sensory processing and emotional engagement.

4. Blank Canvas

   A minimalistic virtual setting without environmental cues, the blank canvas environment served as a baseline condition for isolating the effects of ET and VR ET. It eliminated background stimuli, enabling precise measurement of gaze behaviour and attention allocation. This environment was particularly relevant in Experiment 4, where direct comparisons between screen-based ET and immersive VR ET were required.

5. Café Environment

   Designed to represent a familiar, semi-social context, the virtual café included ambient lighting, interactive elements, and spatial design reflective of actual cafés. This environment was used in Experiment 5 to test the effect of visual context on expectation bias and colour masking during sensory evaluations involving real food samples (cherry tomatoes). The realistic yet controlled setting supported AV testing by balancing ecological relevance with experimental control.

Table 4: Study set up, technology and virtual environment on each experiment.

Experiment	Head-mounted Display (HMD)	Software	Virtual Environment	Product	Sensory Methods
1	HTC VIVE Pro Eye	Unreal Engine	Sensory Laboratory	3D bakery items and smelling stick	Identifying and smelling test
2	HTC VIVE Pro Eye	Unity	Sensory Booth	Lemonades with different sugar concentrations	9-Point Hedonic Scale
3 (Methods)	Meta Quest 2	Unity	Sensory Booth	Biscuit and Orange Juice	Just-about-right (JAR), Check-all-that-apply (CATA) and Preference test
3 (Environment)	Meta Quest 2	Unity	Park and Food Court		
4	Pico Neo 3 Pro Eye and Screen-Based Eye Tracker Tobii Pro Nano.	Unity, Ocumen and Tobii Pro Lab	Empty Canvas	Food packaging with different sustainability labelling	Purchasing Behaviour
5	Meta Quest 2	Unity	Café Environment	Cherry Tomato (Red, Orange, Yellow)	Expectation and Preference test

4.6.2. Experiment 1: Virtual Sensory Laboratory Acceptability

Experiment 1 was designed to introduce participants to the Virtual Reality (VR) environment and validate basic sensory responses under controlled conditions. The virtual sensory laboratory, developed using Unreal Engine, adhered strictly to ISO 8589:2007 standards for sensory testing environments (Figure 12 and Figure 13). Participants evaluated three-dimensional bakery items combined with aromatic scented sticks, assessing both their ability to identify aromas and rate aroma intensity using structured sensory scales. Figure 12 presents an overview of the virtual sensory laboratory layout, depicting sensory booths along with a central table for participant discussions. Figure 13 demonstrates two different points of view participants experienced: standing (A) and seated (B), providing immersive realism.

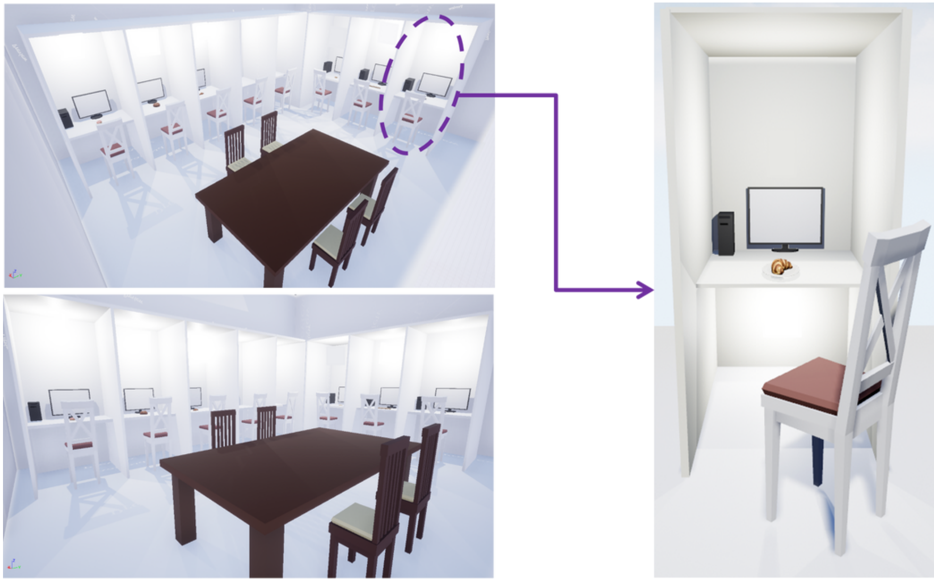
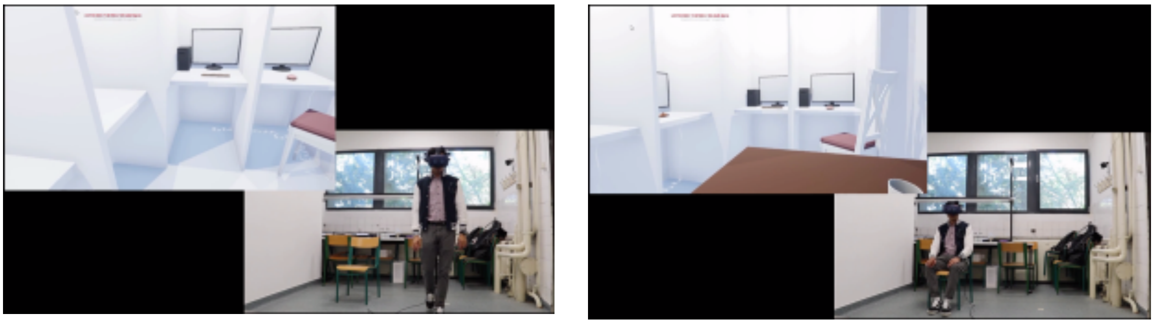


Figure 12: The virtualized sensory lab overview of sensory booths and a discussion table based on ISO 8589:2007 standard using Unreal Engine.



(A) (B)

Figure 13: (A) Point-of-view (POV) while standing, (B) POV while sitting down.

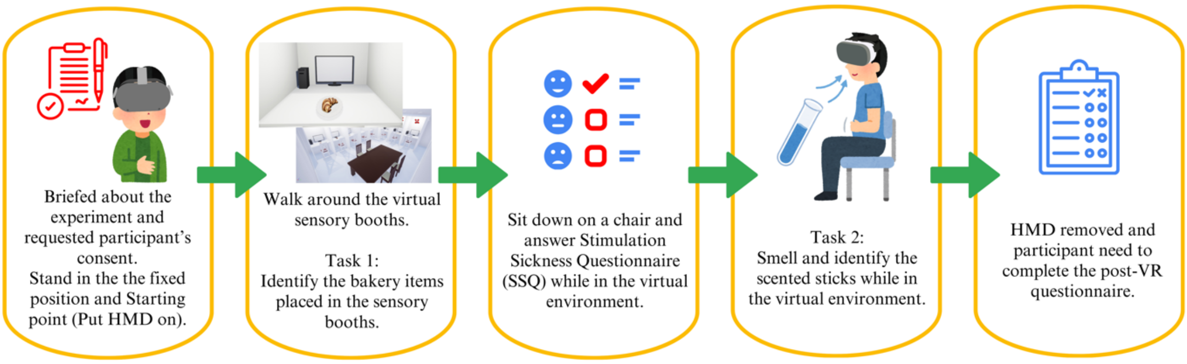


Figure 14: Flowchart of Experiment 1 – Virtual Sensory Laboratory Acceptability involving product identification and scented stick evaluation in a virtual environment.

Figure 14 outlines the detailed procedural flowchart for Experiment 1. Initially, participants were introduced thoroughly to the experimental procedures and study objectives, followed by giving informed consent. Participants were fitted with a head mounted display (HMD) and positioned within the virtual sensory laboratory at a predetermined starting location. Participants then freely explored virtual sensory booths for approximately three minutes, with the objective of becoming familiarized with the VR environment and accurately identifying displayed bakery products.

Subsequently, participants sat at a designated area within the virtual environment and completed the Simulator Sickness Questionnaire (SSQ), measuring VR induced discomfort or sickness. After this, participants were asked to identify aromas from five randomly ordered scented sticks representing Lemon, Strawberry, Cinnamon, Vanilla, and Caramel scents.

The entire duration of this virtual sensory evaluation session lasted approximately seven (7) to ten (10) minutes. After completion of the tasks, participants removed their HMD and completed post VR questionnaires including the Virtual Reality Sickness Questionnaire (VRSQ) and Virtual Reality Narrative Questionnaire (VRNQ) via tablet, to comprehensively capture experiences and feedback. All sensory identification data and aroma intensity ratings were digitally recorded. Participants received a candy as a token of appreciation.

4.6.3. Experiment 2: Comparison between Traditional and VR Sensory Testing

Experiment 2 explored the differences in sensory perception between traditional laboratory sensory evaluation methods and immersive VR sensory methods. The experiment utilized lemonade samples with varying sugar concentrations (10%, 20%, and 30%) to investigate sensory perception consistency between traditional and virtual testing environments. A virtual sensory booth replicating MATE sensory laboratory conditions was created using Unity (Figure 15 and Figure 16).

Figure 15: The virtualized sensory lab overview of sensory booth based on ISO standard using Unity.

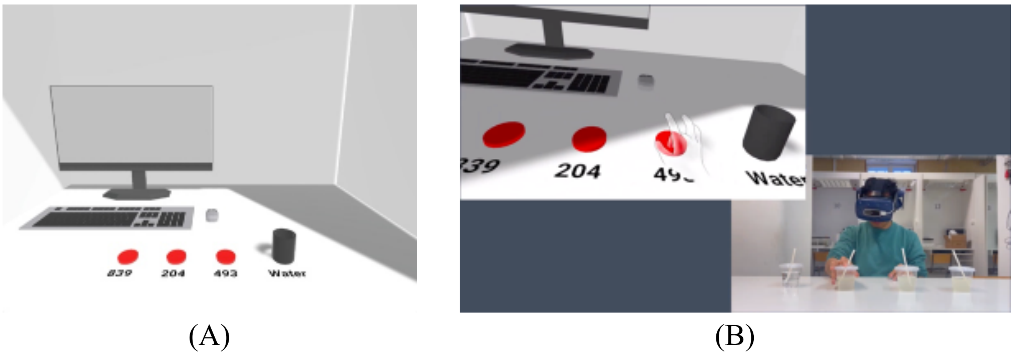


Figure 16: (A) Virtual sensory booth on three randomized digits were placed on a red marker and water in a virtual cup for a palate cleanser, (B) POV on participants doing virtual sensory testing.

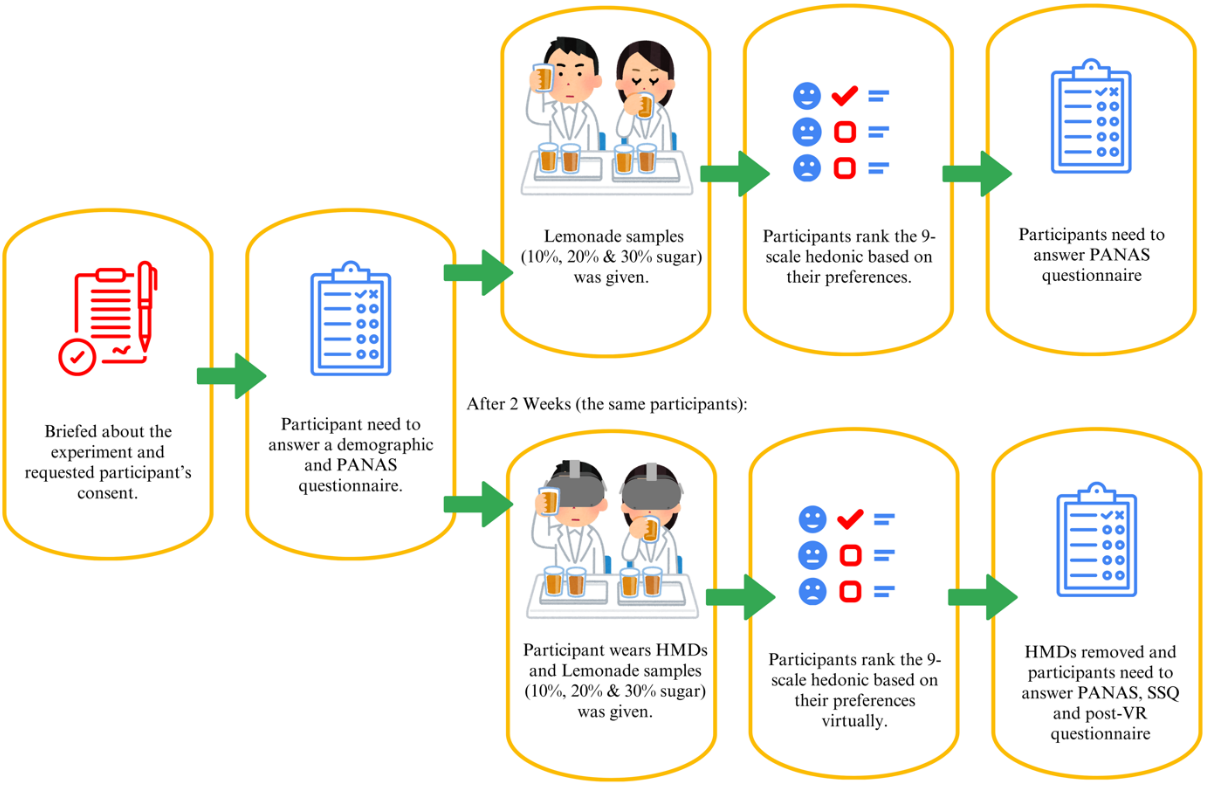


Figure 17: Flowchart of Experiment 2 – Comparison between traditional and VR sensory testing using lemonade samples with different sugar concentrations, evaluated on a 9-point hedonic scale.

Flowchart of Experiment 2 had been shown in Figure 17. Participants were briefed about the study's objectives and procedures. They were asked to complete a demographic questionnaire on a tablet before the experiment. Participants initially evaluated lemonade samples traditionally in a physical sensory booth environment, rating sweetness, sourness, and overall liking using a nine-point hedonic scale. After a two-week interval, chosen to minimize memory effects, sensory fatigue, and carryover bias from initial exposure, participants repeated the evaluation within the VR environment, again rating identical lemonade samples randomly coded to prevent bias from previous exposure. This two-week duration aligns with established sensory testing protocols to ensure accurate and reliable comparative data.

In both experimental conditions, samples were presented in randomized order to avoid bias related to sample sequence. Following the VR evaluations, participants removed the headset and completed the Simulator Sickness Questionnaire (SSQ) and Virtual Reality Narrative Questionnaire (VRNQ) to evaluate comfort, experience quality, and sensory response consistency. All sensory ratings were recorded digitally for statistical comparison between traditional and VR sensory testing outcomes.

4.6.4. Experiment 3: Virtual Sensory Testing with Different Methods and Environments

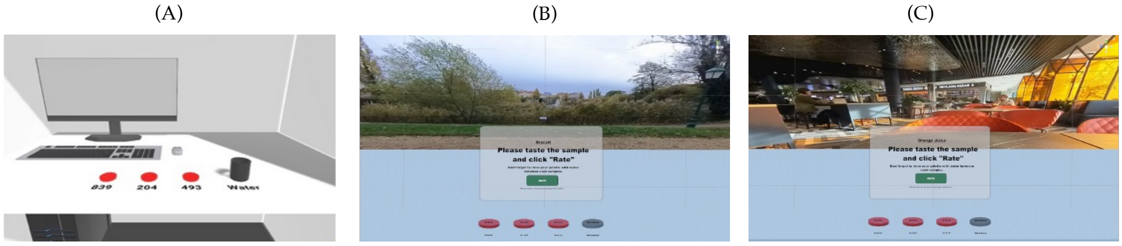


Figure 18: Virtual environments used in the study: (A) Virtual Sensory Booth based on ISO 6658:2017 standards, replicating MATE sensory laboratory; (B) Park, recorded in a Budapest public park; (C) Food Court, captured in a Budapest shopping mall.

Experiment 3 explored how environmental context, and sensory methods influence consumer perception and preferences (Figure 18), and was divided into two parts. Part One, Experiment 3 Methods (M), focused on the sensory methods used to evaluate food products. Participants assessed biscuits and orange juice using Just-About-Right (JAR) scaling to rate sweetness and texture appropriateness, Check-All-That-Apply (CATA) to describe sensory characteristics like flavour and mouthfeel, and Preference Tests to indicate which samples they liked most. Part Two, Experiment 3 Environments (E), focused on the testing environments, where the same evaluations were conducted in three distinct virtual settings: a sensory booth (controlled environment) [Figure 18 (A)], a park [Figure 18 (B)], and a food court [Figure 18 (C)] (virtual environments), all developed using Unity. This two-part design allowed the study to examine both the effect of sensory methodology and the impact of environmental context on consumer perception.

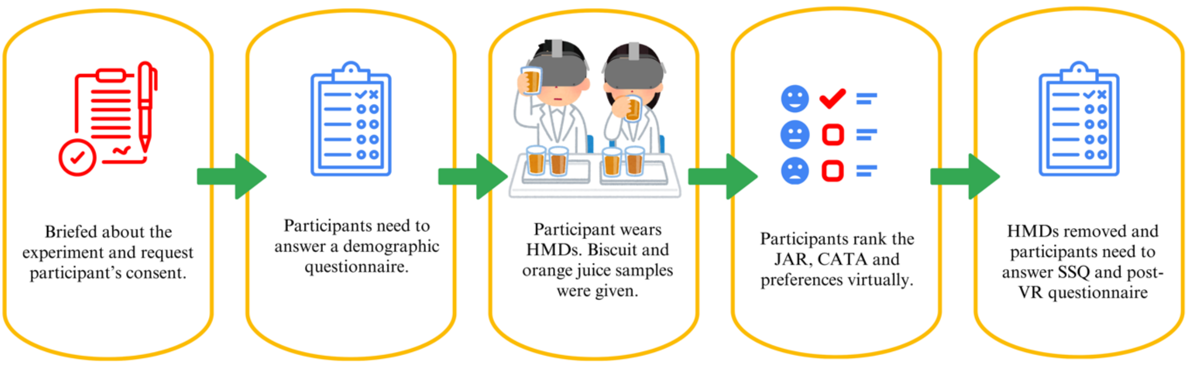


Figure 19: Flowchart of Experiment 3 – Virtual Sensory Testing with Different Methods and Environments involving biscuit and orange juice samples evaluated using JAR, CATA, and preference tests.

Figure 19 shows the flowchart of Experiment 3, which was divided into two parts: sensory methods and environmental context. Participants were first briefed about the study and provided informed consent. They completed a demographic questionnaire and were equipped with a VR headset, entering a controlled virtual environment to begin the evaluation.

Part One focused on the sensory methods used to assess the products. Participants evaluated biscuits and orange juice using three techniques: JAR, CATA and Preference Test. All product samples were presented in random order to minimize bias.

Part Two focused on the environmental context. The sensory evaluations were conducted in two different virtual environments: a park for the biscuit evaluation and a food court for the orange juice evaluation. These environments, created using Unity, allowed for the comparison of sensory perception in controlled versus dynamic settings. The experiment was repeated after a two-week gap to assess consistency across sessions. After removing the HMD, participants completed the Simulator Sickness Questionnaire (SSQ) and a post-VR questionnaire to evaluate discomfort and cognitive load. Participants were given biscuit and orange juice samples (Figure 20) and asked to evaluate them using multiple sensory methods:

- Just-About-Right (JAR) Scale – Participants indicated whether sensory attributes (e.g., sweetness, texture) were optimal.
- Check-All-That-Apply (CATA) – Participants selected terms from a predefined list that described the products' sensory characteristics.
- Preference Test – Participants ranked the products based on overall liking.
- All samples were presented in random order to minimize bias from presentation order.

Figure 20: Products used for sensory evaluation in different virtual environments: biscuits tested in the Park environment, with three flavors from the Győri Édes brand—cacao (A), cacao and whole grain (B), and chocolate chips (C); and orange juice tested in the Food Court environment, featuring three brands—Sió Natura (A), Tesco (B), and Rauch Happy Day (C). Products were selected based on consumer familiarity and sensory differentiation to ensure ecological validity and recognisability during virtual testing.

The experiment was repeated in two different virtual environments, a park and a food court, to assess the impact of environmental context on sensory evaluation. A two-week interval was applied between the sessions to minimise memory effects and sensory fatigue (Yang & Ng, 2017). This duration is consistent with previously established protocols in sensory science to reduce carryover bias between repeated exposures (Lau et al., 2004). After removing the head mounted display, participants completed the Simulator Sickness Questionnaire and a post VR questionnaire to evaluate discomfort and cognitive load.

4.6.5. Experiment 4: ET and VR ET on Sustainable Labelling

Experiment 4 examined how sustainability labelling influences consumer purchasing decisions and gaze behaviour (Figure 21). A blank canvas environment was created using Unity to eliminate background distractions and isolate the effects of visual attention on product labelling [Figure 21 (B)]. Participants were shown food packaging with different sustainability claims and ingredient lists. ET data were collected using both the Pico Neo 3 Pro Eye and a Tobii screen-based eye tracker to measure fixation duration, gaze path, and pupil dilation while participants evaluated the product's perceived sustainability and willingness to purchase. The objective was to identify which labelling elements attract the most attention and how gaze patterns influence product acceptance. This experiment provided insights into the cognitive mechanisms underlying consumer decision-making in relation to sustainable food products.

(A) (B)

Figure 21: (A) Desktop-based eye tracking and (B) VR eye tracking in a blank virtual environment, both used to assess visual attention toward sustainability-labelled food packaging.

Flowchart of Experiment 4 showed in Figure 22. Participants were briefed and asked to complete a demographic questionnaire. The experiment involved evaluating 20 different product packaging designs with varying sustainability claims. ET data were collected using both the Tobii desktop-based eye tracker and the VR-based Ocumen eye tracker. Participants first viewed the product packaging on a computer screen while gaze data were recorded using Tobii Pro Lab.

Fixation count, fixation duration, and saccadic movements were measured to identify which elements of the packaging attracted the most visual attention. Next, participants repeated the experiment in a virtual environment using an HMD equipped with the Ocumen eye tracker. Gaze data were recorded in real-time as participants interacted with the virtual product packaging.

To increase randomization and reduce order bias, participants were randomly assigned to either the desktop or VR condition first. After completing the first session, participants swapped to the other platform to complete the second session. This approach ensured that any order effect was minimized.

All product samples were presented in random order to reduce presentation bias. After both sessions, participants completed a questionnaire on purchase intent and perceived sustainability. Data from the desktop and VR environments were compared to evaluate differences in gaze behaviour and consumer decision-making.

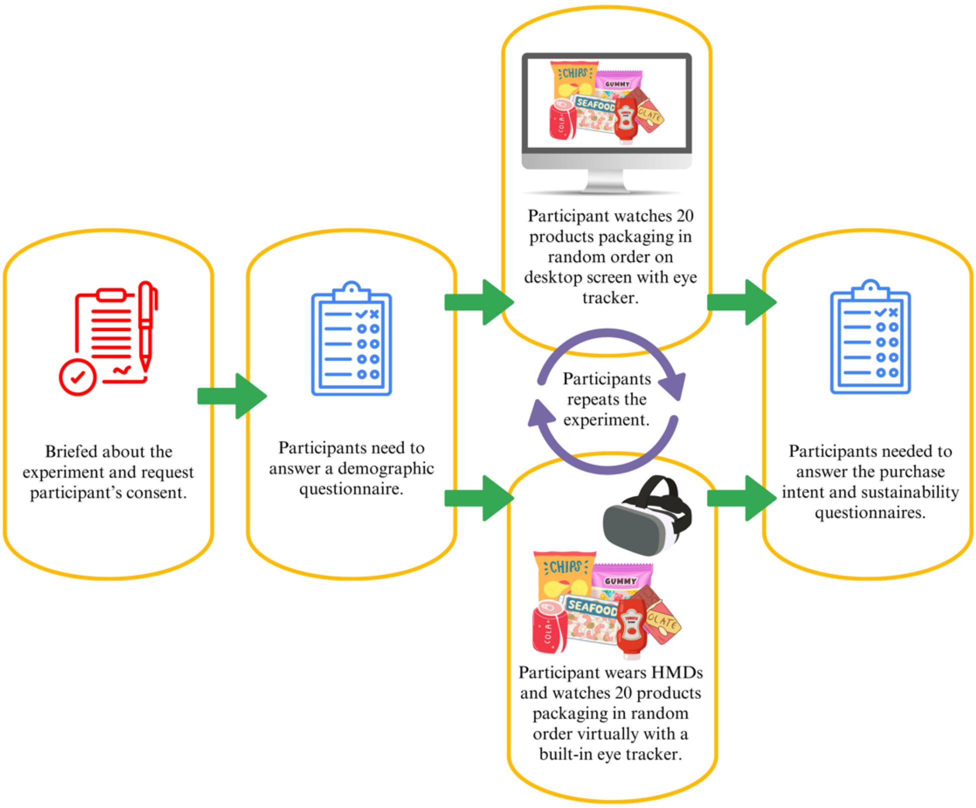


Figure 22: Flowchart of Experiment 4 – ET and VR ET on Sustainable Labelling using Tobii screen-based and Ocumen ET to assess visual attention to product packaging in virtual and real-world settings.

4.6.6. Experiment 5: Introductory Use of Augmented Virtuality (AV) for Colour Masking in Sensory Evaluation

Experiment 5 explored the application of Augmented Virtuality (AV) as a method to reduce perceptual bias in sensory evaluation by masking product colour (Figure 23). A virtual café environment was created, and participants evaluated red, orange, and yellow cherry tomatoes. In the expectation phase, participants viewed coloured images of the samples and rated their expected liking, flavour, sweetness, and sourness. During tasting, the environment was presented in greyscale using AV to remove colour cues while preserving real-world interaction. Participants wore head-mounted displays (HMDs), completed a virtual preference ranking task, and filled out the Simulator Sickness Questionnaire (SSQ) and post-AV questionnaire. The goal was to assess the impact of colour masking on sensory perception and determine the effectiveness of AV in controlling visual input. Differences between expected and preferred sensory ratings, particularly for sweetness and flavour, highlighted how colour influences perception. The study demonstrates the feasibility of AV as a tool for immersive and bias-controlled sensory evaluation.

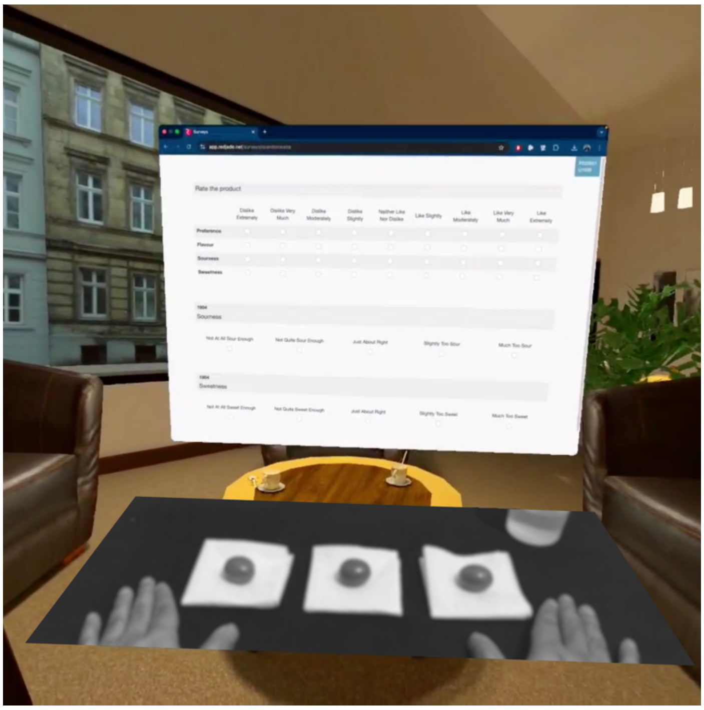


Figure 23: Virtual café environment in Augmented Virtuality (AV), where samples were evaluated in monotone colour while maintaining real-world interaction during sensory testing.

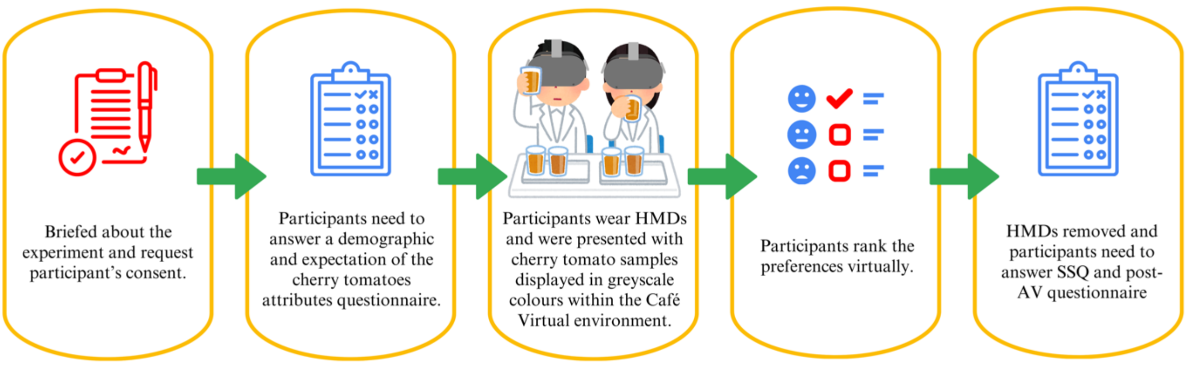


Figure 24: Flowchart of Experiment 5 – Introductory Application of Augmented Virtuality (AV) for Colour-Masked Sensory Evaluation of Red, Orange, and Yellow Cherry Tomatoes in a Virtual Café Environment

The Figure 24 presents the flow of Experiment 5, the first practical application of Augmented Virtuality (AV) introduced in this study. As an introductory experiment, it aimed to explore the feasibility of using AV for sensory analysis by isolating visual cues and reducing perceptual bias. Participants were first briefed and provided informed consent, then completed a demographic and expectation questionnaire related to red, orange, and yellow cherry tomatoes, focusing on expected liking, flavour, sweetness, and sourness based on coloured visual stimuli shown in a virtual café environment.

Participants then wore head-mounted displays (HMDs) and entered the virtual café environment. During the sensory testing phase, real cherry tomato samples were served while their colours were masked using a greyscale filter, allowing only the café background to appear in colour. This setup enabled participants to interact with real samples while removing the influence of colour perception during tasting.

After ranking the samples virtually, participants removed the HMDs and completed the Simulator Sickness Questionnaire (SSQ) and a post-AV experience questionnaire. This introductory experiment demonstrated the potential of AV to control specific sensory inputs—particularly colour and laid the foundation for future applications of AV in immersive, bias-reduced sensory evaluation.

4.7. Software Development

Figure 25 illustrates a multilayer scene developed for sensory evaluation. The software was developed and designed using Unity version (Unity Technologies, Unity Software Inc., San Francisco, California, US) and C++ for Oculus Quest 2 (Reality Labs, Meta Platforms Inc., Menlo Park, California, US). The VR sensory booth was designed to closely resemble the sensory booth (SB) at the Hungarian University of Agriculture and Life Sciences (MATE). Following the ISO 8589:2007 standard guidelines (International Organization for Standardization, 2007), a well-established sensory laboratory must use white (or light grey) colours, good natural lighting (6500 K), and well-ventilated air.

In the virtual SB, there is a setup that includes a computer, monitor, chair, and a sample indicator with three (3) randomized digits. The virtual SB also includes a glass of water for palate cleansing, and the booth dimensions are 1 m × 1 m × 2.5 m.

The layered scenes provide instructions and steps for sensory evaluation, focusing on blind test functionality. This sensory test is limited to the Just-about-right (JAR) and Check-all-that-apply (CATA) sensory methods. The application is divided into three main layers: (i) configuration and calibration (introductory), (ii) sensory evaluation, and (iii) the end scene.

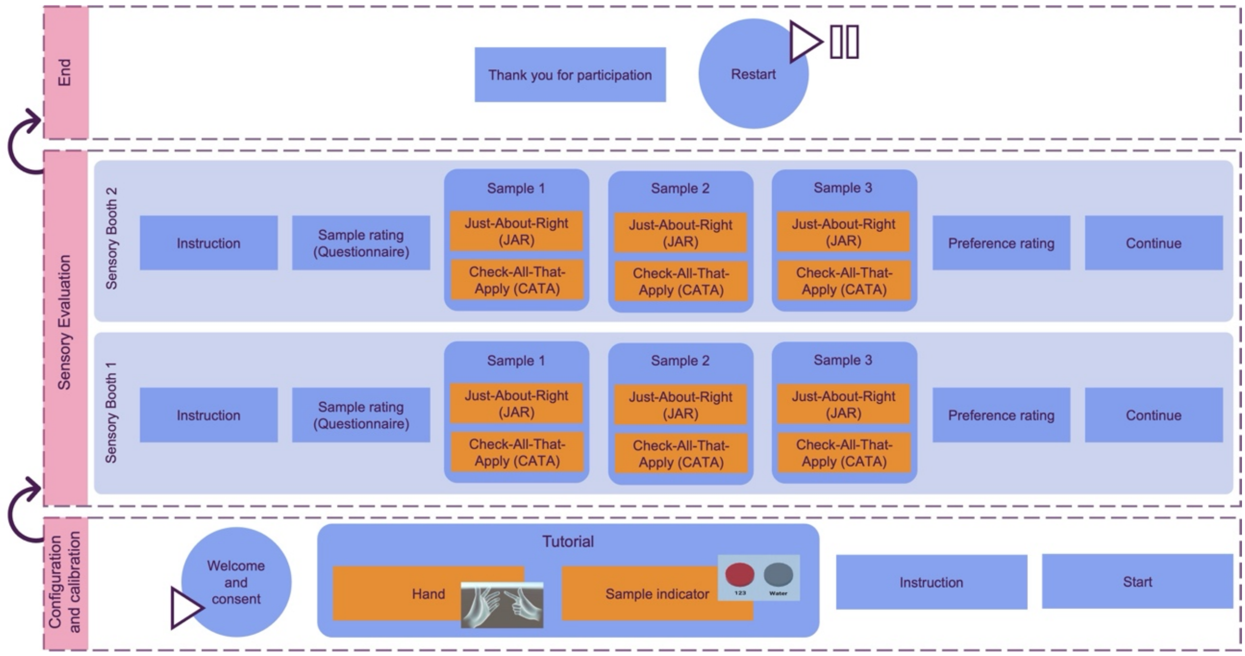


Figure 25: Multi-layer scenes architecture for the development of virtual sensory booth (SB) application. The application consists of three main layers: (i) configuration and calibration (introductory), (ii) sensory evaluation (SB 1 and 2) and (iii) end scene.

4.7.1. Scene Functionality

4.7.1.1. Configuration and Calibration (Introductory Layer)

First, the configuration and calibration scene plays a crucial role in ensuring that the virtual sensory booth is calibrated to meet the specific requirements of the participants, such as adjusting the height, setting the distance of the sample, ensuring the clarity of the scene, and accommodating participants wearing eyeglasses. Calibration is only required once per participant. This scene provides clear instructions and tutorials for the tasks. It also initiates the hand interaction tutorial, which is essential for enabling participants to interact with the virtual SB in a meaningful and engaging way.

Based on Figure 26, the scene comprises several steps. Step 1 [Figure 26(a)] involves displaying a welcome note and obtaining consent from participants to ensure they are aware of the study's objectives. Participants can proceed by clicking the 'Continue' button. The subsequent steps are part of a tutorial, designed as a warm-up session, especially for participants who are new to VR. Step 2 [Figure 26(b)] focuses on hand tracking, allowing participants to use their own hands with the guidance of animated hands showing them how to interact with the VR environment, as the Quest 2 VR headset requires a pinching motion (using the index finger and thumb) for clicking. Step 3 [Figure 26(c)] introduces the sample indicator, where participants can practice picking up and putting back food samples (in this experiment, chocolate biscuits and orange juice). This step also serves as a calibration process for the laboratory assistant to ensure the correct placement of the samples on the right indicator. The final step, step 4 [Figure 26(d)], displays an instruction page specifying product sample categories, sensory evaluation methods, and the estimated time required for the entire testing process. By clicking 'Start,' the next scene will appear. It's worth noting that all the instructions, images, and product samples can be customized in the Unity software.

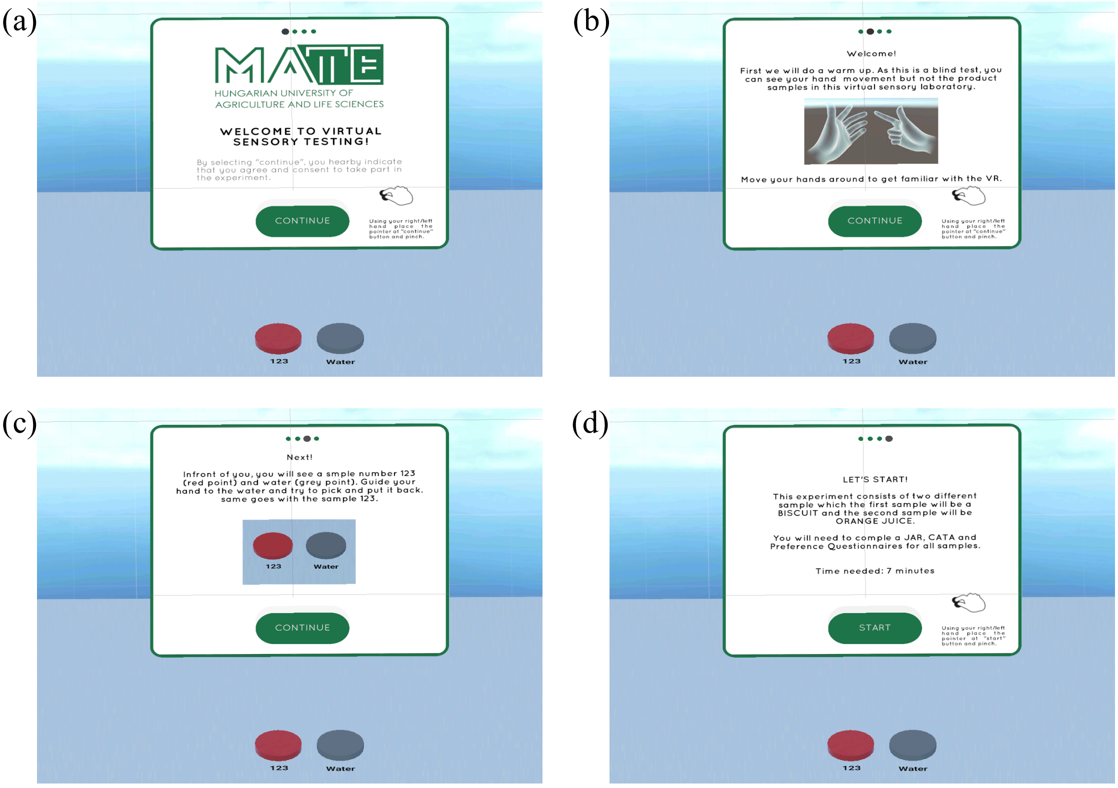


Figure 26: Configuration and calibration (introductory) scene steps; (a) Welcome note and consent, (b) Tutorial on hand tracking, (c) Tutorial on sample indicator, (d) Sensory instruction on methods and products, and starting point.

4.7.1.2. Sensory Evaluation Layer

Secondly, the sensory evaluation layer serves as the core of the application and is responsible for conducting sensory testing on two types of products, as well as answering the sensory questionnaire. In this application, both just-about-right (JAR) and check-all-that-apply (CATA) tests are provided for each sample, allowing participants to engage with the virtual SB.

Figure 27 displays the step scenes for the products. Both SB 1 and 2 have the same flow; the only difference lies in the product sample and its attributes. In both SB 1 and 2, step 1 [Figure 27(a)] presents an instruction page regarding the type of product, and by pressing the 'Rate' button, participants proceed to the next steps. On the table, random three-digit numbers indicate different product samples for testing. Steps 2 [Figure 27(b)] and 3 [Figure 27(c)] in both scenes for SB 1 and 2 are repeated alternately, with the JAR questionnaire coming first, followed by the CATA questionnaire, and this cycle is performed three times for each sample number indicated on the table. Step 4 [Figure 27(d)] involves rating the preference and liking of each sample using a 5-scale (Likert scale) to determine the preferred product. Finally, step 5 [Figure 27 (e)] serves as an indicator that the product sensory test is complete, and participants can continue to the next product or the end scene. All the instructions, images, product samples, sample numbers, and questionnaire attributes can be changed within the Unity software.

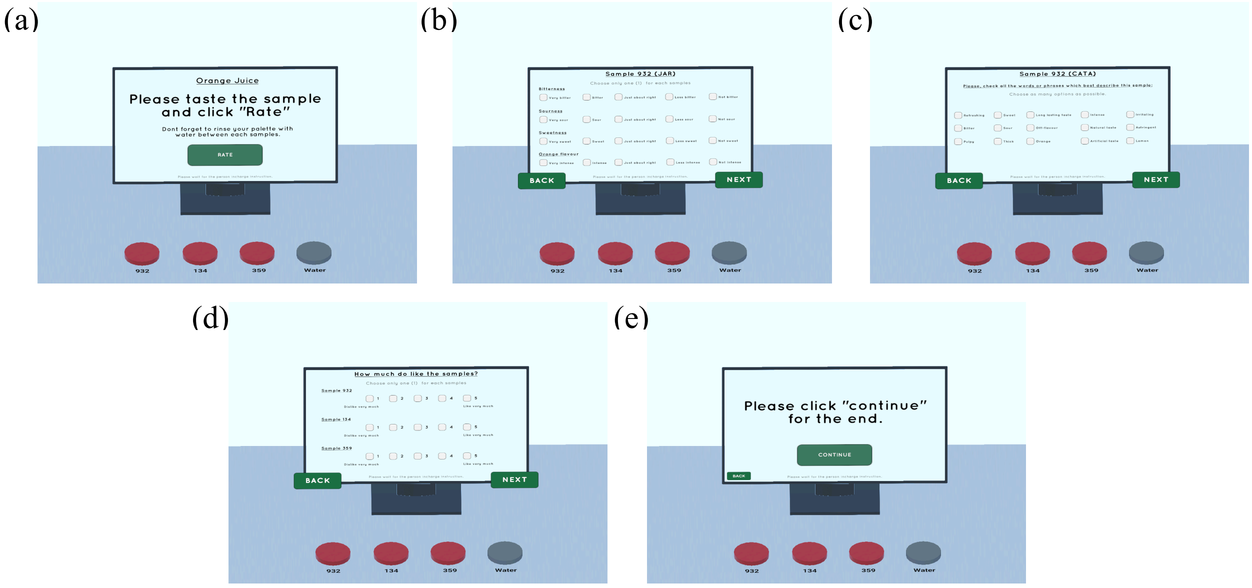


Figure 27: Sensory evaluation booth 1 scene steps; (a) Instruction page with product sample, (b) JAR for samples (will be repeated 3 times), (c) CATA for samples (will be repeated 3 times), (d) Preference on each sample, (e) Finish evaluation for product sample and continue to next product.

4.7.1.3. End Layer

Finally, the end scene (Figure 28) indicates to participants that the experiment is finished and it can be restarted for the next participant.

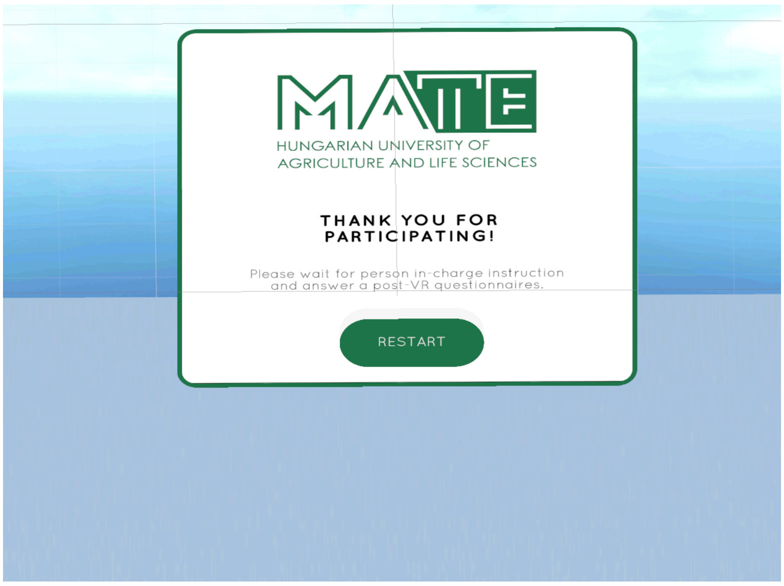


Figure 28: End scene with a restart button.

In the end scene, participants are thanked for participating in the test. The restart button can be clicked by the laboratory assistant to repeat the process for the next participant. Instructions and images can be changed within the Unity software.

4.8. Data Collection Methods

4.8.1. Questionnaires

The study will employ five validated questionnaires to measure physical discomfort, cognitive load, emotional engagement, and sensory conflicts in VR and ET-based sensory testing. These questionnaires were selected based on their relevance to immersive and sensory research, established validity, and ability to capture multidimensional participant experiences. The combination of physiological (e.g., ET), sensory (e.g., hedonic ratings), and psychological (e.g., emotional responses) measures provides a comprehensive understanding of how VR and ET environments shape sensory perception and consumer behaviour. The selected questionnaires address the key factors influencing sensory accuracy and product acceptance.

4.8.1.1. Sensory Questionnaire

Data collection was conducted using structured sensory questionnaires incorporating four sensory evaluation methods: Hedonic Scale, Preference Testing, Just-About-Right (JAR) scale, and Check-All-That-Apply (CATA). These methods were used to collect both affective and descriptive responses based on the characteristics of the tested samples.

I. Hedonic Scale and Preference Testing
A 9-point hedonic scale (1 = Dislike Extremely to 9 = Like Extremely) was used to evaluate liking for individual attributes and overall impression. Preference testing was conducted by asking participants to identify their preferred sample among multiple options. These results provided insight into product acceptance and consumer choices.

II. Just-About-Right (JAR) Scale
The JAR scale assessed the perceived appropriateness of the intensity of selected sensory attributes, depending on the experimental design. A 5-point scale was used, with “Just About Right” at the midpoint. Penalty analysis was applied to examine how deviations from the ideal level affected overall liking.

III. Check-All-That-Apply (CATA)
Participants were shown a list of sensory descriptors and asked to check all that applied to each sample. The descriptors were customized based on the experimental setup. CATA responses were analyzed using frequency and correspondence analysis to identify sensory perception patterns.

For traditional sensory testing, questionnaires were deployed using RedJade sensory software, ensuring accurate digital data collection. For virtual reality (VR) sensory testing, the questionnaires were embedded directly into the VR environment developed in Unity, allowing participants to answer questions while immersed in the virtual setting. This setup enabled seamless integration between sensory evaluation and virtual interaction, maintaining experimental control across testing modes.

4.8.1.2. Simulator Sickness Measures (SSQ)

The SSQ (Table 5) is commonly used to describe and evaluate simulator sickness. Participants are asked to rate 16 symptoms on a four-point scale (0-3). Factor analysis revealed that these symptoms can be classified into three groups: oculomotor, dizziness, and nausea (Kennedy et al., 1993).

The SSQ was calculated using the formula developed by Kennedy et al. (1993), in which each category has its specific SSQ symptoms that make up the score of severity.

The SSQ score is negligible when lower than 5. A minimal score should be between a score of 5 and 10, while a score of 10 to 15 is significant. A score of 15 to 20 is weighed as concerning. Lastly, a score of more than 20 will be severe.

Table 5: Determinations of the SSQ symptoms belonging to categories which are nausea, oculomotor, and disorientation (Kennedy et al., 1993).

SSQ Symptoms	Categories		
	Nausea	Oculomotor	Disorientation
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total	[1]	[2]	[3]

Score Calculation:
Nausea = [1] x 9.54
Oculomotor = [2] x 7.58
Disorientation = [3] x 13.92
Total Score = ([1] + [2] + [3]) x 3.74

4.8.1.3. Virtual Reality Neuroscience Questionnaires (VRNQ)

In VRNQ, adapted from Kourtesis et al. (2019), there were five primary categories: user experience, game mechanics, in-game assistance, and VR-induced symptoms and effects (VRISE). Each category comprised five questions, resulting in a total of 20 questions. All the bilingual questionnaires can be accessed in the Appendices.

4.8.1.4. Virtual Reality System Questionnaires (VRSQ)

The VRSQ (Table 6), adapted from Kim et al. (2018), focused on aspects related to the VR system. It consisted of 20 questions, covering elements such as headgear discomfort, system calibration, image lag, image blurriness, auditory surround, control of movement, ease of pointing and selection, and awareness of body location.

Table 6: The questions in VR System Questionnaire (VRSQ)

VR System Questionnaire (VRSQ) Questions
Head gear is
Calibrating the system and tracking
Image lags when head is turned slowly
Image lags when head is turned quickly
Image is blurred in some areas
All the image blurred
Image skips or break up at times
Image covers 360º surround
Trying to locate source of sounds
Trying to aim or point at targets using head position
Trying to aim or point at targets using hand/controller
Moving through space using head orientation
Orienting one's self in the space
Trying to turn and see what is to the left and right
Trying to turn and see what is behind
Awareness of body location
Location of hands and arms
Physically move in the virtual environment
Pick up and/or place items in the virtual environment
Overall experience with VR

4.8.1.5. Positive and Negative Affect Schedule (PANAS)

The PANAS (Table 7) is a widely used self-report questionnaire designed to measure the two broad dimensions of mood: positive affect (PA) and negative affect (NA) (Watson et al., 1988). Table 8 shows the questionnaire consisting of two separate 10-item scales, one for PA and one for NA. Positive emotions: Interested, Excited, Strong, Enthusiastic, Proud, Alert, Inspired, Determined, Attentive, Active, and Distressed. Meanwhile, negative emotions: Upset, Guilty, Scared, Hostile, Irritable, Ashamed, Nervous, Jittery, and Afraid.

Table 7: Positive and Negative Affect Schedule (PANAS) Questionnaire.

Emotions		Very slightly or not at all	A little	Moderately	Quite a bit	Extremely
PANAS 1	Interested	☐	☐	☐	☐	☐
PANAS 2	Distressed	☐	☐	☐	☐	☐
PANAS 3	Excited	☐	☐	☐	☐	☐
PANAS 4	Upset	☐	☐	☐	☐	☐
PANAS 5	Strong	☐	☐	☐	☐	☐
PANAS 6	Guilty	☐	☐	☐	☐	☐
PANAS 7	Scared	☐	☐	☐	☐	☐
PANAS 8	Hostile	☐	☐	☐	☐	☐
PANAS 9	Enthusiastic	☐	☐	☐	☐	☐
PANAS 10	Proud	☐	☐	☐	☐	☐
PANAS 11	Irritable	☐	☐	☐	☐	☐
PANAS 12	Alert	☐	☐	☐	☐	☐
PANAS 13	Ashamed	☐	☐	☐	☐	☐
PANAS 14	Inspired	☐	☐	☐	☐	☐
PANAS 15	Nervous	☐	☐	☐	☐	☐
PANAS 16	Determine	☐	☐	☐	☐	☐
PANAS 17	Attentive	☐	☐	☐	☐	☐
PANAS 18	Jittery	☐	☐	☐	☐	☐
PANAS 19	Active	☐	☐	☐	☐	☐
PANAS 20	Afraid	☐	☐	☐	☐	☐

Scoring:

- Positive Affect Score: Add the scores on PANAS items 1, 3, 5, 9, 10, 12, 14, 16, 17, and 19. Scores can range from 10 – 50, with higher scores representing higher levels of positive affect.
- Negative Affect Score: Add the scores on PANAS items 2, 4, 6, 7, 8, 11, 13, 15, 18, and 20. Scores can range from 10 – 50, with lower scores representing lower levels of negative affect.

Using a Likert-type scale, participants were asked to rate the extent to which they experienced each emotion or feeling during the VR sensory test. The scale ranged from 1 (very slightly or not) to 5 (extremely).

4.9. Data Processing and Statistical Analysis

The study will employ a combination of specialized software platforms and statistical methods to process and analyse ET data, VR engagement metrics, sensory evaluation results, and AI-based sensory predictions. Data preprocessing and analysis will be conducted using R, XLSTAT, Tobii Pro Lab, and Ocumen SDK (Python) to ensure comprehensive and accurate interpretation of the experimental results. Statistical tests and multivariate analysis methods will be applied to identify significant patterns, relationships, and differences across different experimental conditions.

4.9.1. Statistical Methods for Sensory Evaluation

Statistical analysis was conducted to evaluate differences in sensory perception, product acceptance, and cognitive responses across experimental conditions. The analyses aimed to identify significant effects of environment, method, and stimuli on sensory and behavioural responses, using R and XLSTAT software. Each method was selected for its suitability to the structure and nature of the collected data. All statistical tests were evaluated at a significance level of $\alpha = 0.05$, which was applied consistently across all analyses unless otherwise specified.

- Analysis of Variance (ANOVA) was used to test for statistically significant differences in sensory ratings such as liking, sweetness, and texture between conditions. Both one way and two-way ANOVA were applied depending on the number of independent variables. Post hoc comparisons were carried out using Tukey's Honestly Significant Difference test.
- Multiple Factor Analysis (MFA) was performed to explore relationships among sensory attributes, environmental context, and eye tracking measures. The data were pre-processed using z-score standardisation and grouped by modality blocks to ensure comparability across data types.
- Principal Component Analysis (PCA) was used to reduce the dimensionality of sensory and questionnaire data and to identify key variables contributing to perceptual differences. The first two principal components were visualised to interpret clustering of samples and participant responses.
- Agglomerative Hierarchical Clustering (AHC) was used to segment participants based on their sensory ratings, visual attention behaviour, product acceptance, and simulator sickness scores. Ward's method was applied with Euclidean distance as the dissimilarity metric.
- Wilcoxon Signed Rank Test was applied as a non-parametric alternative when assumptions of normality were violated. It was used to compare paired conditions such as VR versus traditional settings for sensory scores, gaze metrics, and cognitive load measures.
- Penalty Analysis for Just About Right (JAR) data was used to assess the impact of attribute deviations on overall liking. The percentage of respondents rating each attribute as too low or too high and the associated drop in liking were used to quantify penalty effects.
- Check-All-That-Apply (CATA) Analysis was conducted using correspondence analysis to examine associations between sensory terms and products. Cochran's Q test was used to determine if differences between samples were statistically significant.

4.9.2. Analysis of VR Engagement Metrics

VR engagement metrics will be analysed to assess the level of user immersion, cognitive load, and sensory engagement in different virtual environments. The following statistical methods will be applied using R and XLSTAT:

- Analysis of Variance (ANOVA): One-way and two-way ANOVA will be used to analyse differences in fixation count, gaze duration, and pupil dilation across experimental conditions. Post-hoc tests (e.g., Tukey's HSD) will be applied to identify specific pairwise differences.

- Multifactorial Analysis (MFA): MFA will be used to explore the relationship between sensory ratings, gaze behaviour, and environmental context.
- Principal Component Analysis (PCA): PCA will be applied to reduce dimensionality and identify the main factors driving differences in engagement and sensory perception.
- Hierarchical Cluster Analysis: Cluster analysis will group participants based on similarity in gaze behaviour, engagement patterns, sensory perception, and product acceptance. This method will reveal how different participant groups respond to various sensory and contextual factors.
- Wilcoxon Signed-Rank Test: Non-parametric comparisons will be conducted using the Wilcoxon test to identify significant differences in gaze behaviour, sensory ratings, pupil dilation, SSQ scores, and cognitive load between controlled and dynamic environments.

4.9.3. Preprocessing of ET Data

ET data will be collected using two platforms: Tobii Pro Lab (for desktop-based ET) and Ocumen SDK (for VR-based ET). Data preprocessing will involve cleaning, filtering, and extracting relevant ET metrics to ensure consistency and accuracy in gaze behaviour analysis.

<u>Tobii Pro Lab Data Processing</u>

Tobii Pro Lab will be used to collect and preprocess data from the desktop-based Tobii eye-tracker. The following preprocessing steps will be applied:

- Raw Data Cleaning: Removal of invalid data points caused by blinks, head movements, and calibration drift.
- Fixation Identification: Fixations will be classified based on velocity and duration thresholds using the I-VT (Velocity-Threshold Identification) algorithm. Fixations shorter than 60ms will be removed to avoid noise.
- Saccade Filtering: Saccadic movements will be filtered based on amplitude and velocity, with high-velocity saccades removed to prevent false identification of gaze shifts.
- Gaze Path Analysis: Sequence of gaze shifts between different areas of interest (AOIs) will be mapped to identify gaze patterns.

The following ET metrics will be extracted from Tobii Pro Lab:

- Fixation Duration – Average duration of fixations within each AOI
- Fixation Count – Total number of fixations on each AOI
- Gaze Path – Sequence and transition between different AOIs
- Pupil Dilation – Average change in pupil size as a measure of cognitive load
- Saccadic Velocity – Speed of gaze shifts between AOIs

Ocumen SDK Data Processing

ET data from VR-based experiments will be processed using Ocumen SDK in Python. The following steps will be applied:

- Calibration Adjustment: Calibration drift correction using Ocumen's built-in algorithms.
- Blink Removal: Removal of gaze points recorded during blinks or signal loss.
- Spatial Smoothing: Application of spatial filters to reduce noise and enhance gaze path resolution.
- AOI Definition: Virtual objects and labelling elements within the VR environment will be defined as AOIs.
- Heatmap Generation: Heatmaps will be generated to visualize gaze density and attention intensity on specific stimuli.

The following ET metrics will be extracted from Ocumen SDK:

- Fixation Duration – Time spent fixating on virtual objects
- Fixation Count – Number of fixations within defined AOIs
- Gaze Transition Probability – Likelihood of shifting gaze between AOIs
- Saccade Amplitude and Velocity – Magnitude and speed of gaze shifts
- Pupil Dilation – Changes in pupil size reflecting cognitive load and emotional engagement

Processed data from both Tobii Pro Lab and Ocumen SDK will be exported as CSV files and imported into R and XLSTAT for statistical analysis.

4.10. Ethical Considerations

The aim of the study was clearly explained to all participants before the start of the experiment to ensure that they fully understood the study objectives, procedures, and the use of VR headsets and ET technology. Participants were informed that their participation was voluntary and that they could withdraw from the experiment at any time without providing a reason or facing any penalties. Written informed consent was obtained from all participants before the study began. The consent form included the statement: "I am aware that my responses are confidential, and I agree to participate in this experiment." An affirmative reply was required for participation.

Participants were also informed about the potential discomforts associated with VR and ET, such as mild motion sickness, cognitive fatigue, and visual strain. Measures were implemented to minimize discomfort, including allowing participants to take breaks when needed and aiding if they experienced discomfort. If participants exhibited signs of motion sickness or distress, they were immediately withdrawn from the experiment and provided with appropriate support.

Data confidentiality and privacy were strictly maintained throughout the study. All data were anonymized and stored on a secure server accessible only to the research team. Personal identifying information was separated from sensory and ET data to prevent participant identification. Data analysis was conducted using coded participant IDs, and the results were reported in aggregate form to protect participant privacy.

Ethical approval for all five experiments was granted by the Institute of Food Science and Technology of the Hungarian University of Agriculture and Life Sciences (MATE). The approval numbers for each experiment are as follows:

- Experiment 1: MATE-BC/947-1/2023
- Experiment 2: MATE-BC/2098-1/2023
- Experiment 3: MATE-BC/2097-1/2023 and MATE-BC/2096-1/2023
- Experiment 4: MATE-BC/289-1/2024
- Experiment 5: MATE-BC/290-1/2024

The study was conducted in full compliance with the ethical guidelines outlined by the Declaration of Helsinki and the research policies of MATE. Participants were debriefed after the experiment and provided with an opportunity to ask questions or clarify concerns. No adverse events were reported during the study.

5. RESULTS AND DISCUSSION

5.1. Experiment 1: Virtual Sensory Laboratory Acceptability

5.1.1. Evaluation of VR-Induced Symptoms and Acceptance

5.1.1.1. Simulator Sickness Questionnaire (SSQ) Results

Based on Table 8, it is observed that nausea symptoms were minimal in all participants, while oculomotor and disorientation symptoms were severe. This resulted in the total SSQ score being categorized as severe. The symptoms under the nausea category include general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping. Most of these symptoms are related to the digestive system, and it's notable that almost all participants did not experience them. The sudden transition of participants to move after wearing the HMD appears to have affected their adaptation and ability to walk in the real world while in the virtual world.

Meanwhile, oculomotor and disorientation symptoms are more related to the central nervous system. Oculomotor symptoms are primarily associated with adjusting and coordinating eye position during movement, while disorientation plays a role in focusing and adapting to the environment or surroundings. This is particularly relevant when participants do not have experience with VR, as the virtual environment is new for all participants, and they need to adapt quickly.

Table 8: Simulator Sickness Questionnaire (SSQ) Score based on the symptoms.

Simulator Sickness Questionnaire (SSQ) Symptoms	Score ±Standard Deviation (SD)
Nausea	9.4 ±11
Oculomotor	23.2 ±18
Disorientation	36.9 ±29
Total Score	25.1 ±18

Oculomotor cybersickness includes symptoms such as blurred vision, difficulty focusing, and eyestrain. The oculomotor system involves the third cranial nerve (CN III), which controls eye muscle movement, pupil constriction, eye focusing, and upper eyelid position (Palmisano et al., 2020). It's noteworthy that experienced VR users tend to have significantly fewer overall cybersickness symptoms and oculomotor symptoms than inexperienced users (Da Silva Marinho et al., 2022).

5.1.1.2. Virtual Reality System Questionnaire (VRSQ) Results

The Virtual Reality System Questionnaire was used to evaluate participant experiences with the virtual sensory laboratory, focusing on usability, navigation, and visual performance. To assess the reliability of the questionnaire and its subscales, Cronbach's alpha was calculated for each of the 20 items.

Cronbach's alpha is a statistical coefficient commonly used to measure the internal consistency of questionnaire items that are designed to capture the same underlying construct. It provides an estimate of how closely related a set of items are as a group. Alpha values greater than 0.7 are generally considered acceptable, indicating that the scale is reliable.

In this study, all 20 items produced Cronbach's alpha values greater than 0.89, with most values equal to or above 0.90. This suggests that participants responded to the questionnaire items consistently across scenarios and that the instrument was highly reliable in capturing aspects of VR usability and experience.

The assumptions for applying Cronbach's alpha were verified. Although item variances differed, the inter item covariances remained proportionally stable, fulfilling the conditions for this method. Consequently, the high and nearly identical alpha values reflect uniform response behaviour across items and participants.

As shown in Table 9, the highest mean score was for overall experience with VR at 6.3, followed closely by items related to image coverage and head turning. These results confirm the strong acceptance of the virtual sensory lab and support its continued use in future immersive sensory studies.

Table 9: Mean of Virtual Reality System Questionnaire (VRSQ) Score and Cronbach's Alpha value.

Virtual Reality System Questionnaire (VRSQ)	Cronbach's α	Mean ±SD
Head gear is	0.90	5.4 ±1.34
Calibrating the system and tracking	0.90	6.0 ±1.14
Image lags when head is turned slowly	0.89	5.3 ±1.78
Image lags when head is turned quickly	0.90	5.1 ±1.66
Image is blurred in some areas	0.91	4.6 ±1.53
All the image blurred	0.90	5.2 ±2.18
Image skips or break up at times	0.90	5.6 ±1.84
Image covers 360º surround	0.90	6.3 ±1.43
Trying to locate source of sounds	0.90	5.6 ±1.79
Trying to aim or point at targets using head position	0.90	5.9 ±1.50
Trying to aim or point at targets using hand/controller	0.89	5.1 ±1.74
Moving through space using head orientation	0.90	5.8 ±1.38
Orienting one's self in the space	0.90	5.8 ±1.29
Trying to turn and see what is to the left and right	0.90	6.2 ±1.28
Trying to turn and see what is behind	0.90	5.9 ±1.46
Awareness of body location	0.90	5.5 ±1.16
Location of hands and arms	0.90	5.6 ±1.30
Physically move in the virtual environment	0.90	5.5 ±1.08
Pick up and/or place items in the virtual environment	0.90	4.8 ±1.40
Overall experience with VR	0.90	6.3 ±0.78

The similarity in Cronbach's alpha values arises from proportional consistency in inter item covariance across questionnaire items. Despite differing standard deviations, the internal structure of responses was homogenous.

All the questions are above the midpoint score of 4. The lowest average is for the statement "Image is blurred in some areas." This is likely due to the mismatch between eye fixation and the software, leading to blurred areas, especially when participants are looking at the product on the table.

As participants had no prior VR experience and it was a new encounter for them, postural instability could contribute to their adaptation to the VR environment. Research suggests that there is no significant difference in postural instability between experienced and non-experienced VR users if the user has sufficient time to adapt to the VR environment (Da Silva Marinho et al., 2022). Given that participants experienced sickness symptoms in the SSQ after 10 minutes in the VR environment, the time it takes for users to adapt to the environment can be an influential factor in cybersickness (Palmisano et al., 2020).

On the other hand, the highest average is for the statement "Overall VR experience" (6.3 ± 0.8). Participants found the VR experience interesting, exciting, and memorable. This positive feedback indicates that VR has the potential for research, particularly in the sensory science industries. In addition to hardware and system acceptability, cybersickness, as indicated in Table 9, is an important factor in determining overall acceptability in a virtual sensory laboratory.

5.1.1.3. Virtual Reality Neuroscience Questionnaire (VRNQ) Results

In validating both VRSQ and SSQ, VRNQ emerges as the most fitting questionnaire, offering comprehensive coverage of all relevant aspects. As indicated in Table 10, all the scores for Cronbach's α within each category surpass 0.7, signifying acceptable and good reliability as well as internal consistency. This underscores the appropriateness of VRNQ for evaluating the quality of the virtual reality experience, particularly in the realm of sensory science studies.

Table 10: Mean of Virtual Reality Neuroscience Questionnaire (VRNQ) Score and Cronbach's Alpha value.

Virtual Reality Neuroscience Questionnaire (VRNQ)	Cronbach's α	Mean ±SD
User experience	0.70	5.2 ±0.70
Game mechanics	0.83	4.7 ±0.83
In-game assistance	0.82	5.5 ±0.81
VRISE	0.82	6.4 ±0.70

The averages of the VRNQ for each category, with game mechanics registering the lowest average at 4.7. This aligns with the lowest score in VRSQ, specifically, "Image is blurred in some areas," a question falling within the game mechanics category.

The category of Virtual Reality Induced Symptoms and Effects (VRISE) in VRNQ may be correlated with SSQ. In VRNQ, VRISE obtained the highest average of 6.4, while in SSQ, the symptoms were classified as severe. This discrepancy could be attributed to the timing of the assessments. SSQ was administered in the middle of the experiment, when participants needed time to adapt to the environment, whereas VRNQ was conducted after the experiment, when participants were in a seated and rested position, having had ample time to acclimate. Traditional sensory analysis typically does not exceed 10 minutes for testing, as an extended duration may impact results.

5.1.1.4. Combined Analysis of SSQ, VRSQ, and VRNQ

This analysis aimed to explore patterns among participants based on their responses to three VR-related questionnaires: the Simulator Sickness Questionnaire (SSQ), the Virtual Reality Sickness Questionnaire (VRSQ), and the Virtual Reality Neuroscience Questionnaire (VRNQ). Since the scales of the three questionnaires were different, all data were standardised using z-score normalisation before analysis to ensure comparability.

To determine the optimal number of clusters, silhouette analysis was applied following the method described by Rousseeuw (1987). The silhouette index provides a measure of how well participants fit within their assigned cluster compared to other clusters. As shown in Figure 29, the highest silhouette value occurred at two clusters, indicating this as the most appropriate solution. While minor increases were observed between three and six clusters, the overall trend confirmed that two clusters provided the clearest and most stable segmentation. After six clusters, the silhouette values declined, which is expected given the total number of participants.

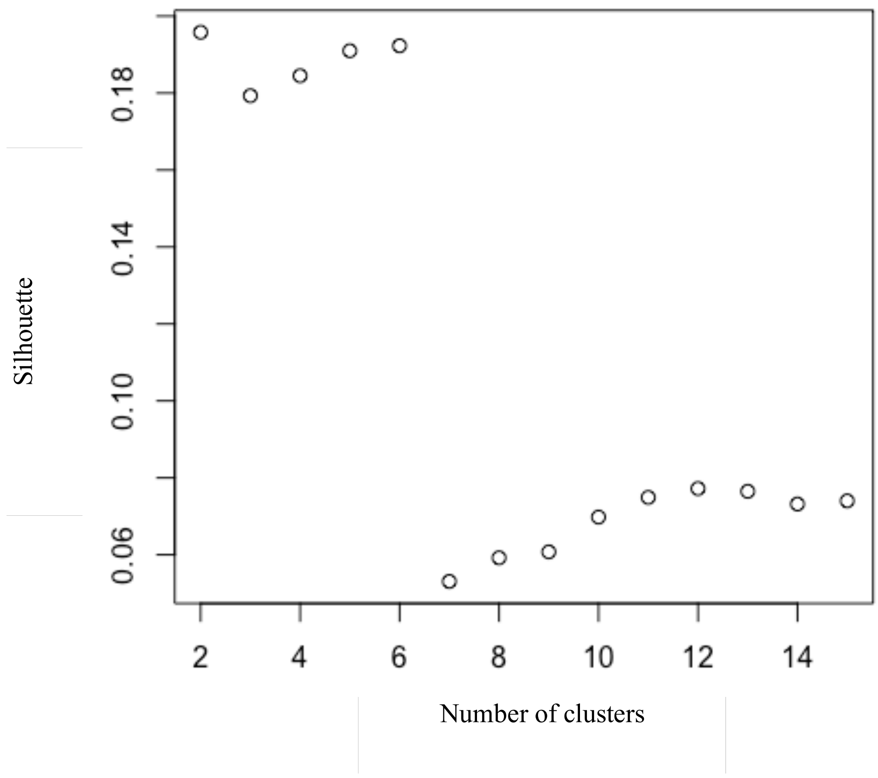


Figure 29: Silhouettes indices of the different cluster numbers.

Cluster analysis was performed using Agglomerative Hierarchical Clustering (AHC) with Ward’s method and Euclidean distance to explore the structure of participant responses. The clustering was visualised using dendrograms and validated using silhouette plots. Figure 29 illustrates the silhouette scores for different cluster solutions. Based on the results, k-means clustering was then applied to confirm the optimal number of clusters, resulting in two distinct participant groups (Figure 30). Cluster one included thirty six participants, while cluster two consisted of twenty four participants.

These clusters were later analysed to explore potential differences in sensory tolerance, discomfort, and engagement with the VR systems. This multivariate approach enabled the identification of subgroups with differing reactions to immersive sensory environments, supporting more tailored methodological recommendations.

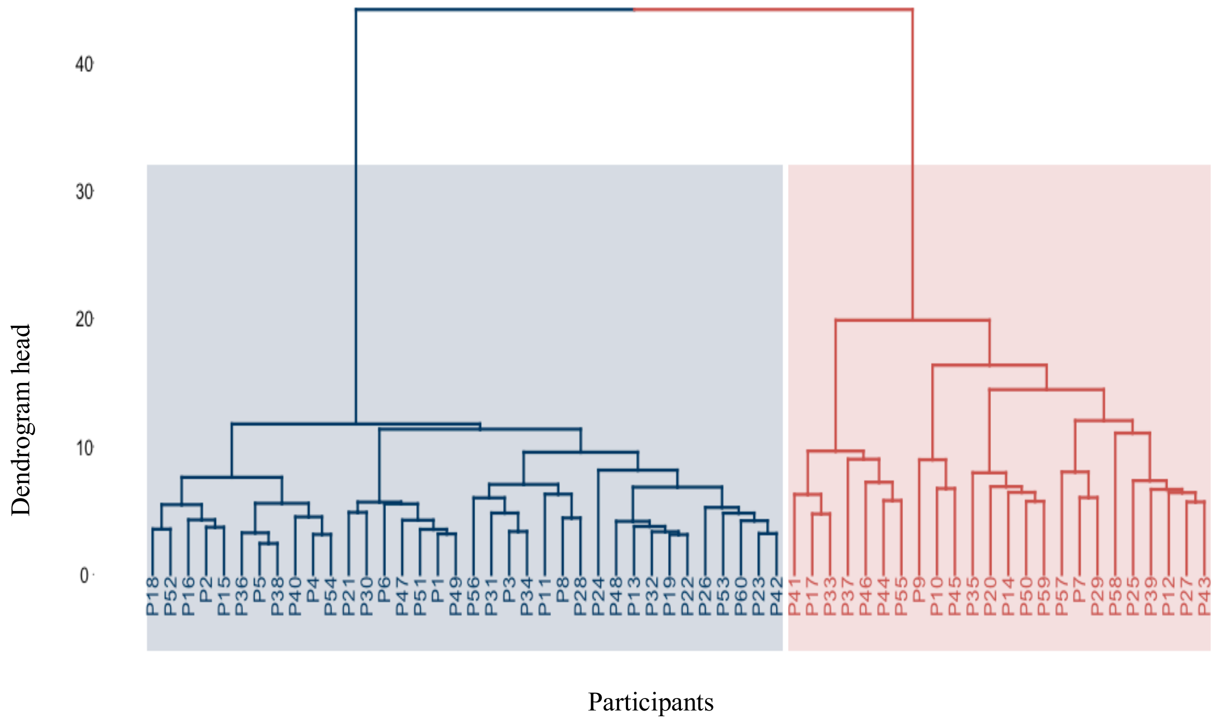


Figure 30: Dendrogram obtained after running k-means clustering with Ward's method on the data of the Simulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ) questionnaires. Blue background shows cluster 1, while the red background shows the members of cluster 2.

From the two clusters, mean and standard deviations had been calculated to determine the difference between the two clusters (Table 11). According to Table 11, the differences between Cluster 1 and Cluster 2 were examined, and distinctions for each item were identified through a Welch's t-test, where a p-value below 0.05 indicated a significant difference. In SSQ, all items exhibited a significant difference between the two clusters. In VRSQ, items such as "Location of hands and arms" and "Overall experience with VR" did not show significant differences, while other items displayed significant distinctions between the clusters. For VRNQ, only "Virtual Reality Induced Symptoms and Effects (VRISE)" showed significant differences between the two clusters.

This outcome is noteworthy, particularly for VRISE in VRNQ, as it is a condensed version of the SSQ questions. The sickness-related segment displayed a significant difference between the two clusters. A more detailed analysis of the SSQ results revealed that in Cluster 1, nausea and oculomotor symptoms were below severity, while disorientation was categorized as severe. In Cluster 2, only nausea was below severity, while oculomotor and disorientation fell within the severity range. The total SSQ score between the two clusters showed a significant difference, with Cluster 1 in the concerning score and Cluster 2 in the severe score. Regarding VRISE in VRNQ, Cluster 1 had a mean score of 6.6, and Cluster 2 had a mean of 6.1. Despite the significant difference, both scores are considered good on a 7-point hedonic scale.

Table 11: Score or mean on each cluster with Simulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ) and Virtual Reality Neuroscience Questionnaire (VRNQ) questionnaire.

Questionnaire	Symptoms/Questions/Categories	Cluster 1 Score/Mean ±SD	Cluster 2 Score/Mean ±SD
SSQ**	Nausea*	5 ±7.4	16 ±13
	Oculomotor*	15 ±9.2	36 ±21
	Disorientation*	24 ±19.1	57 ±31
	Total score*	16 ± 9.6	39 ±19
VRSQ***	Head gear is*	5.7 ±1.09	5.0 ±1.6
	Calibrating the system and tracking*	6.4 ±0.69	5.5 ±1.4
	Image lags when head is turned slowly*	6.1 ±0.98	4.2 ±2.1
	Image lags when head is turned quickly*	5.7 ±1.34	4.2 ±1.7
	Image is blurred in some areas	4.8 ±1.53	4.2 ±1.5
	All the image blurred*	6.1 ±1.47	4.0 ±1.5
	Image skips or break up at times*	6.4 ±0.90	4.3 ±2.2
	Image covers 360º surround*	6.8 ±0.55	5.7 ±2.0
	Trying to locate source of sounds*	6.3 ±0.98	4.6 ±2.2
	Trying to aim or point at targets using head position*	6.6 ±0.65	5.0 ±1.9
	Trying to aim or point at targets using hand/controller*	5.9 ±1.22	4.0 ±1.9
	Moving through space using head orientation*	6.5 ±0.70	4.9 ±1.6
	Orienting one's self in the space*	6.3 ±0.85	5.2 ±1.6
	Trying to turn and see what is to the left and right*	6.6 ±0.73	5.7 ±1.7
	Trying to turn and see what is behind	6.2 ±0.99	5.4 ±1.9
	Awareness of body location*	5.8 ±0.96	5.0 ±1.3
	Location of hands and arms	5.9 ±0.89	5.2 ±1.7
	Physically move in the virtual environment*	5.9 ±0.71	4.9 ±1.2
	Pick up and/or place items in the virtual environment*	5.2 ±0.97	4.2 ±1.7
	Overall experience with VR	6.4 ±0.55	6.1 ±1.0
VRNQ***	User experience	5.2 ±0.72	5.1 ±0.69
	Game mechanics	4.7 ±0.76	4.7 ±0.94
	In-game assistance	5.5 ±0.80	5.4 ±0.86
	VRISE*	6.6 ±0.39	6.1 ±0.90

Simulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ).
*The items had a significance difference where the p-value is less than 0.05.
** SSQ using a score which a score below than 5 is negligible, between 5 to 10 is minimal, between 10 to 15 is significant, between 15 to 20 is concerning and score above 20 is severe.
***VRSQ and VRNQ score is a 7-point hedonic scale which 1 is the lowest and 7 is the highest.

5.1.2. Smelling Task Performance and Results

The smelling task was designed to assess participants' ability to identify aromas commonly associated with bakery products. This task followed an earlier phase in the experiment, where participants explored a virtual sensory booth and identified various bakery items. As such, participants were already exposed to bakery-related stimuli before completing the smelling task, and this prior exposure was expected to influence their olfactory responses.

Five aromas were selected based on their relevance to bakery products: lemon, strawberry, cinnamon, vanilla, and caramel. These scents were coded with three-digit random numbers and prepared using the following chemical compounds: D-Limonene (lemon, CAS: 5989-27-5), Ethyl methylphenylglycidate (strawberry, CAS: 77-83-8), Cinnamaldehyde (cinnamon, CAS: 14371-10-9), Vanillin (vanilla, CAS: 121-33-5), and Maltol (caramel, CAS: 118-71-8). The scents were prepared according to ISO 5496:2006 standards (International Organization for Standardization, 2006) and placed inside airtight test tubes containing absorbent paper strips. Participants smelled each strip and attempted to identify the aroma.

The purpose of this task was to evaluate the feasibility of integrating olfactory evaluation in a VR-based sensory setting using simple aroma cues from bakery contexts.

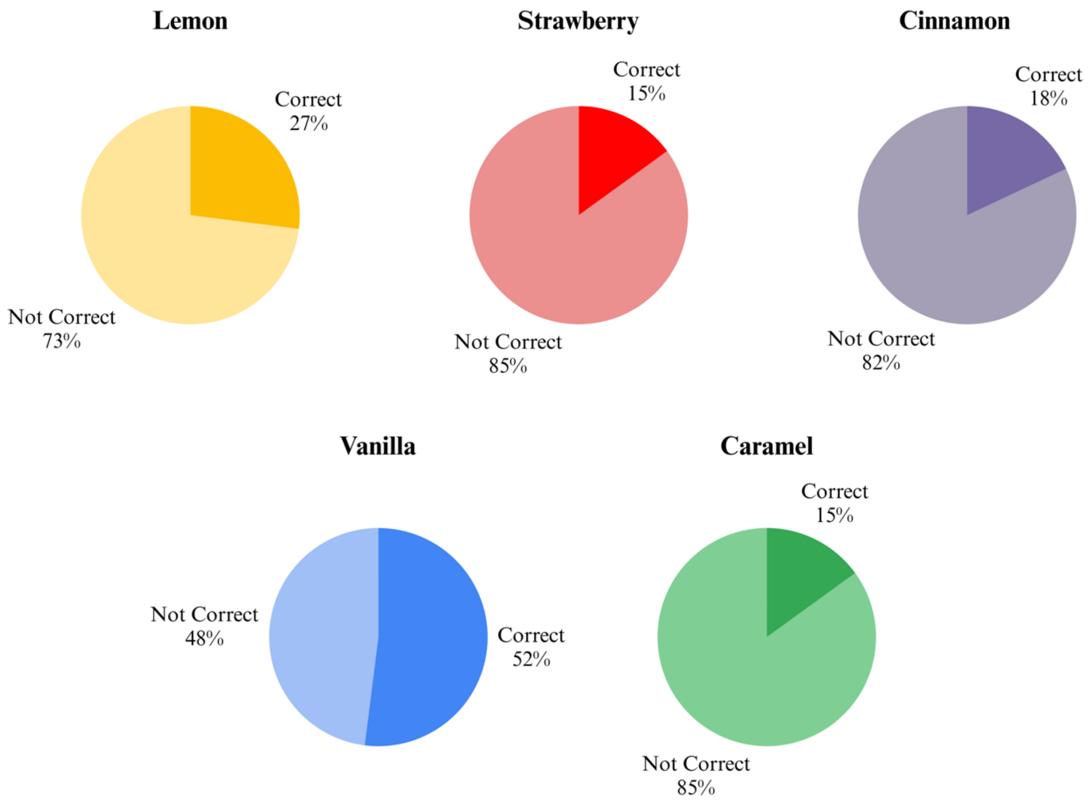


Figure 31: The results of the participants that can identify the sensory sticks with five aromas (lemon, strawberry, cinnamon, vanilla, and caramel)

According to the Figure 31, 52% of participants were successful in correctly identifying the vanilla scent. Other scents that were correctly identified but fell short of 20% included lemon

(15%), strawberry (17%), cinnamon (18%), and caramel (17%). The smelling task was affected by the participants' exposure to various bakery products and manipulation of their olfactory systems in the first task of the experiment, which required them to identify various bakery items in a virtual sensory booth.

This finding aligns with studies by Brengman et al. (2022) and Flavián et al. (2021) that examine into scents and VR. The environmental context or imagery played a role in influencing the perception of smell, along with exposure. The initial task of the experiment, where participants identified various bakery items in the virtual sensory booth, likely influenced the smelling task by exposing participants to an array of bakery products and manipulating their olfactory systems.

5.1.2.1. Scent identification and within same category

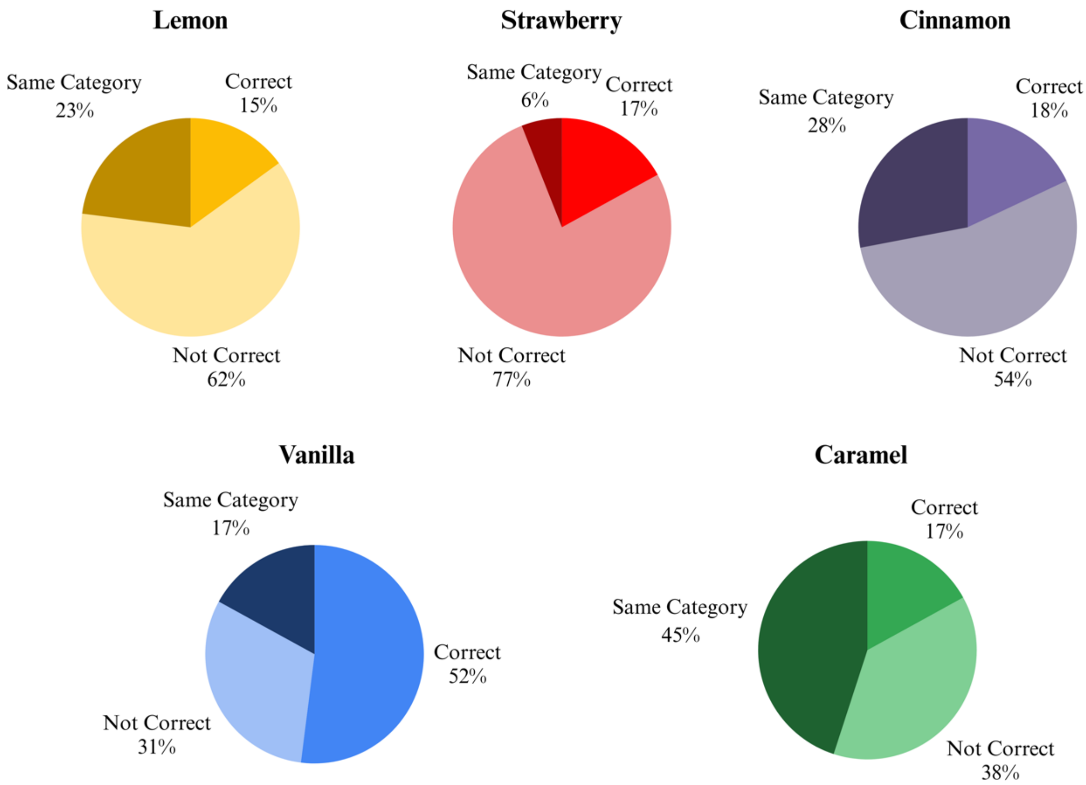


Figure 32: Scent identification including the same category from the participants of lemon, strawberry, cinnamon, vanilla, and caramel.

One of the easiest scents to be identify is vanilla as it is a common scent that is associated with bakery or pastry products. Figure 32 shows the detailed answer of vanilla which 52% of participants were able to identify the scent. 31% cannot identify the scent and 17% were able to identify the scent in the same category (Sweet, Sugar, Candy). The aroma of vanilla has been found to have cross modal effects on perception. In a study on cross modal correspondences between scents and shapes, vanilla was correlated with rounded shapes (Brianza et al., 2022). This suggests that the perception of vanilla scent may influence how people perceive the shape or form of bakery products, potentially enhancing the perception of softness and smoothness (Brianza et al., 2022).

The scent of cinnamon is usually associated with seasonal bakery products such as Christmas or Thanksgiving festive. Only 18% of the participants could identify the scent correctly while 28% identified on the same category (Spices, Almond). Most (54%) of the participant were unable to identify the scent but the participant had associated the smell with seasonal products. The scent of cinnamon in bakery products is often associated with feelings of nostalgia and can have a significant impact on consumer perception and behaviour (Brianza et al., 2022). The aroma of cinnamon can evoke positive emotional responses and trigger memories of past experiences, creating a sense of familiarity and comfort (Brianza et al., 2022). This nostalgic effect of cinnamon scent can contribute to the overall sensory experience of bakery products and enhance their appeal to consumers.

For the caramel scent, 38% cannot identify the scent or mixed up with vanilla scent. While 17% of the participants were able to guess the scent and 45% were guessed in the same category (Burnt, Coffee, Chocolate, Bourbon, Butter). A lot of participants guessed in the same category as caramel can be paired with smell of burnt and creamy. Caramel scent can indeed be challenging to identify in certain bakery items. The caramel scent in bakery products is a desirable and distinct aroma that adds depth and richness to various baked goods. Caramelization, which occurs when sugar is heated, plays a crucial role in the formation of the caramel scent and flavour in bakery products (Ertuğral, 2021). During the caramelization process, sugars undergo non-enzymatic chemical reactions, such as the Maillard reaction and caramelization, resulting in the formation of various aroma compounds (Ertuğral, 2021).

77% of the participants were unable to identify the strawberry scent while 17% were able to identify correctly. The other 6% can identify on the same category (Berry, Raspberry). This is a bit difficult to identify as the bakery items shown does not related with strawberry scent. While strawberry is considered to have a distinct and recognizable aroma, it may not always be easy to identify in bakery products due to the presence of other ingredients and flavours (Choudhary et al., 2021). Research has shown that the aroma of strawberry is complex and consists of various volatile organic compounds that contribute to its characteristic scent. These compounds work together to create the unique and fruity aroma of strawberry (Szakál et al., 2022).

The scent of lemon was the most difficult for participants to identify among all tested aromas. Only 15% of participants correctly identified it as lemon, while 23% selected related descriptors such as citrus, orange, or vitamin C, which belong to the same general aroma category. The remaining 62% were unable to identify the scent. Recognising the lemon scent in bakery products can be particularly challenging due to the complexity of aroma profiles and the influence of other ingredients. Lemon essential oil is commonly used as a flavouring agent in bakery applications such as confectionery, desserts, and baked goods, but its characteristic profile may be masked or altered when combined with other strong sensory elements (İncegül et al., 2018). While these components can contribute to the flavour profile of the baked goods, the scent might not be as prominent as in other contexts like cleaning products or personal care items (İncegül et al., 2018).

Scents and VR were used in Brengman et al. (2022) and Flavián et al. (2021) studies. Both the smell and the exposure were affected by the environment or image's set off. The perception of food smell and the influence of the environment or image's set off in VR can be understood through the concept of cross-modal correspondences and the impact of sensory cues on perception. Odour quality and the ability to discriminate odours can be affected by previous experiences and associations (Adams et al., 2014). This suggests that the environment or image's set off in VR, which includes visual cues, can influence the perception of food smell by activating relevant memories and associations.

5.1.2.2. Analysis of smell identification.

Multiple Factor Analysis (MFA) was performed to jointly analyse the sensory identification data and the associated emotional responses. This method allowed for the integration of multiple data types and revealed dimensions of shared variability among aroma recognition patterns and affective responses.

Based on Figure 33, only one participant (P42) was able to correctly identify all five aromas, while seventeen participants failed to identify any of the scents. The relationships between correct and incorrect responses revealed distinct clustering patterns. For example, lemon and caramel responses, both correct and incorrect, appeared closely related. Similarly, vanilla, cinnamon, and strawberry responses were grouped together for both correct and incorrect identifications.

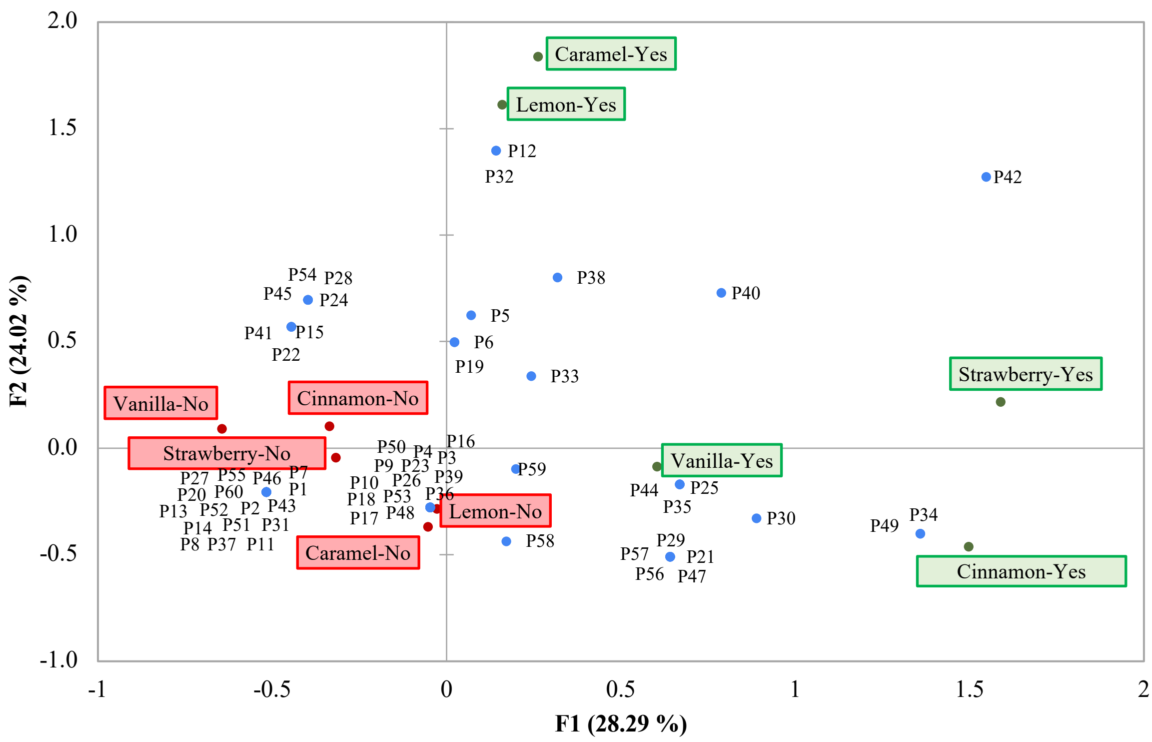


Figure 33: Multiple Factor Analysis (MFA) on the participants who can and cannot identify the scent (vanilla, cinnamon, caramel, strawberry, and lemon). YES and NO indicates if the scent was identified correctly or not. Scents closer to each other indicate that they were identified by the same participants.

Vanilla was identified by the highest number of participants. This finding aligns with earlier studies indicating that vanilla is one of the most pleasant and easily recognisable odours (Arshamian et al., 2022). These results suggest that certain aromas, such as vanilla, are more universally recognised, while others, including lemon and caramel, may be more difficult to identify due to perceptual ambiguity or individual differences in olfactory sensitivity.

5.1.3. Comments and Participant's Experience

Several participants provided positive and insightful feedback during the experiment, particularly as they were new to the VR experience. Many expressed sentiments such as "It was a very interesting experience" and "It was a very good experience." Some comments focused on the image quality and graphics, with remarks like "The image is pixelated, there is a delay when moving your head quickly. Sitting down on a chair is a bit bizarre/scary if the chair is there." Participants also shared observations related to disorientation and feelings of sickness, noting that "It gives a good picture of the environment, but it is more difficult to move and coordinate in the meantime" and "It was a good experience to be in a VR environment, but afterwards there was a slight dizziness to return to reality."

Additionally, there were intriguing comments about the impact of the virtual sensory laboratory's images on the perception of scents. Participants mentioned, "It was a thrilling experience, and it was interesting how our senses (primarily sight) can be deceived", "It was surprisingly easy to move around in the virtual space, it was very lifelike, recognizing scents was not easy", and "I felt the pictures made me smell different than what it actually was". These comments provide valuable insights into the participants' experiences and perceptions during the VR experiment.

5.1.4. Implications for Virtual Sensory Laboratory Development

Considering the Simulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ) scores or means, and the participants comments the inclusion of all participants in the experiment give a valuable implication to this study are extensive, with profound effects on various domains, including academia and industry. Stakeholders such as sensory scientists, the food industry, educators, technology developers, and marketing professionals can extract substantial benefits from the development and validation of the virtual sensory laboratory (Crofton et al., 2019b).

For sensory scientists, this study represents a significant leap in research methodologies. The integration of virtual reality (VR) technology into sensory science opens up unexplored avenues for comprehending consumer behaviour, preferences, and product evaluations (R. Liu et al., 2019). The virtual sensory laboratory stands out as a pioneering tool, allowing researchers to examine into and analyse sensory experiences in a meticulously controlled yet immersive environment. This development propels the evolution of sensory science methodologies, ushering in a new era of research possibilities (Hathaway & Simons, 2017). The food industry emerges as a major beneficiary, tapping into the insights gleaned from VR-based sensory studies. Understanding consumer reactions and preferences within a virtual environment offers invaluable information for product development and marketing strategies (Lombart et al., 2020). The innovative use of VR in product design enhances the industry's ability to create offerings that align closely with consumer expectations, thereby contributing to increased consumer satisfaction and the overall success of food-related businesses (Sinesio et al., 2019).

The virtual sensory laboratory plays a dual role in education, serving as both a research tool and a training platform (Sánchez-Cabrero et al., 2019). As an educational tool, it provides a controlled yet immersive environment for training sensory scientists, food technologists, and industry professionals. This bridge between theoretical knowledge and practical application enhances the skill development of individuals in the sensory evaluation field, ensuring a well-equipped workforce for the industry. Moreover, the study offers valuable feedback for the ongoing development of VR technology tailored specifically for sensory analysis (Stelick et al., 2018). Identifying challenges related to image quality, adaptation time, and overall user experience guides technological advancements, contributing to the refinement of VR tools. This, in turn, fosters continuous improvement in the broader field of VR research, setting the stage for future innovations and applications.

The consumer-centric insights derived from this study hold substantial importance for businesses and marketing professionals. Understanding consumer behaviour in a virtual environment provides a unique perspective on product preferences, purchasing decisions, and overall consumer experiences (Lombart et al., 2020). This depth of insight informs targeted marketing strategies and product positioning, offering a competitive advantage in the market. The interdisciplinary nature of VR research in sensory science emphasized by this study encourages cross-disciplinary collaboration. The intersection of psychology, technology, and food science calls for collaborative efforts between researchers, computer scientists, and sensory analysis experts (Crofton et al., 2019b; Gere, Zulkarnain, et al., 2021). This collaborative approach is poised to further refine and expand the applications of VR in diverse fields, unlocking new possibilities and avenues for exploration. The implications of this study extend far beyond the confines of traditional sensory science. They pave the way for a paradigm shift in research methodologies, educational practices, technological innovations, and industry applications. As the virtual sensory laboratory becomes a cornerstone for future research endeavours, its impact is poised to resonate across academia and industry, shaping the trajectory of sensory science in the dynamic landscape of virtual reality

5.2. Experiment 2: Comparison between Traditional and VR Sensory Testing

5.2.1. Comparison on Traditional and VR Sensory Analysis.

The Figure 34 shows the Multiple Factor analysis (MFA) between types of sensory testing (traditional and VR) which is the factor distance between the types of sensory testing is closely to each other. The average (mean±SD) score of the types of sensory testing based on 9 scores hedonic test, traditional sensory testing have 5.23±0.87 while VR sensory testing is 5.53±0.73. There are no significant differences between the types of sensory testing p-value = 0.43.

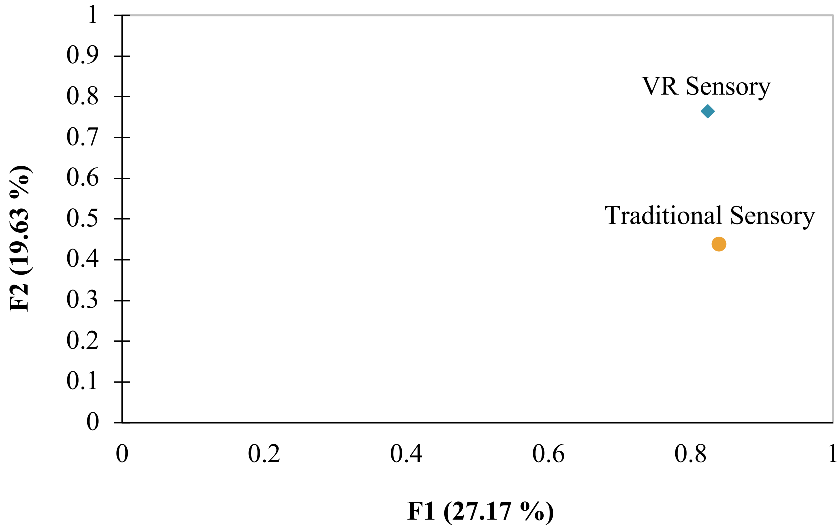


Figure 34: Multiple Factor analysis (MFA) between types of sensory testing (traditional and virtual reality)

5.2.2. Comparison on Traditional and VR Sensory attributes.

A study was conducted to compare traditional sensory testing with virtual reality (VR) sensory testing. The analysis will include each product attribute and the type of testing. According to the results of the two-factorial ANOVA, there were no significant differences found between the type of testing and the attributes of sweetness (p-value = 0.054), sourness (p-value = 0.991), and overall liking (p-value = 0.632). The data in Figure 35 illustrates the MFA of traditional and VR sensory attributes. This can be validated further which shows that the distance between each traditional and VR attribute are close to each other.

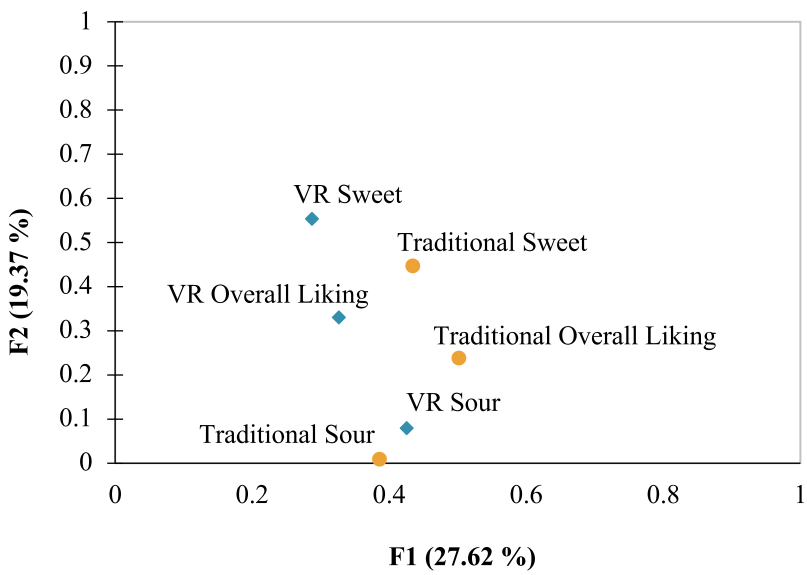


Figure 35: Multiple Factor analysis (MFA) between traditional and virtual reality sensory attributes

5.2.3. Comparison of Traditional and VR Sensory attributes for each category.

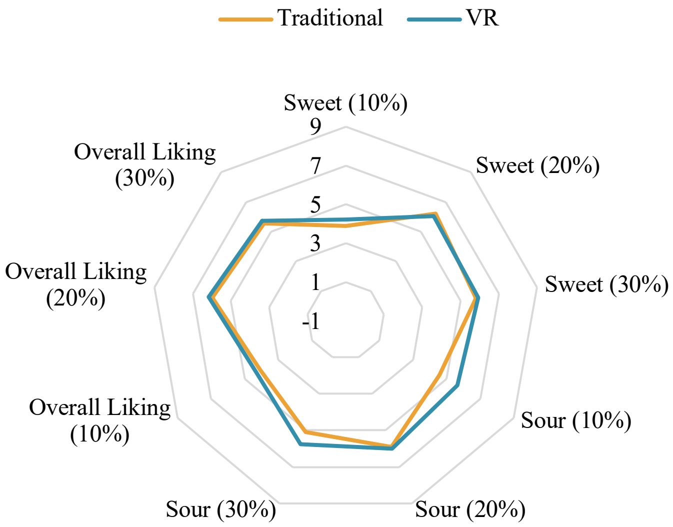


Figure 36: Radar chart comparing the different types (Traditional and Virtual Reality sensory) of testing with individual attributes.

Figure 36 is a radar chart comparing the different types (Traditional and VR sensory) of testing with individual attributes and based on the table presents a comparison of sensory attributes—Sweetness, Sourness, and Overall Liking between traditional and virtual reality (VR) methods at three sugar concentrations (10%, 20%, and 30%). Across all sugar levels, mean scores for VR samples were slightly higher or comparable to their traditional counterparts, suggesting a consistent trend toward equal or enhanced perception in the VR setting. However, statistical analysis revealed no significant differences in any of the attributes at any sugar level, with all p-values exceeding 0.05. These findings indicate that while VR may provide an immersive testing environment, it does not significantly alter sensory perception outcomes compared to traditional methods (Table 12).

Table 12: Sensory scores (mean ± SD) for Sweetness, Sourness, and Overall Liking under Traditional and VR conditions at 10%, 20%, and 30% sugar levels with p-values.

Attribute	Method	10% Mean ± SD	20% Mean ± SD	30% Mean ± SD	p-value (10%)	p-value (20%)	p-value (30%)
Sweetness	Traditional	3.88 ± 2.61	6.21 ± 2.44	5.81 ± 2.52	0.141	0.642	0.753
	VR	4.24 ± 2.55	6.05 ± 2.52	5.93 ± 2.59			
Sour	Traditional	4.57 ± 3.22	5.90 ± 2.55	5.07 ± 2.22	0.108	0.856	0.180
	VR	5.64 ± 2.82	6.00 ± 2.24	5.76 ± 2.22			
Overall Liking	Traditional	4.07 ± 2.74	5.98 ± 2.41	5.55 ± 2.33	0.675	0.700	0.733
	VR	4.31 ± 2.43	6.17 ± 2.09	5.71 ± 2.13			

The Figure 37 shows the Multiple Factor analysis (MFA) between types of sensory testing and each of the individual attributes, which is the factor distance between the types of sensory testing is close to each other except for sour attributes.

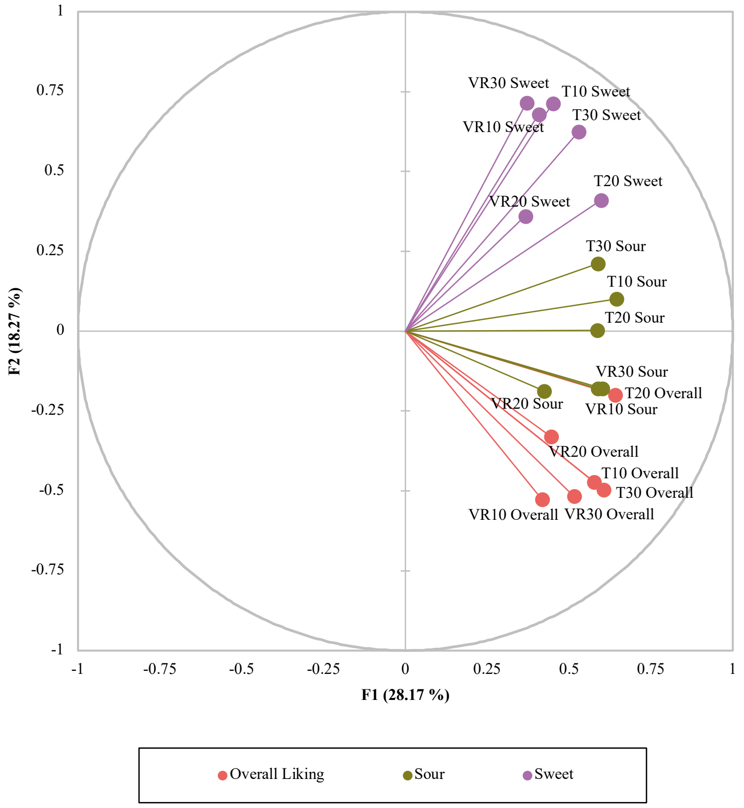


Figure 37: Multiple Factor analysis (MFA) between types of sensory testing (traditional and virtual reality) and each of the individual attributes.

5.2.3.1. Sour Attributes

Although there are no significant differences in the sour attribute, it is interesting to observe in Figure 38 MFA that the sour distance distribution for the traditional method is closely grouped, while the VR distribution is also closely grouped. This differs from other attributes, where the traditional and VR distributions for each attribute are more closely related.

Sensory analysis of sour taste in lemonade can be challenging due to the complex nature of taste perception. Sour taste perception is triggered by acidic foods and substances (Diószegi et al., 2019). The perception of sourness can vary between different types of teas, as evidenced by the stronger sour taste in black tea compared to green tea (Zhang et al., 2022). Additionally, individual differences in taste sensitivity and taste modality recognition can lead to taste confusion, such as sour–bitter and umami–salty (Puputti et al., 2019). Furthermore, the quality of sour food products, such as red sour soup, can be evaluated through the sensory analysis (Yangbo et al., 2021). The addition of dried sour plum has been shown to improve the sensory properties of pineapple drinks, indicating the potential for enhancing sour taste in beverages (Hamzah & Sarbon, 2022).

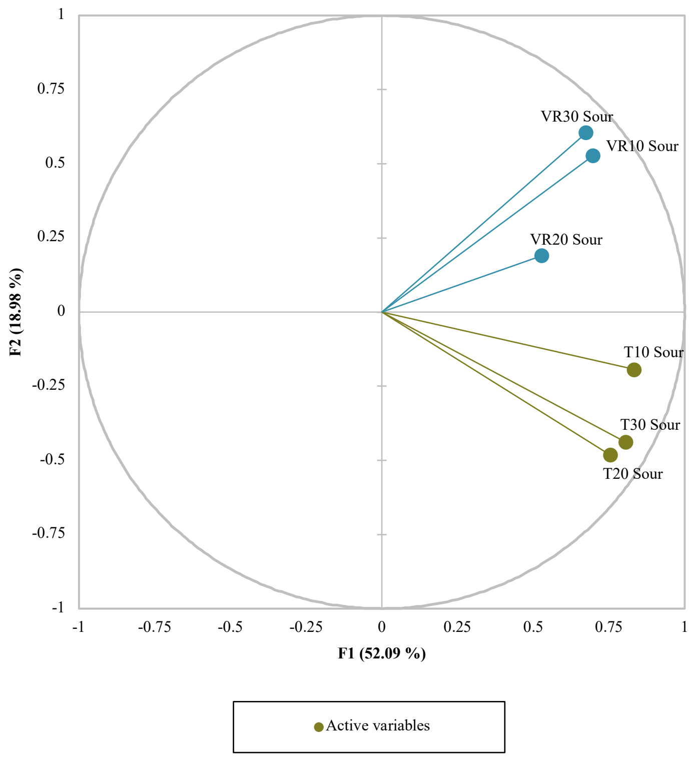


Figure 38: Multiple Factor analysis (MFA) between types of sensory testing (traditional and virtual reality) and each of the individual attributes of sour.

Moreover, the human ability to recognize five basic tastes, including sour, has been well-established (Jeruzal-Świątecka et al., 2020). The interaction between sweetness and sourness has been studied, showing high sensitivity to both tastes (Junge et al., 2020). Establishing a standardized method for analysing sourness is crucial for obtaining uniform conclusions in the sensory analysis (Mao et al., 2021). Furthermore, there is a significant positive correlation between bitter and sour taste perception, indicating potential interactions between these taste modalities (Pagliarini et al., 2021).

The perception of sour flavour involves multisensory integration, and the brain responses to sour taste and smell have been investigated in young healthy adults (Suen et al., 2021). Additionally, the dynamic perception of simplified lemonade has been studied using temporal dominance of sensations and temporal check-all-that-apply methods, shedding light on the temporal aspects of the sour taste perception (Wu et al., 2019). The sensory analysis of sour taste in lemonade is influenced by various factors, including individual differences in taste perception, the interaction between sourness and other tastes, and the temporal aspects of sour taste perception. Understanding these complexities is essential for accurately evaluating and enhancing the sensory properties of sour beverages.

5.2.4. Emotional Response Analysis Using Positive and Negative Affect Schedule (PANAS)

5.2.4.1. Overall PANAS Score

In Figure 39, the PANAS Score indicates that positive emotions before the experiment had a mean score of 32.79±10.19, which increased to 35.33±9.12 after the experiment. However, there was no significant difference (p-value = 0.115) in the emotional state before and after the experiment. On the other hand, the negative emotions before the experiment had a mean score of 15.31±7.34, which decreased to 12.52±3.88 after the experiment. This indicates a statistically significant difference in the emotional state before and after the experiment (p-value = 0.016).

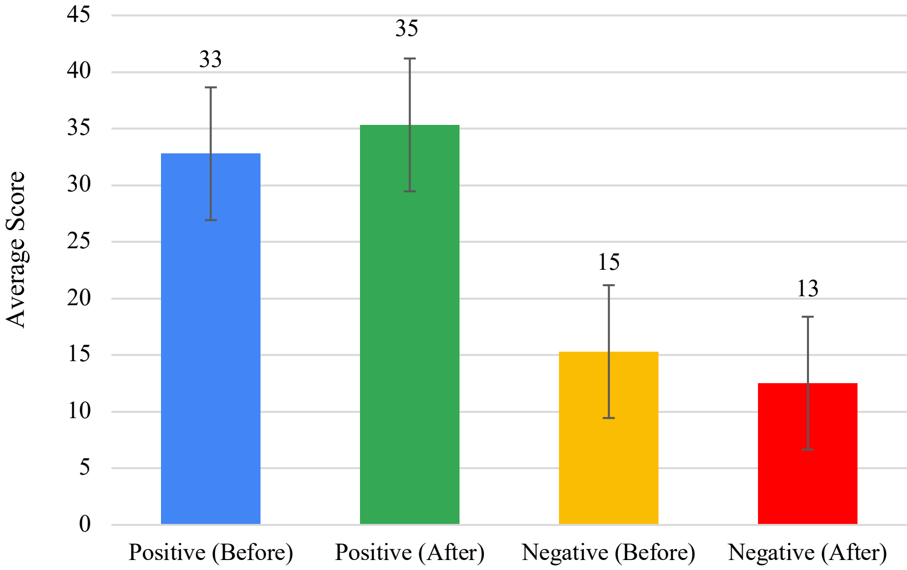


Figure 39: Positive and Negative Affect Schedule (PANAS) Score before and after experiment. The whiskers indicate the minimum and maximum values observed, illustrating the full range of responses for each condition.

Previous studies showed that VR was associated with positive emotion increases and negative emotion decreases. Yeo et al. (2020) found that computer-generated VR was linked to significantly more significant improvements in positive affect compared to other media, mediated by greater experienced presence and increases in nature connectedness. Similarly, Browning et al. (2020) observed that positive affect remained constant in the virtual condition while negative affect decreased. Furthermore, Ślósarz et al. (2022) reported a significant increase in positive emotions following VR intervention, compared to negative emotions during the post-test. These findings collectively support the notion that VR experiments can lead to an increase in positive emotions and a decrease in negative emotions.

Moreover, Pavic et al., (2023a) highlighted encouraging results regarding the effectiveness of VR in fostering positive emotions. Additionally, Lavoie et al. (2021) suggested that stronger experiences of emotions, particularly fear, in VR tasks are associated with higher levels of asymmetry for negative emotions. This indicates that VR can elicit intense emotional responses, potentially leading to a decrease in negative emotions. Furthermore, Liu et al. (2020) found that using VR headsets significantly increased self-efficacy, increased positive emotions, and decreased negative emotions in patients with fibromyalgia.

However, it is essential to note that VR experiences can also have potential negative emotional consequences. Basbasse et al. (2022) revealed that intensified negative emotions resulting from VR significantly correlated with negative rumination. Similarly, Frentzel-Beyme & Krämer (2023) discussed how emotionally charged historical VR experiences might decrease critical, cognitive reflection and lead to strong emotional reactions. Therefore, while VR experiments have the potential to increase positive emotions and decrease negative emotions, they may also have adverse emotional effects.

5.2.4.2. Individual PANAS Item Analysis

Table 13: Mean of Positive and Negative Affect Schedule Questionnaire Scores.

	Emotions	Before			After			p-value	Emotion increased (↑) or decreased (↓)
		Mean ± SD			Mean ± SD				
Positive	Interested	3.95	±	1.13	4.45	±	0.67	0.008	↑
	Excited	3.50	±	1.27	4.00	±	1.13	0.030	↑
	Strong	3.21	±	1.35	3.33	±	1.44	0.349	
	Enthusiastic	3.38	±	1.19	3.64	±	1.27	0.166	
	Proud	2.93	±	1.47	3.67	±	1.43	0.011	↑
	Alert	2.64	±	1.39	2.21	±	1.57	0.095	
	Inspired	3.33	±	1.26	4.00	±	1.10	0.006	↑
	Determine	3.07	±	1.30	3.17	±	1.50	0.378	
	Attentive	3.21	±	1.42	3.07	±	1.63	0.335	
	Active	3.55	±	1.23	3.79	±	1.12	0.178	
Negative	Distressed	1.88	±	1.15	1.74	±	1.21	0.291	
	Upset	1.48	±	1.09	1.24	±	0.79	0.127	
	Guilty	1.48	±	0.99	1.10	±	0.43	0.013	↓
	Scared	1.29	±	0.77	1.14	±	0.52	0.162	
	Hostile	1.50	±	0.99	1.33	±	0.72	0.191	
	Irritable	1.62	±	1.13	1.33	±	0.90	0.101	
	Ashamed	1.29	±	0.64	1.10	±	0.37	0.049	↓
	Nervous	1.95	±	1.19	1.17	±	0.44	6.399E-05	↓
	Jittery	1.67	±	1.00	1.36	±	0.82	0.063	
	Afraid	1.17	±	0.38	1.02	±	0.15	0.013	↓

Darker shade represents a significant increase in positive emotions, while lighter shade represents a considerable decrease in negative emotions.

Table 13 shows the average of emotions before and after the experiment with a p-value showing the results of two-sample t-tests. Several emotions had significance before and after the experiment. The positive emotions that had significant differences and increased after the experiment are "Interested," "Excited," "Proud," and "Inspired," in which the emotions increase. The Negative emotions that decreased were "Guilty," "Ashamed," "Nervous," and "Afraid" (Table 13), in which the emotions decreased.

5.2.4.3. Participants Positive and Negative Affect Schedule (PANAS) score

Figure 40 shows individual PANAS scores. 61.90% of the participants increased in positive emotions, while 38.10% decreased in positive emotions. Meanwhile, 57.14% of participants fell in negative emotions, and 7.14% increase in negative emotions. Individuals with significant positive emotion differences are P2, P33, P34, P37, P38, P39, and P40. At the same time, highly significant differences in negative emotion were found for P7, P22, P29, P31, and P32.

This reinforces the discussion regarding the interplay between VR sensory evaluation and participants' emotional states. The observed rise in positive emotions aligns with the immersive nature of VR experiences, suggesting its potential to evoke positive effects. Simultaneously, decreasing negative emotions implies a positive emotional impact associated with engaging in VR sensory evaluations. These findings contribute to a comprehensive understanding of how VR environments influence and enhance emotional states, highlighting the potential for positive emotional effects and reducing negative emotional responses within the sensory analysis.

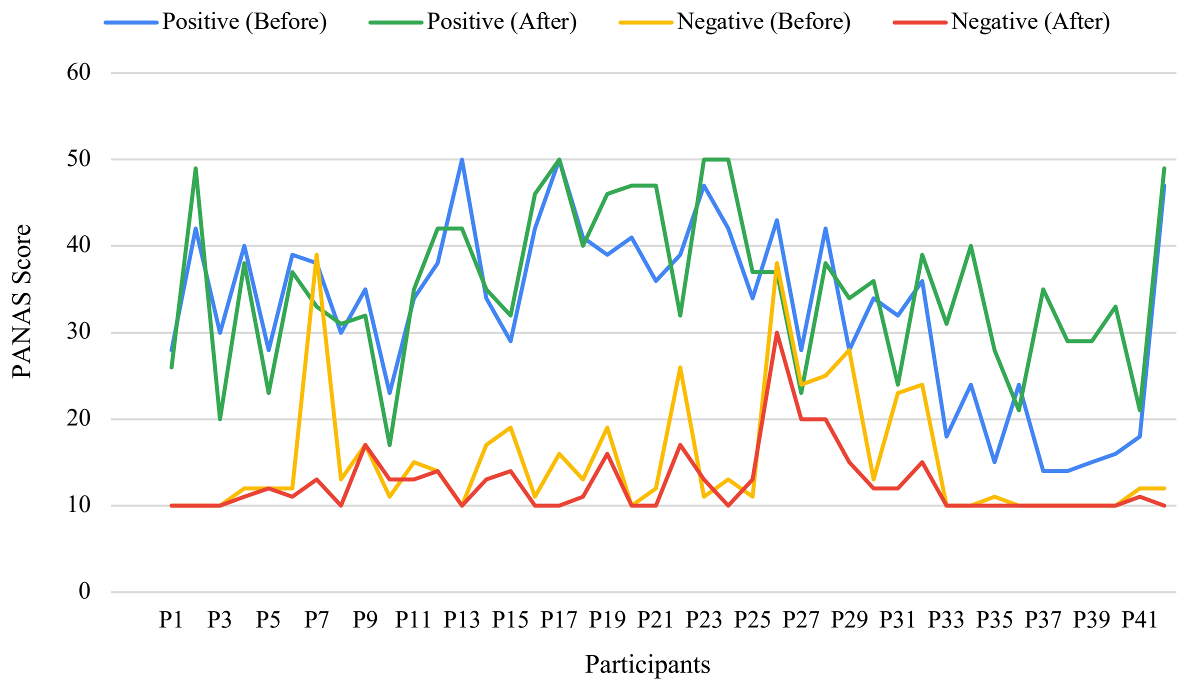


Figure 40: Average Positive and Negative Affect Schedule Score before and after the experiment.

The use of VR has been shown to have a significant impact on individuals' emotional states. Several studies have demonstrated that VR interventions can lead to an increase in positive emotions and a decrease in negative emotions. For instance, Browning et al. (2020) found that adverse effects decreased after exposure to 360-degree nature videos in VR. Similarly, Ślósarz et al. (2022) observed a significant increase in positive emotions following a VR intervention, compared to the intensity of negative emotions. Moreover, Pavic et al. (2023) highlighted the effectiveness of VR in inducing positive emotions across various settings and adult lifespan. Lavoie et al. (2021) also reported significantly reduced negative emotions in individuals exposed to a VR-based restorative environment. They suggested that VR tasks evoked more realistic fears and could lead to intensified negative emotions.

However, it is essential to note that the impact of VR on emotions is not universally positive. Found that negative emotions intensified by VR were correlated with negative rumination, Basbasse et al. (2022) indicated potential negative emotional consequences of VR experiences. Furthermore, Li et al. (2021) highlighted that the negative effects of immersive VR were associated with a reduction in felt pleasantness, indicating potential negative emotional outcomes.

5.2.4.4. Multivariate Analysis of Emotional Responses (PANAS)

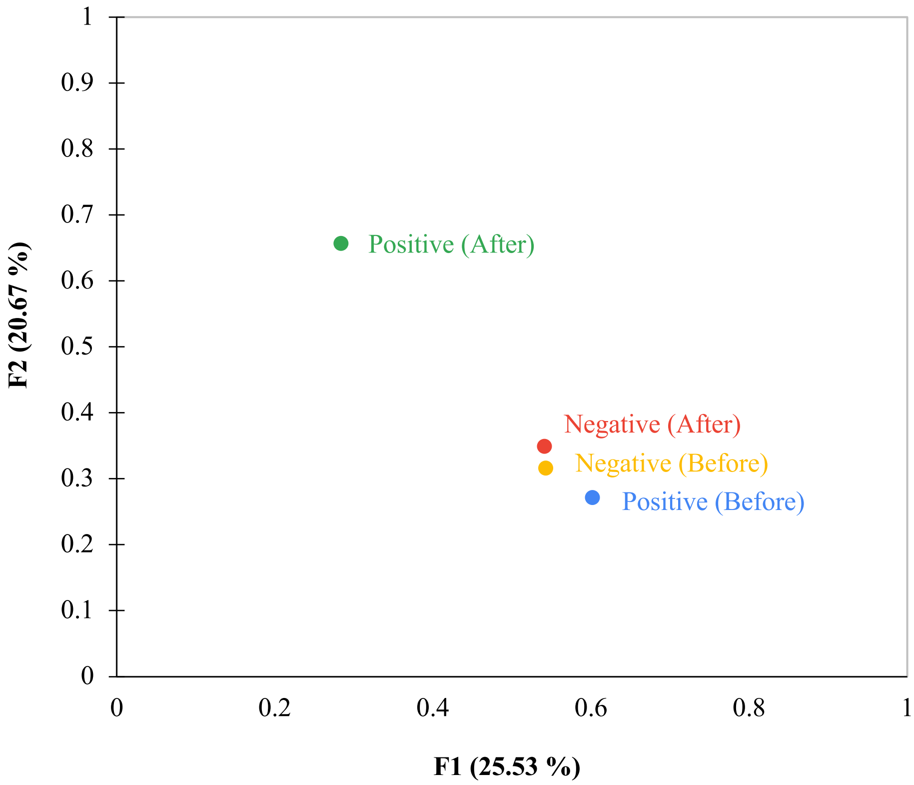
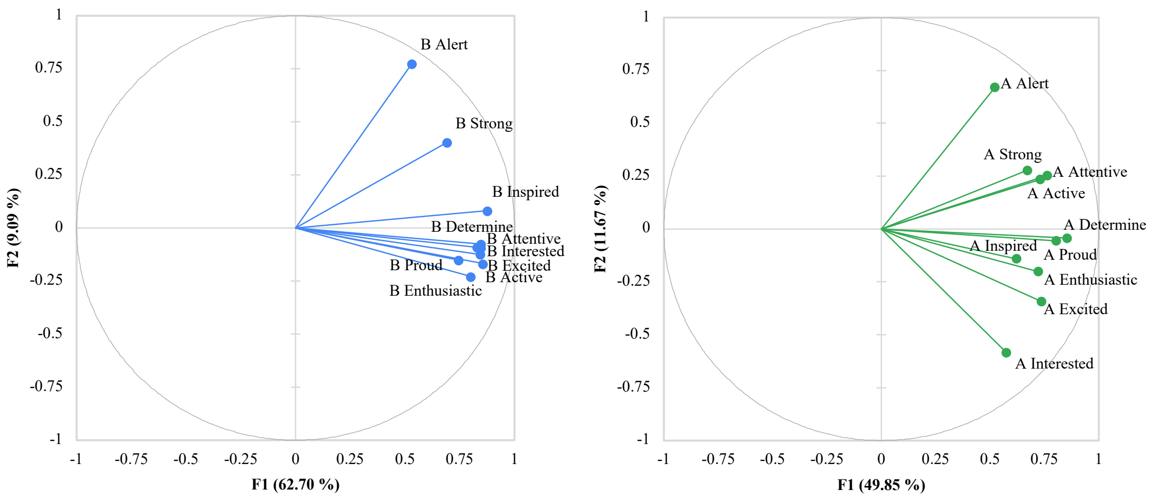


Figure 41: Multiple Factor Analysis on Positive and Negative Affect Schedule (PANAS) before and after the experiment.

In the experiment, the data in Figure 41 illustrates the MFA of both positive and negative emotions before and after the experiment. This can be validated further by Figure 39, which shows that the positive emotions increase while negative emotions decrease after the experiment.

Furthermore, according to Figure 42, VR has the potential to significantly impact emotional experiences, especially in enhancing positive emotions and reducing negative emotions. The study suggests that VR can successfully induce positive emotional states, which ensures that no bias is introduced to the sensory test due to any changes in the emotional state while working in a VR environment.

The role of VR in eliciting positive emotions was also explored in various contexts. Wang et al. (2023) demonstrated the role of emotional responses in VR exhibitions, where participants reported feeling pleasure and satisfaction, indicating the potential of VR environments to evoke positive emotions. Additionally, Mahmud et al. (2022) found that exposure to relaxing virtual environments induced positive emotions and reduced negative emotions, highlighting the potential therapeutic effects of VR in promoting positive emotional experiences.



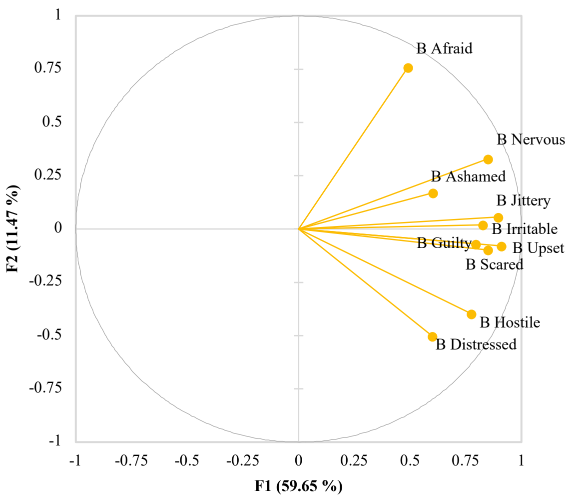
(a) (b)

Figure 42: Comparison of Positive emotions variables before (a) and after (b) the experiment.

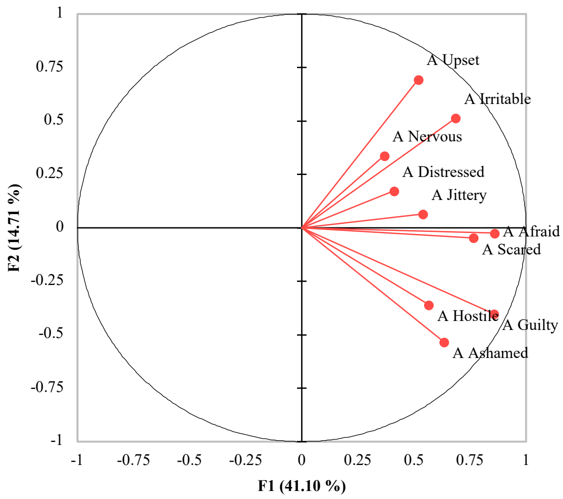
Furthermore, the impact of VR on emotional empathy was investigated, with reporting that VR increases emotional empathy. In particular, Martingano et al. (2021) suggested the potential of VR to enhance positive emotional connections. Additionally, it was shown that using VR in mindfulness skills training exercises reduces negative emotions and increases positive emotions in individuals. Gomez et al. (2017) indicated VR's potential in promoting positive emotional well-being.

The impact of VR on emotions is multifaceted, with studies demonstrating both positive and negative emotional outcomes. While VR can reduce negative emotions, as shown in Figure 43, it can also intensify negative emotions and harmful self-related thoughts. Meanwhile, the specific VR context and content influence emotional experiences in VR environments.

Chirico et al. (2016) have highlighted that VR has the potential to elicit both positive and negative emotions, indicating that emotional experiences in VR environments are of a dual nature. Meanwhile, X. Wang et al. (2023) have emphasized that the emotional impact of VR is influenced by the specific VR context, as demonstrated by the processing of balanced words. Furthermore, Ślósarz et al. (2022) have observed an increase in the intensity of positive emotions following VR intervention, compared to the intensity of negative emotions during the post-test, indicating a potential positive influence of VR on emotions. Similarly, (Pallavicini & Pepe, 2020) have found that VR content, including VR video games, can effectively induce positive emotions and decrease negative emotions and anxiety in individuals, further supporting the potential positive impact of VR on emotions.



(a)



(b)

Figure 43: Comparison of Negative emotions variables before (a) and after (b) the experiment.

However, Lemmens et al. (2022) demonstrated that commercial VR games can affect feelings of presence and players' physiological and emotional state, indicating the potential for negative emotional effects. Stallmann et al. (2023) also expected participants to react negatively to being excluded in immersive VR, suggesting that VR experiences can elicit negative emotions such as ostracism and exclusion.

5.2.5. Post-VR Questionnaire

The post-VR questionnaire investigates the acceptability of a virtual sensory booth (SB). It comprises five questions, as shown in Figure 44, addressing the level of immersion, the quality of graphics, the ability to pick up and place items in the virtual environment, the overall quality of the VR technology, and the overall experience with VR. Participants provide ratings for the virtual SB by selecting a value on a parameter scale between 1 (very low/very difficult/negative) and 9 (very high/very easy/positive), with higher values indicating a more favourable experience (Likert Scale).

All the scores obtained from the post-VR questionnaire are above 7, indicating that the participants received the virtual SB well. The highest average score was given to 'Overall experience with VR' (8.17±1.21), whereas the lowest was to 'Pick up and/or place items in the virtual environment' (7.10±1.95). The scores for the other questions, in descending order, are as follows: 'The quality of the VR technology overall' (7.90±1.14), 'The level of immersion' (7.36±1.69), and 'The quality of the graphics' (7.26±1.47). This suggests that the participants found the VR experience to be immersive.

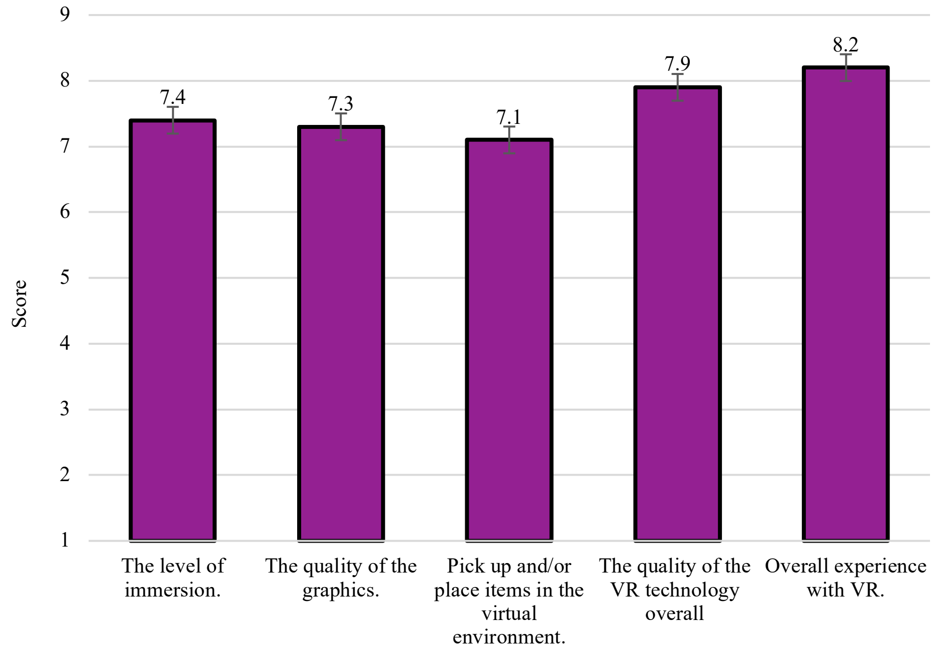


Figure 44: Average score of post-Virtual Reality questionnaire

Several studies have been conducted to explore the influence of Virtual Reality (VR) on emotional experiences. One such study reviewed previous research on VR, focusing on fear cues, emotions, and presence. They aimed to identify the most critical aspects of emotional experience in VR and their interrelationships (Diemer et al., 2015).

5.2.6. Comments and Participants' Experience

Some participants gave positive and informative comments throughout the experiment. As most of the participants did not have experience with VR before, 74% of participants gave very positive comments, and comments were related to “It was a very interesting experience” and “It was a very good experience”. Out of 74% positive comments, 19% of participants said that the virtual sensory booth felt like a traditional or real sensory booth. Since the experiment is dealing with humans, not all comments are positive; 26% of participants gave constructive comments, especially focused on the VR mechanics and graphics, e.g.: “The instrument is a bit heavy while placed on the head … the vision can be a bit blurry and dizzy”, “I think it is better if we could put the experience in the sensory box with boundary, which is helpful to not pour out of the sample during the test” and “It would be a much more immersive experience if the graphic, nature and environment of the VR is as close as to the one in real life (ie; duplicating the room to which this test is taken place, the subject has a body)…”. Obtaining comments and insights from participants is of utmost importance when it comes to creating an environment that is not only seamless but also as identical as possible to the traditional sensory laboratory. This feedback helps in identifying areas that require modification and allows for the implementation of changes that result in a more realistic and immersive experience.

5.3. Experiment 3: Virtual Sensory Testing with Different Methods and Environments

5.3.1. Just-About-Right (JAR) Analysis

5.3.1.1. Comparison of JAR in Biscuit

The Figure 45 shows how three biscuits, A, B, and C, were rated for hardness, grittiness, sweetness, and chocolate intensity across two environments: the VR Sensory Booth and the VR Park. Each attribute is measured using “Too little,” “JAR” (Just-About-Right), and “Too much,” revealing how the sensory experience differs between the two settings.

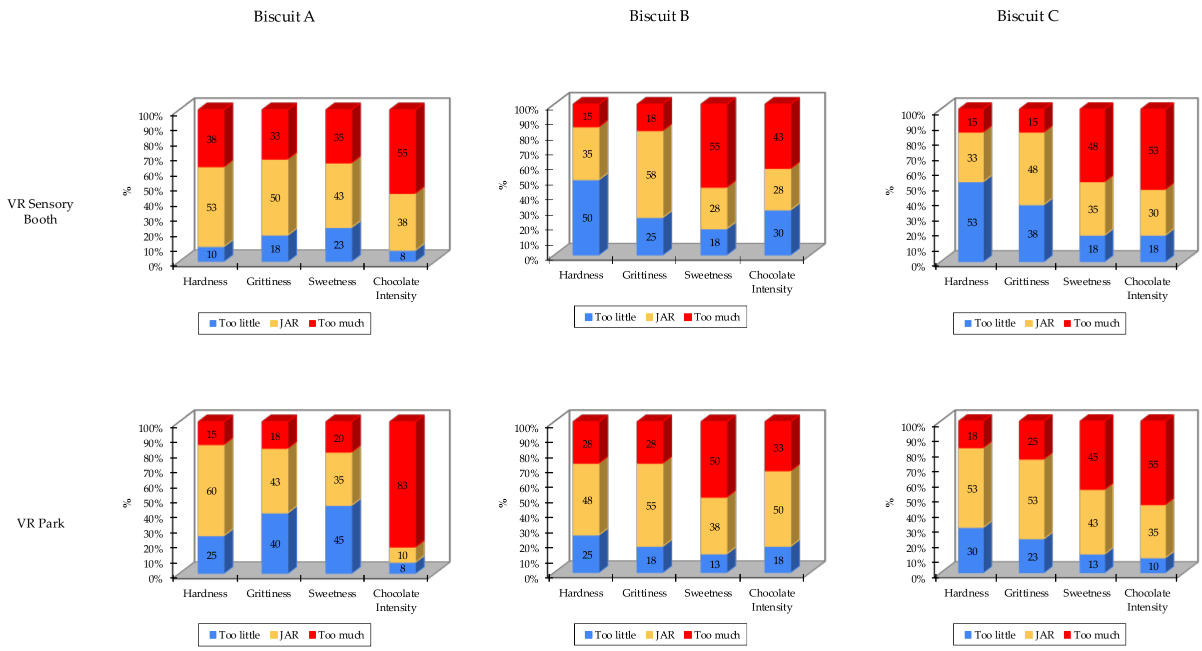


Figure 45: Just-About-Right (JAR) results for biscuits A, B, and C on four attributes across VR Sensory Booth and VR Park, using "Too little," "JAR," and "Too much" scales.

For Biscuit A, in the VR Sensory Booth, only 38% found hardness to be JAR, while 43% thought it was too much. Grittiness and sweetness had moderate acceptance, with 50% and 43% falling into JAR, but chocolate intensity stood out as a problem, with only 38% in JAR and a high 55% saying it was too much. In the VR Park, results improved for hardness, with 60% rating it JAR and fewer people finding it too much. Sweetness also rose to 55% JAR, showing better acceptance, though chocolate intensity was still an issue with 83% feeling it was excessive.

Biscuit B had mixed results in the VR Sensory Booth. Grittiness was more acceptable, with 58% JAR, while sweetness and chocolate intensity struggled, with 43% and 38% JAR, respectively. Hardness caused issues, with 50% finding it too little. In the VR Park, improvements were noticeable, especially for grittiness, where 55% reached JAR. Chocolate intensity rose to 50% JAR, though hardness remained divisive, with 28% saying it was too little and 48% at JAR.

For Biscuit C, the VR Sensory Booth results were inconsistent. Grittiness had 48% JAR, but chocolate intensity struggled, with just 30% JAR and 53% finding it too much. Sweetness and hardness had lower JAR ratings as well. In the VR Park, there were improvements in key areas. Hardness reached 53% JAR, grittiness hit 50%, and sweetness rose to 55%. However, chocolate intensity continued to be problematic, with only 48% in JAR and 53% still finding it excessive.

When comparing the two environments, the VR Park consistently showed better results, with more attributes falling into the JAR range. Hardness and sweetness saw notable improvements, indicating that the VR Park provided a more favourable setting for participants to experience and rate the biscuits. It's likely the immersive environment allowed for more relaxed evaluations. However, chocolate intensity remained a challenge in both settings, with large percentages still finding it too strong. Overall, the VR Park seemed to enhance the sensory experience, making attributes like grittiness and sweetness more acceptable while slightly easing the issues seen in the VR Sensory Booth.

5.3.1.2. Comparison of JAR in Orange Juice

The JAR results for Orange Juices A, B, and C across the VR Sensory Booth and the VR Food Court follow similar trends, with variations in bitterness, sourness, sweetness, and orange flavour in Figure 46.

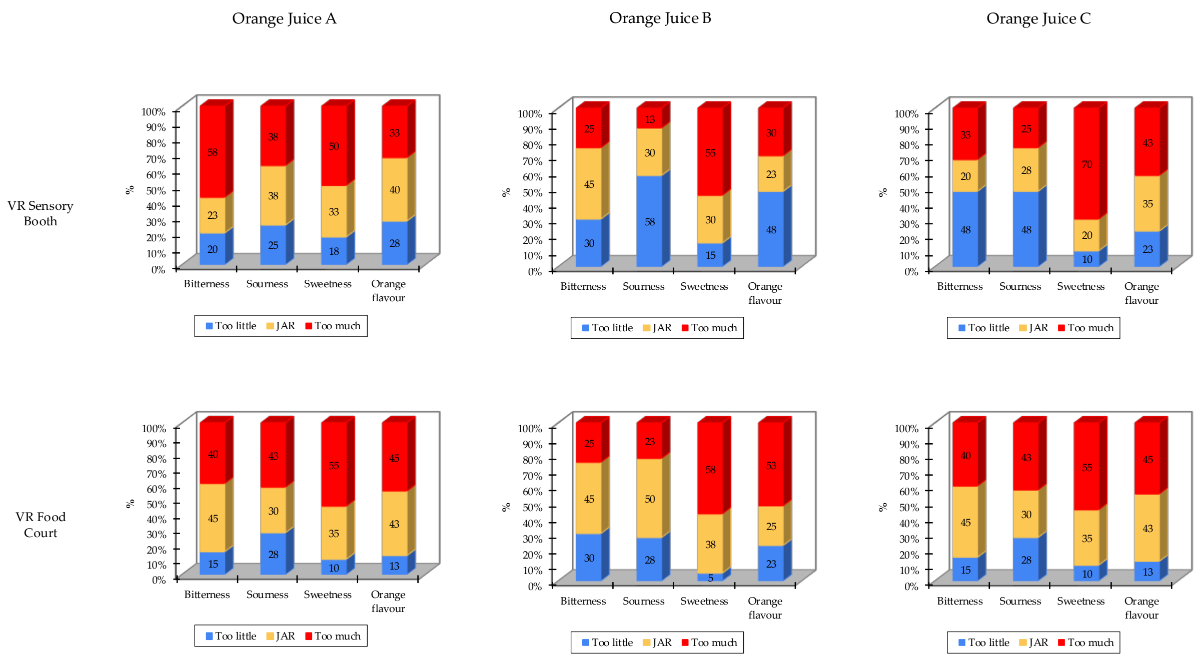


Figure 46: Just-About-Right (JAR) results for Orange Juices A, B, and C on bitterness, sourness, sweetness, and orange flavour across the VR Sensory Booth and VR Food Court, showing variations in sensory perceptions.

For Orange Juice A in the VR Sensory Booth, bitterness was not well received, with 58% finding it "Too much" and only 23% rating it JAR. Sourness performed better, with 38% at JAR, but sweetness and orange flavour both struggled, with 50% and 33% saying they were excessive. In the VR Food Court, results improved slightly. Bitterness dropped to 40% "Too much," and JAR increased to 45%. Sourness improved to 30% JAR, but sweetness remained problematic, with 55% considering it excessive. Orange flavour was still divisive, with 43% finding it "Too much."

Orange Juice B showed a similar pattern. In the VR Sensory Booth, bitterness was split, with 30% at JAR and 30% saying it was "Too little." Sourness had 40% in JAR, though 28% rated it "Too much." Sweetness performed better, with 53% JAR, while orange flavour was evenly split with 33% at JAR and 30% "Too much." In the VR Food Court, bitterness saw improvements, with JAR increasing to 45% and fewer participants finding it too little. Sourness improved to 35% JAR, and sweetness remained steady at 53% JAR. Orange flavour, however, stayed inconsistent, with only 38% JAR and 25% still considering it excessive.

Orange Juice C faced the most challenges. In the VR Sensory Booth, bitterness was polarizing, with 35% at JAR and 40% "Too much." Sourness fared slightly better, with 28% JAR and 25% "Too much," but sweetness and orange flavour were major issues, as only 20% found them JAR while over 43% rated them excessive. The VR Food Court brought some improvements. Bitterness had 45% JAR, and sourness increased to 30% JAR. Sweetness improved slightly to 35% JAR, though orange flavour was still problematic with 43% reporting it "Too much."

When comparing the VR Sensory Booth and VR Food Court, the VR Food Court provided a more balanced experience for all attributes. Bitterness and sourness consistently improved across all juices, with more participants rating them at JAR and fewer finding them too extreme. Sweetness and orange flavour, however, remained persistent issues in both environments, with high percentages reporting them as "Too much." The VR Food Court seemed to create a more relaxed and forgiving setting, allowing for slightly better results, especially in bitterness and sourness, but further adjustments are needed for sweetness and flavour intensity to reach an acceptable level.

5.3.2. Check-All-That-Apply (CATA) Analysis

5.3.2.1. Comparison of CATA in Biscuit

Figure 47 shows the CATA results for Biscuits A, B, and C reveal how sensory attributes such as hardness, sweetness, bitterness, and flavours differ between the VR Sensory Booth and the VR Park. The data is represented as symmetric plots, where axis F1 captures 77.02% of the variability and F2 adds 22.98%, highlighting clear differentiation in sensory characteristics.

In the VR Sensory Booth, Biscuit A aligns with citrus flavour, sweet taste, and a slightly granular texture. Biscuit B is more associated with chocolate flavour, a more intense profile, and a crumbly texture, while being negatively linked to hardness and vanilla flavour. Biscuit C is strongly linked to grainy flavour, bitter taste, salty taste, and attributes like dry and hard, which indicate a less favourable perception.

In the VR Park, notable shifts occur. Biscuit A retains its citrus flavour and sweet taste, while gaining associations with grainy flavour and crumbly texture. Biscuit B moves toward pasty, bitter taste, and long-lasting taste, indicating a richer sensory experience. Biscuit C shows significant improvement, shifting away from the hard and dry attributes of the VR Booth to more positive perceptions like nutty flavour, vanilla flavour, and a crunchy texture.

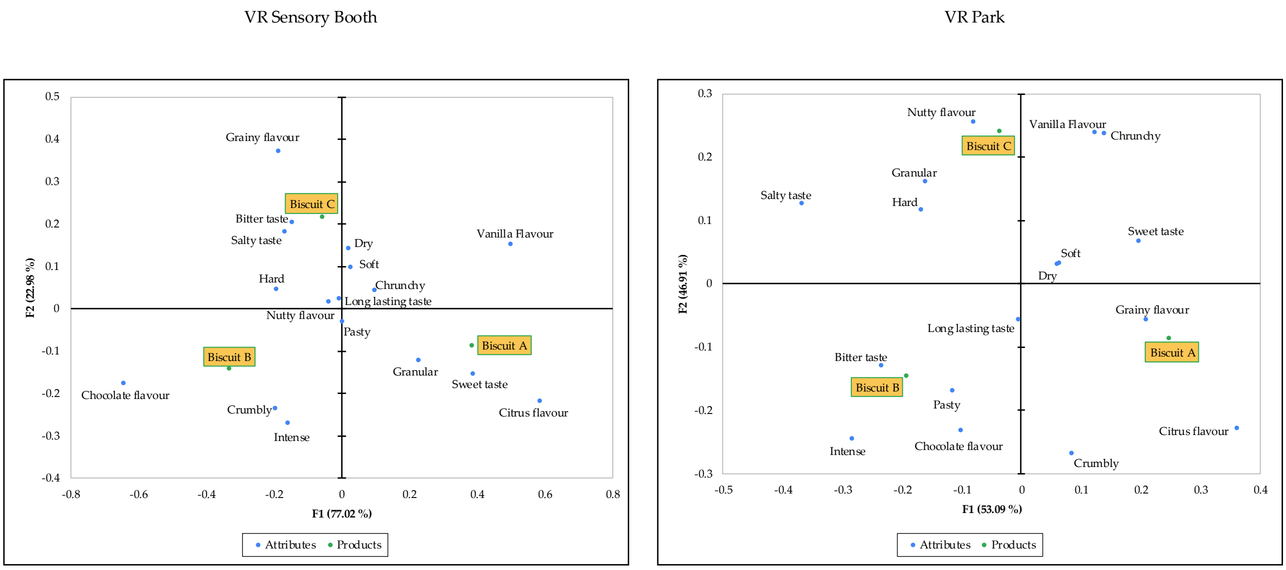


Figure 47: Check-All-That-Apply (CATA) results for Biscuits A, B, and C, showing sensory attribute differences between the VR Sensory Booth (F1: 77.02%, F2: 22.98%) and VR Park (F1: 77.02%, F2: 22.98%) in symmetric plots.

Comparing the two environments, the VR Park enhances the sensory experience for all biscuits. Biscuit C, which struggled with hardness and bitterness in the Sensory Booth, gains more desirable qualities like nutty and vanilla flavours. Biscuit A remains consistent but performs better with additional attributes like crumbly texture. Biscuit B benefits from a more complex profile in the VR Park, adding richness with bitter and long-lasting taste. Overall, the VR Park provides a more favourable and engaging sensory experience, while the VR Sensory Booth highlights stronger or less balanced attributes.

5.3.2.2. Comparison of CATA in Orange Juice

The CATA results for Orange Juices A, B, and C show how sensory attributes like sweetness, bitterness, refreshing, and flavours differ between the VR Sensory Booth and the VR Food Court in Figure 48. The symmetric plots reflect the relationships between attributes and the juices, with axis F1 capturing 78.37% of the variability and F2 accounting for 21.63% in the VR Sensory Booth. In the VR Food Court, F1 explains 58.21% of the variability and F2 41.79%.

In the VR Sensory Booth, Orange Juice A aligns closely with natural taste and artificial taste, but slightly negatively with attributes like refreshing and sweet. Orange Juice B is associated with refreshing, intense, and long-lasting taste, while being negatively linked to irritating. Orange Juice C is more aligned with negative attributes such as bitter, thick, and astringent, as well as the presence of lemon and sour notes, which might explain its polarised perception.

In the VR Food Court, shifts in sensory perceptions are evident. Orange Juice A is associated with pulpy and artificial taste, but it also picks up some alignment with sweet and irritating. Orange Juice B maintains connections with natural taste but loses associations with refreshing and intense attributes. Orange Juice C improves its positioning, aligning more with positive attributes like refreshing, long-lasting taste, and intense, while still slightly connected to negative notes such as off-flavour.

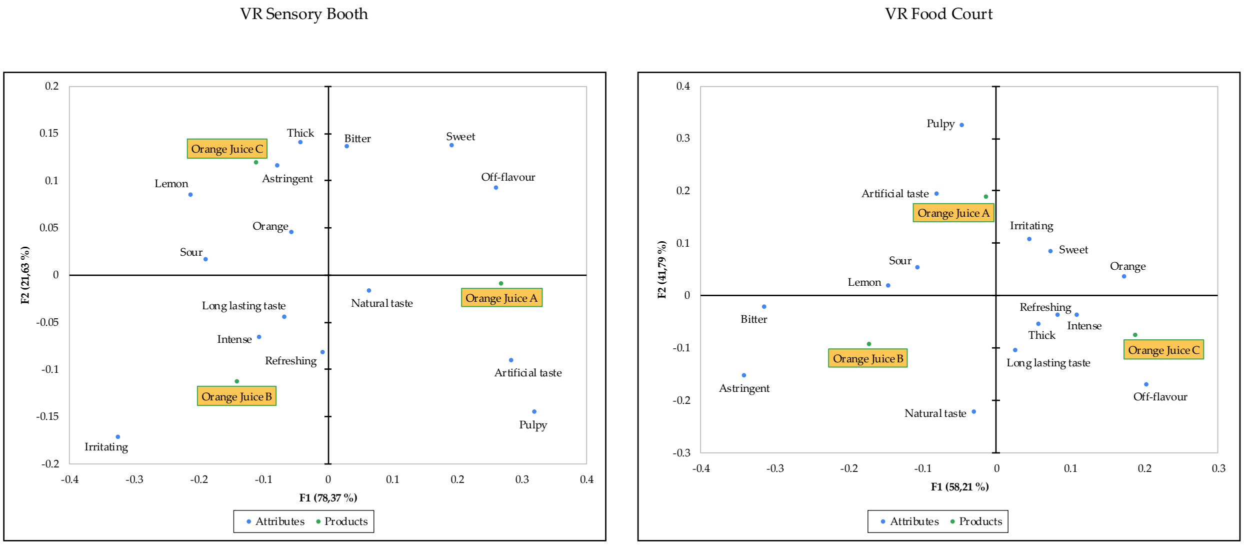


Figure 48: Check-All-That-Apply (CATA) results for Orange Juices A, B, and C, showing sensory attribute differences between the VR Sensory Booth (F1: 78.37%, F2: 21.63%) and VR Food Court (F1: 58.21%, F2: 41.79%) in symmetric plots.

When comparing the two environments, the VR Food Court enhances positive attributes for Orange Juice C, which gains refreshing and long-lasting perceptions compared to its previous association with bitterness and thickness in the Sensory Booth. Orange Juice A, however, leans more towards artificial and pulpy characteristics in the Food Court, which could be less favourable. Orange Juice B maintains its positive natural taste attribute across both settings but loses its refreshing and intense appeal in the Food Court. Overall, the Food Court setting allows for a more dynamic and varied sensory experience, where juices like Orange Juice C show significant improvement in perceived positive attributes, while the Sensory Booth highlights harsher or less favourable qualities.

5.3.3. Post-VR Questionnaire Results Across Environments

The results (Figure 49) show a comparison between the VR Sensory Booth and the VR Environment Overall across five key factors, expressed as mean ± standard deviation. For the VR Sensory Booth, the level of immersion scored 6.88 ± 1.73, while the quality of the graphics achieved 6.78 ± 1.70. Participants rated the ability to pick up and/or place items in the virtual environment at 6.48 ± 2.06. The quality of the VR technology overall was scored at 7.28 ± 1.48, and the overall experience with VR received the highest rating at 7.90 ± 1.32.

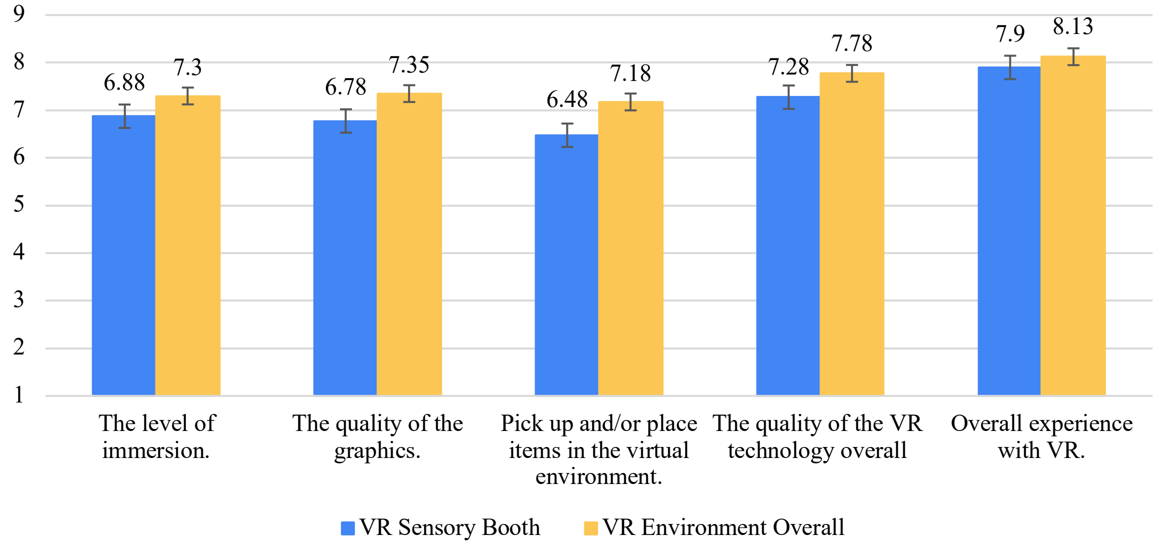


Figure 49: Comparison of VR Sensory Booth and VR Environment Overall on immersion, graphics, item interaction, VR quality, and overall experience (mean ± SD).

In comparison, the VR Environment Overall received higher ratings across all factors. The level of immersion improved to 7.30 ± 1.88, while the quality of the graphics reached 7.35 ± 1.75. The interaction for picking up and/or placing items in the virtual environment was rated at 7.18 ± 2.00. The quality of the VR technology overall increased to 7.78 ± 1.88, and the overall experience with VR climbed to 8.13 ± 1.40.

These results suggest that the VR Environment Overall provided a more engaging and satisfactory experience, with higher mean ratings across all factors. While the standard deviations indicate some variability, the improvements highlight the enhanced performance and user satisfaction in the VR Environment compared to the VR Sensory Booth.

5.3.4. Immersion Level Analysis

Figure 50 shows the results for the Level of Immersion show notable differences across the three environments: VR Sensory Booth, VR Park, and VR Food Court. The VR Sensory Booth scored 6.88 ± 1.73, reflecting moderate immersion with a relatively consistent response among participants. The VR Park achieved a slightly lower score of 6.73 ± 1.88, indicating a similar level of immersion but with slightly higher variability in responses. The VR Food Court, however, received the highest score at 7.55 ± 2.07, showing a clear improvement in perceived immersion. Although the VR Food Court demonstrated the strongest immersion, the responses also exhibited greater variability, suggesting more diverse opinions among participants.

Overall, these results suggest that the VR Food Court provided the most immersive experience, likely due to its dynamic and engaging environment, which enhanced the participants' sense of presence. While the VR Sensory Booth and VR Park delivered comparable immersion levels, the VR Food Court stood out as the preferred setting for creating a more immersive and stimulating virtual experience.

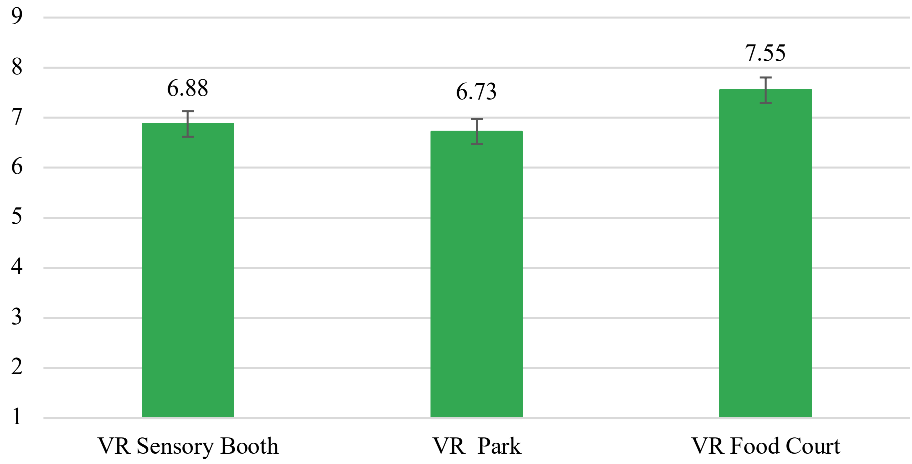


Figure 50: Level of immersion across three environments: VR Sensory Booth (6.88 ± 1.73), VR Park (6.73 ± 1.88), and VR Food Court (7.55 ± 2.07), with the VR Food Court showing the highest immersion but greater response variability.

5.3.4.1. Multivariate Exploration of Immersion Factors Across VR Environments

The PCA biplot displays the distribution of participants and VR environments across two principal components, F1 (63.24%) and F2 (32.89%), capturing a total of 96.13% of the variability in the data. This highlights clear relationships between the environments (VR Sensory Booth, VR Park, and VR Food Court) and participant responses (Figure 51).

The VR Sensory Booth is strongly associated with F2 and positioned in the upper quadrant, showing a unique contribution along this axis. In contrast, both the VR Park and VR Food Court align closely with F1 in the positive direction, indicating similar associations and a stronger link to the variability captured by the first principal component. The VR Park shows slightly more central positioning compared to the Food Court, suggesting a more balanced relationship across participants.

Participants exhibit clear groupings relative to the environments. For instance, individuals such as P18, P25, and P33 are positioned closer to the VR Sensory Booth, indicating a stronger alignment with the characteristics represented by this environment. Participants like P9, P11, and P39 cluster near the VR Park, while P2, P4, and P19 align more closely with the VR Food Court, showing higher variability along F1. On the opposite side, participants like P3, P27, and P37 appear further from the main environments, suggesting divergent perceptions or experiences.

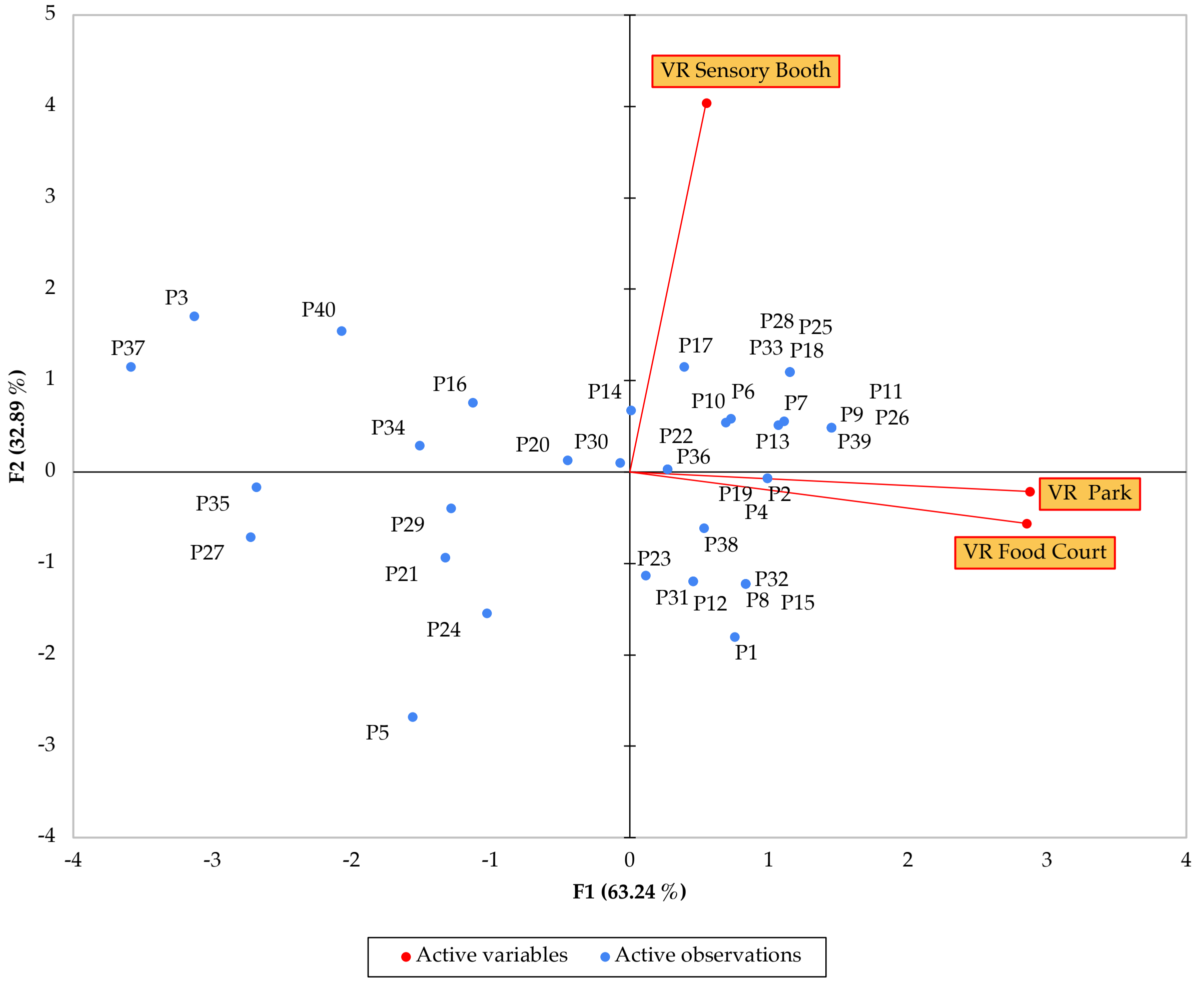


Figure 51: PCA biplot showing participant distribution across VR environments (VR Sensory Booth, VR Park, VR Food Court) along F1 (63.24%) and F2 (32.89%).

Overall, the PCA highlights that the VR Food Court and VR Park environments drive variability primarily along F1, contributing more to the perceived positive or immersive qualities. Meanwhile, the VR Sensory Booth differentiates itself along F2, reflecting unique attributes or participant experiences. This clear separation suggests that while the VR Food Court and VR Park deliver similar immersive benefits, the VR Sensory Booth evokes a distinct sensory response

5.3.4.2. Analysis of Agglomerative Hierarchical Clustering (AHC) across VR environments

The AHC results reveal two distinct clusters with differing characteristics across the VR Sensory Booth, VR Park, and VR Food Court (Figure 52). Cluster 1, which includes 32 participants, shows a high level of homogeneity with a within-cluster variance of 5.386. Participants in this cluster gave higher scores to the VR Park (7.50) and the VR Food Court (8.38), indicating strong positive experiences in these environments, while the VR Sensory Booth received a moderately positive score of 6.78. The average distance to the centroid for Cluster 1 is 2.038, with participants relatively close to the centre, though the maximum distance reaches 5.895, suggesting some spread within the group.

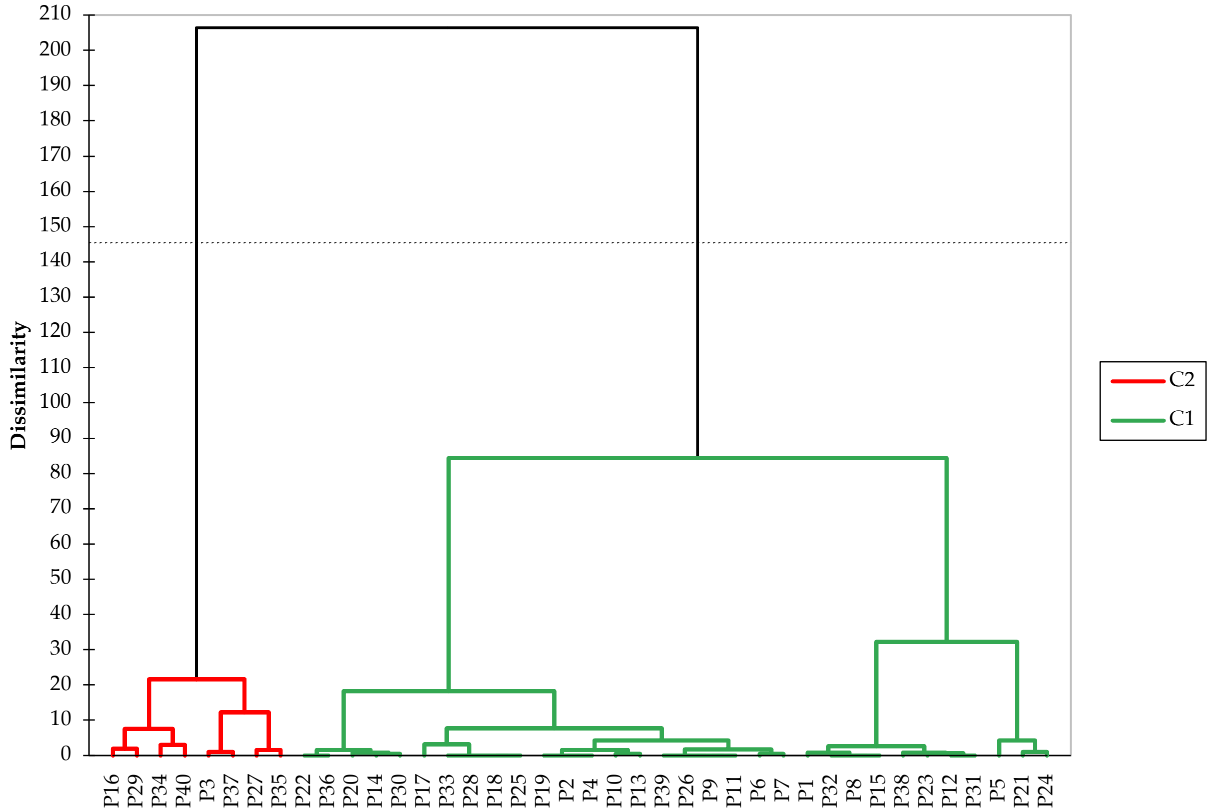


Figure 52: AHC results identify two clusters across the VR Sensory Booth, VR Park, and VR Food Court. Cluster 1, with 32 participants, shows homogeneity (variance: 5.386) and higher scores for the VR Park (7.50) and VR Food Court (8.38) compared to the VR Sensory Booth (6.78). Average distance to the centroid is 2.038, with a maximum distance of 5.895. C1 represent Cluster 1 and C2 is Cluster 2

In contrast, Cluster 2 comprises only 8 participants and exhibits greater variability with a within-cluster variance of 6.982. The VR Sensory Booth received a slightly higher score of 7.25, but participants rated the VR Park (3.63) and the VR Food Court (4.25) much lower, indicating a less favourable perception of these two environments. The average distance to the centroid is 2.391, and while the maximum distance is 3.044, this group remains somewhat tighter in their spread compared to Cluster 1 despite its higher variance.

Comparing the two clusters, Cluster 1 represents most participants who found the VR Park and VR Food Court environments more engaging and enjoyable, reflecting stronger preferences and greater consistency. On the other hand, Cluster 2 consists of a smaller group of participants who reported lower satisfaction overall, particularly in the VR Park and Food Court, but displayed a slightly stronger preference for the VR Sensory Booth. These findings highlight two distinct participant profiles: one group more aligned with dynamic and immersive environments and another group showing less satisfaction across the board, favouring the VR Sensory Booth. Understanding these clusters provides insight into varying user preferences, allowing for more targeted improvements to enhance the virtual experiences across different environments.

5.3.5. Discussion on Optimal VR Environments for Sensory Testing

The JAR (Just-About-Right) and CATA (Check-All-That-Apply) analysis reveal how VR environments influence sensory perception of biscuits and orange juice. Combined with Post-VR Questionnaires, PCA, and AHC analyses, these findings highlight that immersive settings affect food evaluations, with some environments enhancing specific attributes more than others.

The JAR results show that VR environments influence food perception. In the VR Park, Biscuit A had improved hardness and sweetness ratings, but chocolate intensity remained too strong. Biscuit B showed better grittiness and chocolate intensity in the VR Park, though hardness remained inconsistent. Biscuit C, initially rated as too hard and bitter in the Sensory Booth, was perceived as sweeter and more balanced in the VR Park. These results suggest that immersive environments enhance sensory acceptance but do not completely alter dominant flavours (Kong et al., 2020). For orange juice, Juice A remained too bitter in both environments, but sweetness was rated higher in the VR Food Court. Juice B showed better balance in the VR Food Court, while Juice C, previously described as thick and bitter in the Sensory Booth, was perceived as more refreshing and intense. The Food Court setting likely created a more familiar and enjoyable context, shifting attention to positive attributes (Schouteten et al., 2024).

CATA results confirm these trends. In the Sensory Booth, biscuits were described with negative attributes like "hard" and "dry," while in the VR Park, terms like "crumbly" and "sweet" were used. Similarly, in the Sensory Booth, orange juices were associated with "bitter" and "astringent" attributes, whereas in the VR Food Court, descriptors like "refreshing" and "sweet" were more common. This suggests that controlled environments encourage critical evaluation, while immersive settings enhance product appeal (Torrico et al., 2021).

Post-VR Questionnaire results align with these observations. Participants rated the VR Food Court highest for immersion (7.55 ± 2.07), followed by the VR Sensory Booth (6.88 ± 1.73) and VR Park (6.73 ± 1.88). This indicates that realistic environments enhance engagement, potentially affecting sensory perceptions (E. Crofton et al., 2021; Schouteten et al., 2024; Torrico et al., 2021). PCA and AHC analyses revealed two participant clusters: one favouring the VR Park and Food Court for their immersive and positive associations, and another preferring the Sensory Booth for its controlled setting (Ribeiro et al., 2024).

Beyond sensory perception, immersive environments may influence appetite-related cues, including food desirability and satiety perception (Van Bergen et al., 2021). The VR Park and Food Court enhanced perceptions of positive sensory attributes such as sweetness and freshness, compared to the VR Sensory Booth. This supports previous findings that ambiance, social context, and sensory stimulation shape food expectations and satiety perception (Hendriks et al., 2021). The VR Food Court, simulating a familiar dining setting, likely encouraged a more enjoyable sensory experience, leading to higher food desirability and more favourable flavour evaluations (Crofton et al., 2021). In contrast, the Sensory Booth's static setting may have heightened analytical focus, leading to more critical judgments and reduced hedonic appeal (Tapia et al., 2021).

These findings have important implications for consumer behaviour, sensory science, and food product development. VR allows researchers to simulate different consumption settings and analyse their effects on sensory evaluations and consumer preferences (Gere, Zulkarnain, et al., 2021). This enhances sensory testing by incorporating realistic and immersive environments that better reflect actual experiences (Wang et al., 2021a). By manipulating virtual environments, researchers can assess how ambiance, social context, and visual stimuli impact food perception and acceptance (Zulkarnain, Kókai, et al., 2024b). This approach is valuable for product reformulation, predicting consumer responses, and reducing the need for large-scale physical testing.

5.4. Simulator Sickness Questionnaire (SSQ) in Experiment 1, 2 and 3

5.4.1. SSQ Score

5.4.1.1. SSQ individual score

Table 14 shows the average of 16 symptoms in four different studies. On the symptoms, the SSQ had a scale of 0 (None), 1 (Slight), 2 (Moderate), and 3 (Severe). Values of all symptoms were lower than 1 (slight) on the scale, which is a positive result that can be accepted.

Table 14: Mean and standard deviation of SSQ symptoms registered over the three experiments.

Symptoms	Experiment (Mean ± SD)			
	#1	#2	#3(M)	#3(E)
General Discomfort	0.22 ± 0.45	0.38 ± 0.70	0.48 ± 0.74	0.40 ± 0.72
Fatigue	0.32 ± 0.57	0.21 ± 0.52	0.31 ± 0.52	0.09 ± 0.36
Headache	0.07 ± 0.25	0.29 ± 0.64	0.19 ± 0.45	0.02 ± 0.15
Eye strain	0.62 ± 0.72	0.64 ± 0.79	0.60 ± 0.77	0.33 ± 0.71
Difficulty focusing	0.73 ± 0.71	0.40 ± 0.73	0.50 ± 0.77	0.31 ± 0.63
Salivation increase	0.23 ± 0.46	0.60 ± 0.86	0.48 ± 0.71	0.24 ± 0.61
Sweating	0.10 ± 0.30	0.40 ± 0.80	0.19 ± 0.59	0.16 ± 0.47
Nausea	0.05 ± 0.22	0.10 ± 0.30	0.10 ± 0.30	0.07 ± 0.33
Difficulty Concentrating	0.33 ± 0.54	0.26 ± 0.66	0.31 ± 0.72	0.27 ± 0.54
"Fullness of head"	0.43 ± 0.62	0.45 ± 0.77	0.48 ± 0.77	0.18 ± 0.44
Blurred vision	0.78 ± 0.72	0.64 ± 0.82	0.74 ± 0.91	0.38 ± 0.75
Dizziness with eyes open	0.20 ± 0.40	0.31 ± 0.68	0.24 ± 0.48	0.22 ± 0.56
Dizziness with eyes closed	0.20 ± 0.48	0.24 ± 0.58	0.14 ± 0.42	0.09 ± 0.29
Vertigo	0.25 ± 0.47	0.14 ± 0.47	0.10 ± 0.37	0.07 ± 0.25
Stomach awareness	0.03 ± 0.18	0.10 ± 0.37	0.10 ± 0.37	0.04 ± 0.21
Burping	0.02 ± 0.13	0.12 ± 0.40	0.19 ± 0.59	0.04 ± 0.21

The analysis of the three experiment reveals that Experiment 1, involving movement to identify bakery items in a virtual sensory laboratory, led to high discomfort, particularly from blurred vision and difficulty concentrating. While symptoms like nausea and burping were milder, the overall discomfort made this setup challenging.

In Experiment 2, participants completed a hedonic sensory test in a virtual booth, where blurred vision was the most severe symptom. The high variability in responses, along with symptoms like difficulty concentrating and focusing, made this study the least favourable due to significant discomfort experienced by some participants.

Experiment 3(M), using JAR and CATA methods in a virtual booth, showed similar severe symptoms, particularly blurred vision and difficulty concentrating. However, while some participants tolerated the environment, the variability in discomfort levels indicated a less favourable experience overall.

In contrast, Experiment 3(E), set in a virtual park and food court with JAR and CATA methods, induced moderate symptoms with lower variability. Blurred vision was still an issue, but symptoms like burping and vertigo were less pronounced, making this the most balanced and comfortable design for participants. The immersive environment likely reduced discomfort, making Experiment 3(E) the most effective design.

5.4.1.2. SSQ symptoms categories

Table 15 shows the results of four studies examining the average and standard deviation of symptoms across four categories: Nausea, Oculomotor, Disorientation, and Total Score. The severity of symptoms is analysed for each study, with details provided for the most to the least severe symptoms within each category.

Table 15: Comparison of each SSQ symptoms categories on the severity of the symptoms scores in percentage.

Experiment	SSQ Symptoms Category (Mean ± SD)											
	Nausea			Oculomotor			Disorientation			Total Score		
1	9.38*	±	11.18	23.25****	±	18.19	36.89****	±	29.31	25.06****	±	18.38
2	18.63***	±	25.46	21.48****	±	27.86	31.82****	±	47.36	26.45****	±	35.24
3(M)	17.49***	±	22.69	23.64****	±	25.78	31.82****	±	38.06	27.07****	±	29.93
3(E)	11.66**	±	20.63	13.64**	±	20.98	18.25***	±	28.90	16.21***	±	23.87

None (< 5), *Minimal (≥ 5 to < 10), **Significant (≥ 10 to < 15), ***Concerning (≥ 15 to < 20), ****Severe (≥ 20)

In Experiment 1, Disorientation was the most severe symptom (average: 36.89, SD: 29.31), followed by Oculomotor symptoms (average: 23.25, SD: 18.19), and the Total Score (average: 25.06, SD: 18.38). Nausea was the least severe (average: 9.38, SD: 11.18).

Experiment 2, Disorientation again was the most severe (average: 31.82, SD: 47.36), followed by the Total Score (average: 26.45, SD: 35.24), and Oculomotor symptoms (average: 21.48, SD: 27.85). Nausea had a higher score (average: 18.63, SD: 25.46) than in Experiment 1.

Meanwhile, in Experiment 3(M), Disorientation remained the most severe (average: 31.82, SD: 38.06), followed by Oculomotor symptoms (average: 23.64, SD: 25.78) and the Total Score (average: 27.07, SD: 29.93). Nausea was the least severe (average: 17.49, SD: 22.69).

Furthermore, Experiment 3(E), Disorientation was still the most severe (average: 18.25, SD: 28.9), followed by the Total Score (average: 16.21, SD: 23.87) and Oculomotor symptoms (average: 13.64, SD: 20.98). Nausea was the least severe (average: 11.66, SD: 20.63).

Overall, Disorientation was the most severe symptom in all studies, while Nausea was the least severe. The variability in symptoms (as shown by the standard deviations) suggests significant individual differences within each experiment.

Experiment 3(E) had the least severe symptoms, with the lowest average scores in Nausea (11.66), Oculomotor (13.64), Disorientation (18.25), and the Total Score (16.21). Conversely, Experiment 3 showed the most severe symptoms, with high average scores in Nausea (17.49), Oculomotor (23.64), Disorientation (31.82), and Total Score (27.07).

5.4.1.3. Analysis of SSQ in Multiple correspondence analysis (MCA)

Figure 53 displays the Multiple Correspondence Analysis (MCA) plot, illustrating the relationship between the three experiments and simulator sickness symptoms assessed using the SSQ. The principal components F1 (24.95% variance) and F2 (8.17% variance) highlight differences in symptom presence, intensity, and prevalence across VR environments and tasks.

In experiment 1, symptoms like vertigo, blurred vision, eye strain, difficulty concentrating, dizziness (eyes open and closed), stomach awareness, fullness in the head, and burping are linked to sensory conflicts from walking and identifying products in a VR sensory lab. Vertigo results from visual-vestibular input mismatches (Wang et al., 2023), blurred vision and eye strain stem from prolonged VR exposure (R. Hussain et al., 2021), and gastrointestinal symptoms like stomach awareness indicate motion sickness (H. Kim et al., 2021).

In contrast, experiment 2 is associated with nausea and headaches, arising from cognitive strain and sensory conflict during a hedonic scale task in a virtual sensory booth. The conflict between visual inputs and taste perception contributed to nausea (H. Kim et al., 2021), while sustained focus caused headaches.

Furthermore, experiment 3(M) shows moderate symptoms like sweating, fatigue, discomfort, and increased salivation. These symptoms are linked to cognitive and physical strain from detailed tasks in a virtual sensory booth. Sweating indicates motion sickness (Fulvio et al., 2021), and increased salivation signals sensory conflict (Saredakis et al., 2020).

Experiment 3(E), set in familiar VR environments (a park and food court), showed the absence of most symptoms, including dizziness, nausea, and blurred vision. These environments minimized sensory conflicts and cognitive load, reducing symptoms and improving comfort (Mimnaugh et al., 2023).

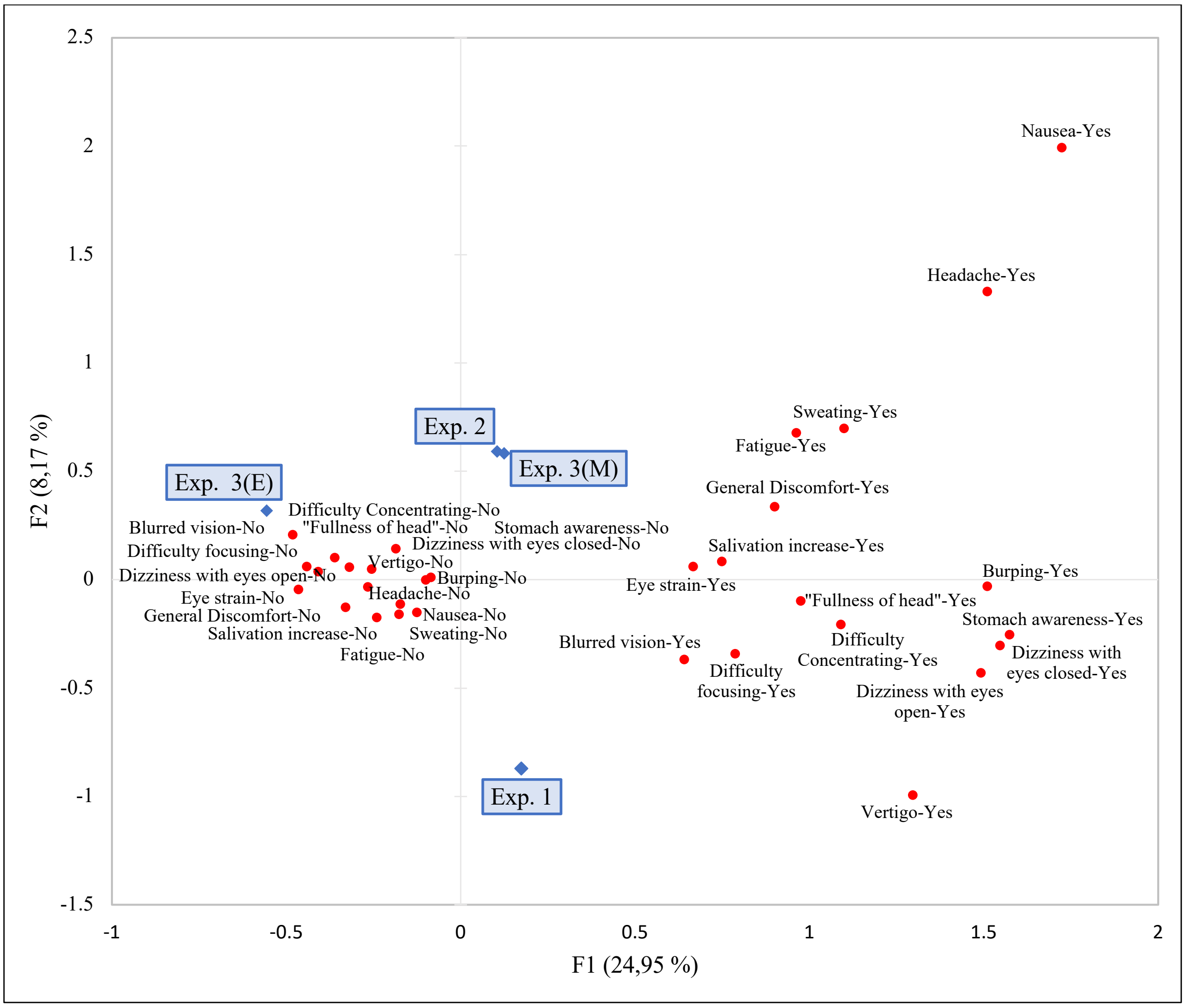


Figure 53: Multiple correspondence analysis of the simulator sickness questionnaire (SSQ) answers registered throughout the four studies.

Finally, the F1 axis distinguishes between the presence and absence of symptoms, with experiments 1 and 2 showing higher sickness levels, while experiment 3(M) shows lower levels. The F2 axis differentiates symptom intensity and prevalence; Experiment 2 exhibits more intense symptoms, while Experiment 3(E) shows milder or no symptoms. This analysis provides insights into how different VR environments influence simulator sickness, emphasizing the importance of optimizing VR conditions to reduce discomfort and improve user experience.

5.4.2. Multivariate Characterization of Simulator Sickness Symptoms (SSQ)

The Principal Component Analysis (PCA) plots provide a comprehensive visualization of the relationships between four distinct experiments and various symptoms related to simulator sickness, as measured by the SSQ in a VR context. Each figure in Figure 54 represents a different aspect of the SSQ symptoms, offering insights into the symptom profiles and their associations with the respective experiments.

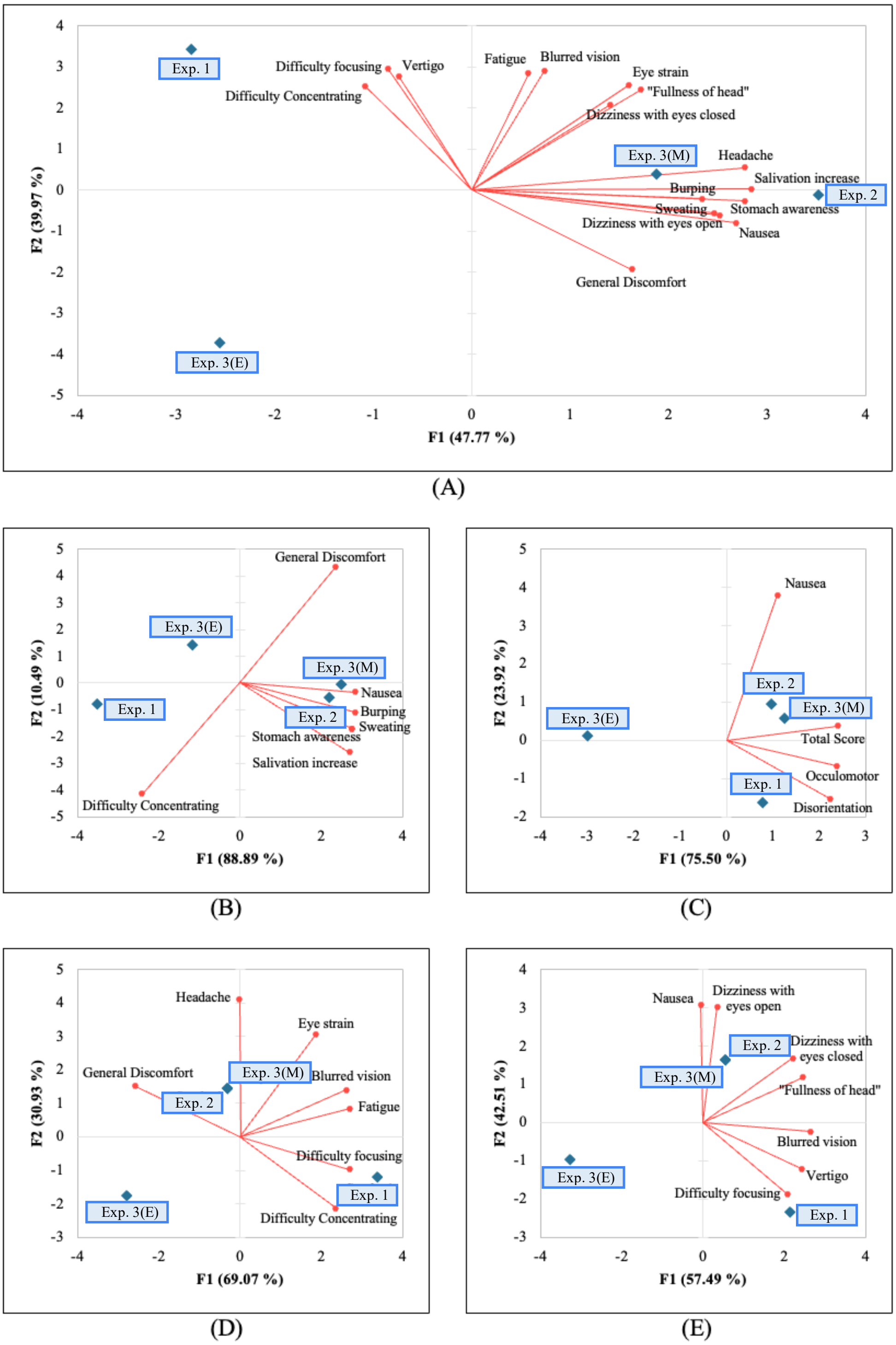


Figure 54: (A) Principal Component Analysis (PCA) plot of each individual symptom distribution across the four studies with F1 (47.77%) and F2 (29.97%), (B) PCA plot of the SSQ symptoms category distribution across the three experimets with F1 (88.89%) and F2 (10.64%), (C) PCA plot of the of nausea symptoms distribution across the three experiments with F1 (75.50%) and F2 (23.43%), (D) PCA plot of the of oculomotor symptoms distribution across the three experiments with F1 (69.07%) and F2 (30.93%), (E) PCA plot of the of disorientation symptoms distribution across the three experiments with F1 (57.49%) and F2 (42.51%).

Figure 54(A) shows the PCA of SSQ symptoms. The first principal component (F1) explains 47.77% of the variance, and the second (F2) accounts for 39.97%. Experiment 1 is linked to cognitive and visual strain (difficulty concentrating, focusing, vertigo), reflecting sensory conflicts during walking and product identification tasks in VR. Experiment 2 is associated with gastrointestinal discomfort (salivation, stomach awareness, nausea, headache), suggesting sensory conflict and cognitive strain. Experiment 3(M) shows vestibular and visual strain (dizziness, eye strain, fullness of head) due to prolonged VR exposure. Experiment 3(E), set in familiar environments, had minimal severe symptoms, indicating lower sensory strain and cognitive load.

Next, Figure 54(B) categorizes SSQ symptoms, with the first principal component (F1) explaining 88.89% of the variance and the second (F2) accounting for 10.99%. Experiment 1 reflects significant cognitive strain from complex VR tasks. Experiment 2 shows strong gastrointestinal symptoms, indicating a high level of simulator sickness. Experiment 3(M) reports mild discomfort, while Experiment 3(E) demonstrates effective symptom management in familiar environments, highlighting the role of environmental familiarity in minimizing simulator sickness.

Furthermore, Figure 54(C) focuses on nausea-related symptoms, with the first principal component (F1) explaining 75.50% of the variance and the second (F2) accounting for 23.92%. Experiment 1 shows nausea linked to visual fatigue and cognitive strain. Experiment 2 shows strong gastrointestinal distress due to intense VR tasks. Experiment 3(M) also shows nausea but less severe, suggesting moderate discomfort from less demanding tasks. Experiment 3(E) exhibits minimal nausea, showing that familiar environments reduce gastrointestinal discomfort.

Moreover, Figure 54(D) highlights oculomotor symptoms, with the first principal component (F1) explaining 69.07% of the variance and the second (F2) accounting for 30.93%. Experiment 1 shows visual fatigue from constant adjustments, causing eye strain and difficulty concentrating. Experiment 2 reflects discomfort and headache, suggesting oculomotor strain from visual demands. Experiment 3(M) shows eye strain and blurred vision, indicating visual fatigue. Experiment 3(E) shows minimal oculomotor symptoms, reflecting the benefits of familiar environments in reducing strain.

Finally, Figure 54(E) focuses on disorientation, with the first principal component (F1) explaining 57.49% of the variance and the second (F2) accounting for 42.51%. Experiment 1 shows cognitive strain with difficulty focusing and vertigo. Experiment 2 shows dizziness and fullness of head, indicating severe disorientation. Experiment 3(M) shows moderate disorientation, while Experiment 3(E) shows minimal symptoms, demonstrating the positive effect of familiar environments in reducing disorientation and maintaining orientation.

5.4.3. Discussion based on SSQ on each experiment

The SSQ results revealed clear variation in simulator sickness symptoms across experimental conditions. Experiment 1 showed strong cognitive and visual strain, with symptoms such as difficulty concentrating, focusing, and vertigo. These were likely caused by the combined demands of walking, identifying products, and engaging in VR-based sensory tasks. The vertigo suggests a sensory mismatch between visual and vestibular inputs (Wang et al., 2023), while cognitive overload was reflected in attention-related symptoms (Ding et al., 2023; Shanmugasundaram & Tamilarasu, 2023).

Experiment 2 elicited the most intense gastrointestinal and cognitive discomfort. Symptoms such as nausea, headache, increased salivation, and stomach awareness were linked to the high sensory load of simultaneously evaluating lemonade samples through visual, olfactory, and gustatory inputs (Cohen et al., 2019; Fan et al., 2023; Kim et al., 2021). The immersive nature of the task likely overwhelmed sensory systems, resulting in heightened discomfort.

Experiment 3(M) produced moderate symptoms, primarily eye strain, blurred vision, and dizziness, associated with detailed food evaluation tasks (Fulvio et al., 2021; Yoon et al., 2021). In contrast, Experiment 3(E) showed minimal discomfort. Participants engaged with the same tasks in familiar VR environments like a park or food court, which likely reduced cognitive and vestibular strain by providing spatial orientation cues (Mimnaugh et al., 2023; Vatsal et al., 2024).

Across all studies, nausea symptoms were generally less frequent than oculomotor and disorientation symptoms. These findings are consistent with prior research showing that users with limited VR experience are more likely to experience severe symptoms, especially those related to visual fatigue and sensory conflict (Corrêa et al., 2023; Da Silva Marinho et al., 2022; Kim et al., 2021). Adaptation mechanisms, such as habituation to VR, may have helped reduce symptoms for some participants (Adhanom et al., 2022).

Overall, the SSQ provided a reliable means to assess the physiological and perceptual impact of VR during sensory evaluation. Results indicate that task complexity and environmental familiarity play critical roles in determining the severity of simulator sickness, and these factors should be carefully considered when designing VR-based sensory studies.

5.5. Experiment 4: Screen-Based Eye Tracking and VR ET on Sustainable Labelling

5.5.1. Heatmap Analysis

Figure 55 displays heatmaps showing participants' fixation patterns on six sustainability labels under Eye-Tracking (ET) and Virtual Reality Eye-Tracking (VR ET) conditions. Warmer colours (red and yellow) indicate areas of high visual attention. Overall, fixations were more focused and concentrated under ET, while VR ET produced broader, more scattered attention patterns. This difference reflects the impact of immersive environments, where increased visual complexity and cognitive load lead to more exploratory and less targeted viewing behaviour.

Participants directed strong, focused attention toward the Euroleaf label in ET, as evidenced by tightly clustered fixations on the logo. In VR ET, however, fixations were more widely dispersed across the label and surrounding product surface, suggesting that environmental distractions made it harder for participants to sustain focused attention on this specific element.

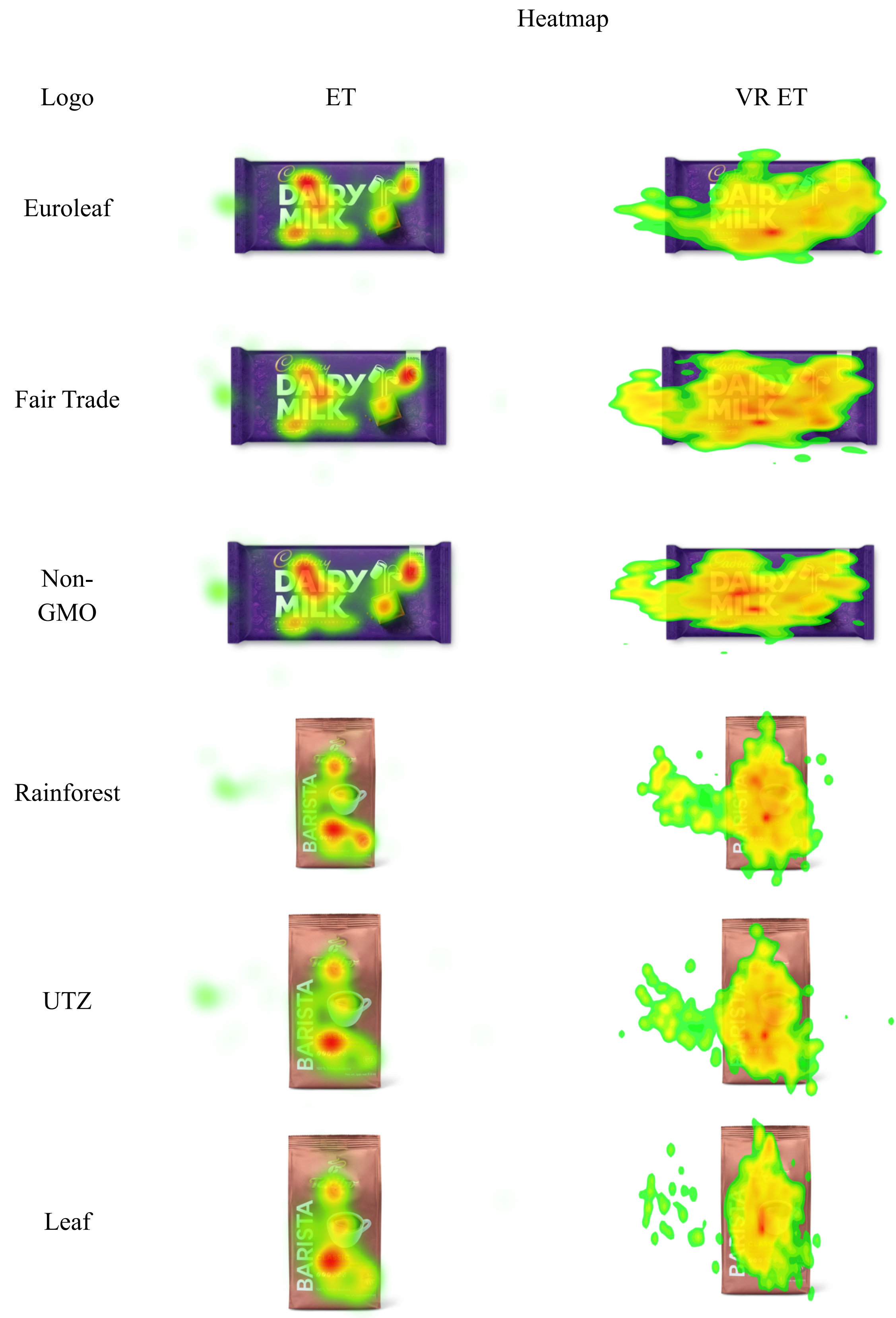


Figure 55: Heatmap of each logo in eye tracking (ET) and Virtual Reality Eye Tracking (VR ET)

Similarly, the Fair Trade label attracted intense fixation under ET, with dense red clusters indicating strong visual engagement. Under VR ET, participants' attention was more distributed across the package, implying that the immersive context reduced the label's ability to anchor their focus, even though it remained visible.

The GMO-Free label demonstrated the highest visual salience across both ET and VR ET. In ET, fixations were highly concentrated on the label, while in VR ET, although the pattern was slightly more spread out, participants still directed strong attention toward it. This consistency suggests that the GMO-Free label stood out visually, likely due to its design or perceived importance, capturing attention regardless of environmental complexity.

For the Rainforest label, ET data showed moderate but focused attention, with fixations centred on the logo. In contrast, VR ET revealed a broader and less intense pattern, indicating that participants were more engaged with the overall packaging in the immersive setting and less able to isolate the label itself.

The UTZ label also received strong attention under ET, with clustered fixations concentrated on the logo. In VR ET, the fixations became more dispersed, though the label still attracted relatively high engagement. This suggests that while attention was diluted, the UTZ label maintained a degree of visual prominence within the immersive setting.

By comparison, the Leaf label consistently showed the lowest fixation intensity in both ET and VR ET. Fixation patterns were weak and scattered, indicating that the label failed to attract meaningful visual attention in either condition. This may reflect low visual salience due to less distinctive design, positioning, or familiarity.

Overall, fixation patterns were more concentrated in the controlled ET environment, where participants could focus directly on specific label elements. In contrast, the immersive and visually dynamic VR ET environment resulted in broader attention distribution, with participants engaging more with the overall product design than with individual labels. These findings highlight the importance of visual salience and environmental context in guiding consumer attention during product evaluation.

5.5.2. Mean Fixation Count and Trends

The fixation counts revealed a consistent trend across ET and VR ET (Table 16), with the ranking of attention toward each label remaining stable between the two environments. The GMO-Free label consistently attracted the highest attention (78.91 for ET and 60.41 for VR ET), followed by the Fair Trade label (70.19 for ET and 48.79 for VR ET) and the Euroleaf label (54.69 for ET and 43.69 for VR ET). The UTZ label showed moderate engagement (52.12 for ET and 26.95 for VR ET), while the Rainforest label (29.36 for ET and 14.67 for VR ET) and the Leaf label (17.91 for ET and 11.38 for VR ET) ranked lowest in both conditions.

The consistent rank order indicates that participants underlying visual preferences for the labels were preserved across both testing conditions. The higher fixation counts under ET reflect the controlled nature of the real-world setting, where distractions are minimised, allowing participants to engage more intensely with product-specific cues. In contrast, the lower fixation counts under VR ET suggest that the immersive environment introduced greater cognitive load and background complexity, leading to more exploratory viewing behaviour and reduced fixation intensity.

Table 16: Mean Fixation Count and Trends on each logo labels

Label	Mean ET Fixation Count	Mean VR ET Fixation Count	T-Test (p-value)	Rank in ET	Rank in VR ET	Trend
GMO-Free	78.91	60.41	0.091	1	1	Highest in both
Fair Trade	70.19	48.79	0.075	2	2	Higher in ET
Euroleaf	54.69	43.69	0.375	3	3	Similar in both
UTZ	52.12	26.95	0.054	4	4	Moderate engagement in both
Rainforest	29.36	14.67	0.067	5	5	Lower in both
Leaf	17.91	11.38	0.227	6	6	Lowest in both

The similarity in rank order between ET and VR ET indicates that participants directed their attention toward the same labels regardless of the testing environment. The lower fixation counts in VR ET reflect the increased cognitive load and environmental complexity introduced by the virtual environment, which may have reduced participants ability to sustain focused attention. However, the consistent pattern of label preference across both conditions confirms that participants maintained a stable hierarchy of attention toward the different labels. This suggests that the salience and perceived importance of the labels were preserved across both real-world and virtual environments.

5.5.3. Comparative Statistical Analysis of Eye-Tracking Methods (ET and VR ET)

An ANOVA was conducted to determine whether there were statistically significant differences in fixation counts between ET and VR ET across the six sustainability labels (Table 17). The overall ANOVA results revealed a significant difference between ET and VR ET fixation counts ($p = 0.001$). The mean fixation count for ET (50.528) was higher than for VR ET (34.313), indicating that participants engaged more with product labels under controlled ET conditions than in the more complex and dynamic VR environment. The standardized difference between the two conditions was 3.310, which exceeded the critical value of 1.965, confirming that the difference was statistically significant. The minimum significant difference was 9.624, reinforcing that the gap between ET and VR ET was meaningful and unlikely to be due to random variation.

Table 17: Mean Fixation Count in eye tracking (ET) and Virtual Reality Eye Tracking (VR ET)

Condition	Mean Fixation Count	Standard Error	Lower Bound (95%)	Upper Bound (95%)	Significance
ET	50.528	3.463	43.723	57.333	Significant
VR ET	34.313	3.463	27.509	41.118	Significant

The significant difference in mean fixation counts confirms that participants maintained more concentrated and focused attention on product labels under ET than VR ET. The controlled nature of ET allowed participants to isolate the product labels and engage with them more effectively. In VR ET, the increased complexity of the virtual environment, including background elements, spatial depth, and dynamic lighting, introduced additional cognitive load and competing stimuli. This resulted in a broader distribution of fixations and lower fixation counts, as participants were forced to divide their attention between the label and the surrounding visual elements.

The t-test results provided further insight into label-specific differences between ET and VR ET fixation counts. The UTZ label showed the most notable difference ($p = 0.054$), which is not statistically significant at the conventional 95 percent confidence level ($p \leq 0.05$). However, since the value is very close to 0.05, it can be considered marginally significant or suggestive of a meaningful trend. This suggests that participants were more likely to fixate on the UTZ label under ET than VR ET, but the difference was not strong enough to meet the strict threshold for statistical significance.

The Fair Trade ($p = 0.075$), GMO-Free ($p = 0.091$), and Rainforest ($p = 0.067$) labels also showed near-significant differences, suggesting that these labels attracted more focused visual attention under ET than in VR ET. While none of these p-values met the conventional significance threshold, their proximity to 0.05 suggests that there may still be meaningful differences that were not detected due to sample size or variance within the data. The higher fixation counts under ET for these labels indicate that participants were better able to isolate and engage with them under controlled conditions. However, the relatively strong fixation counts under VR ET suggest that these labels remained visually dominant and continued to attract attention even when cognitive load and background complexity were higher.

The Euroleaf ($p = 0.375$) and Leaf ($p = 0.227$) labels did not show significant differences between ET and VR ET. This suggests that participants engagement with these labels remained stable across both real-world and virtual environments. The consistent fixation counts for these labels imply that their design or positioning may have made them less sensitive to changes in environmental complexity. This stability may reflect lower visual salience or reduced participant interest in these labels compared to the higher-ranked labels.

The fact that the rank order of fixation counts remained stable between ET and VR ET confirms that participants underlying visual preferences for specific labels were preserved across both conditions. This indicates that participants were able to identify and prioritise visually salient labels even under increased cognitive load and environmental complexity. The reduction in fixation counts under VR ET reflects the increased difficulty of maintaining focused attention in a more complex visual environment, but the consistent ranking suggests that participants ability to evaluate and prioritise product labels was not significantly impaired.

The slightly elevated p-values for the Fair Trade, GMO-Free, Rainforest, and UTZ labels suggest that the sample size or variability within the data may have contributed to the lack of statistical significance. A larger sample size or reduced within-subject variability could strengthen the statistical power and potentially reveal significant differences for these labels. The trend toward higher fixation counts for these labels under ET suggests that they possessed stronger visual salience and were more effective at capturing attention when cognitive load was lower.

The consistent rank order of fixation counts across ET and VR ET reinforces the conclusion that participants underlying visual preferences remained stable across both environments. The near-significant differences for some labels suggest that the increased cognitive load and complexity of VR ET influenced participants ability to maintain focused attention but did not alter their fundamental attention hierarchy toward different product labels.

5.6. Experiment 5: Introductory Use of Augmented Virtuality (AV) for Colour Masking in Sensory Evaluation

5.6.1. Statistical Comparison of Expected and Preferred Product Attributes

An Analysis of Variance (ANOVA) with Tukey's Honest Significant Difference (HSD) test was performed to examine whether visual expectations significantly influenced post-tasting sensory perception under Augmented Virtuality (AV) conditions. The comparison focused on four sensory attributes liking, flavour, sweetness, and sourness across red, orange, and yellow cherry tomatoes. Expected ratings were collected during a visual-only phase, while preferred ratings were recorded after tasting the samples under a greyscale VR environment.

I. Expected liking and preferred liking

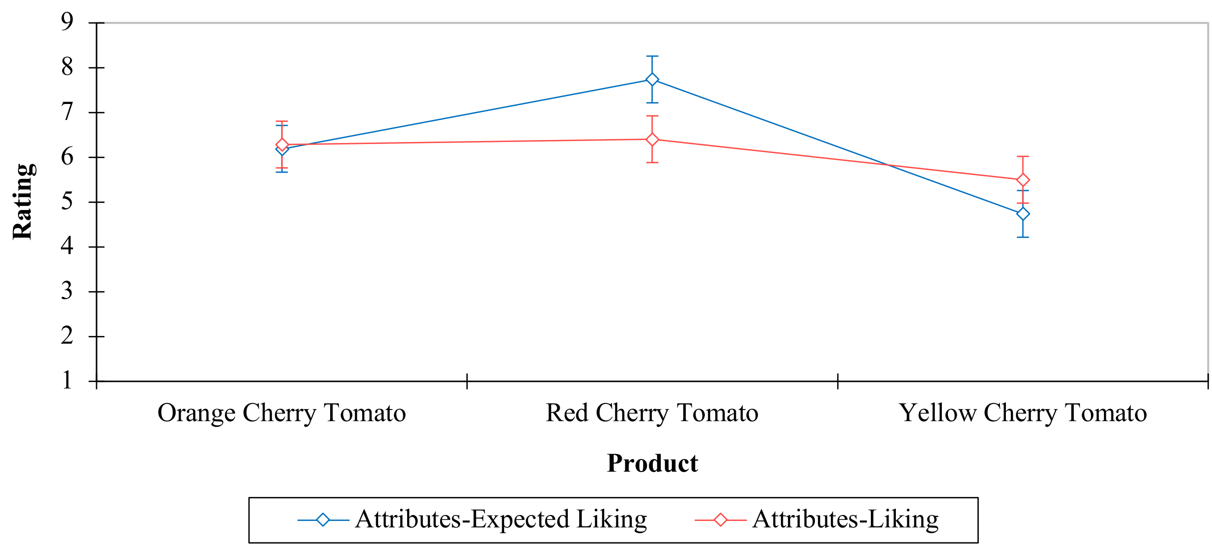


Figure 56: Mean expected vs preferred liking ratings across cherry tomato types. Error bars represent standard errors.

Figure 56 shows red cherry tomatoes exhibited a drop in mean scores from expected liking (7.74) to preferred liking (6.41). Orange tomatoes showed stable scores (expected = 6.19; preferred = 6.29), while yellow tomatoes showed an increase from 4.74 to 5.50. Despite these trends, Tukey's test indicated no significant difference between expected and preferred liking (p = 0.463), suggesting that liking perception was not statistically altered by initial expectations under AV.

II. Expected flavour and preferred flavour

In Figure 57, red cherry tomatoes had high expected flavour ratings (7.38), which decreased post-tasting (6.38). Orange tomatoes showed an increase from 5.74 to 6.12, while yellow tomatoes rose from 4.41 to 5.43. Nonetheless, the difference was not statistically significant (p = 0.515), indicating no measurable impact of visual expectations on flavour perception.

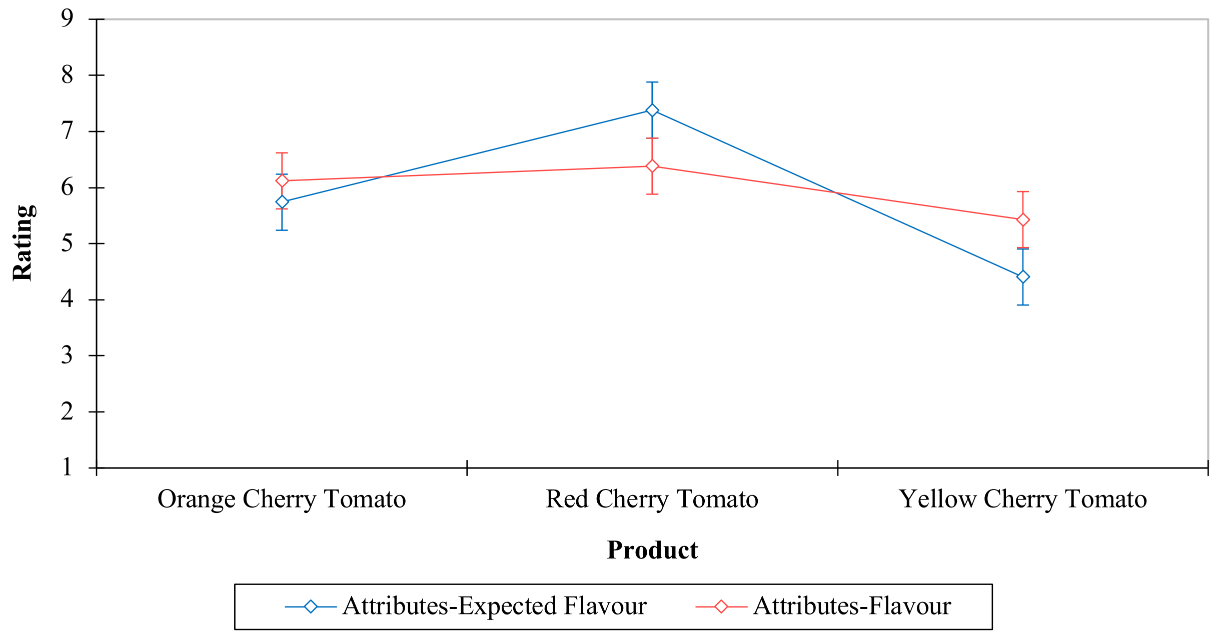


Figure 57: Mean expected vs preferred flavour ratings across cherry tomato types. Error bars represent standard errors.

III. Expected sweetness and preferred sweetness

Sweetness expectations were highest based on Figure 58 for red tomatoes (6.43) but dropped after tasting (5.52). Orange tomatoes increased from 4.91 to 5.55, and yellow tomatoes from 3.86 to 4.88. Despite visible shifts, Tukey's test revealed no significant difference between expected and preferred sweetness ratings (p = 0.280), suggesting colour masking may have neutralized expectation bias.

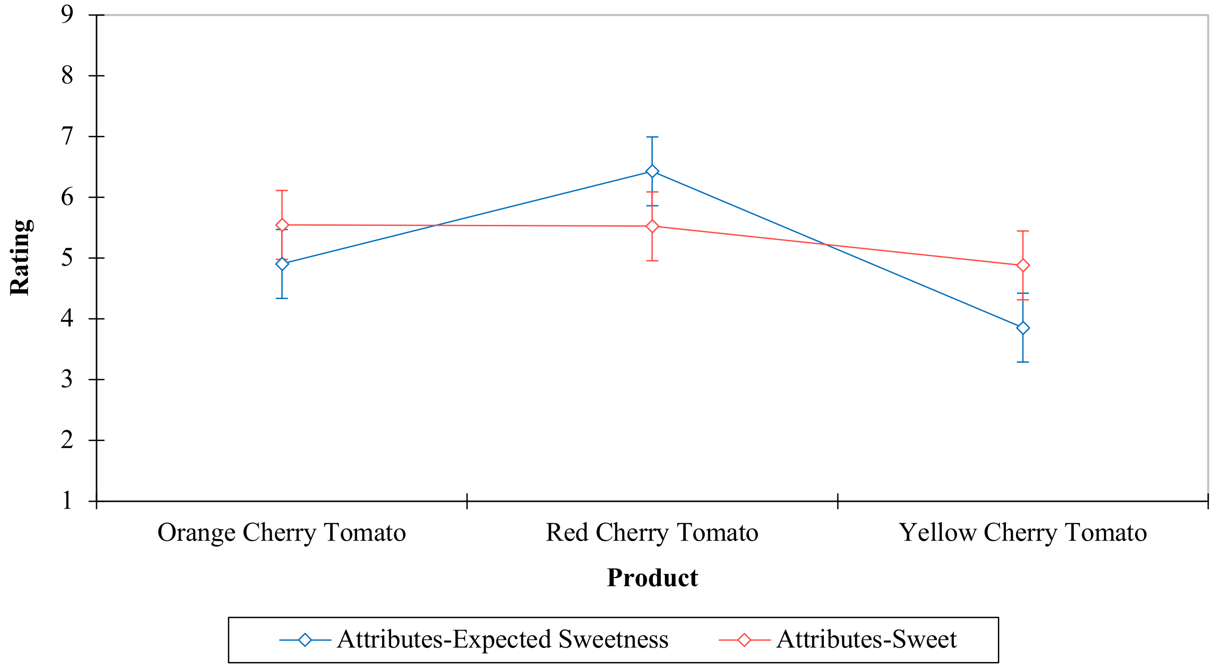


Figure 58: Mean expected vs preferred sweetness ratings across cherry tomato types. Error bars represent standard errors.

IV. Expected sourness and preferred sourness

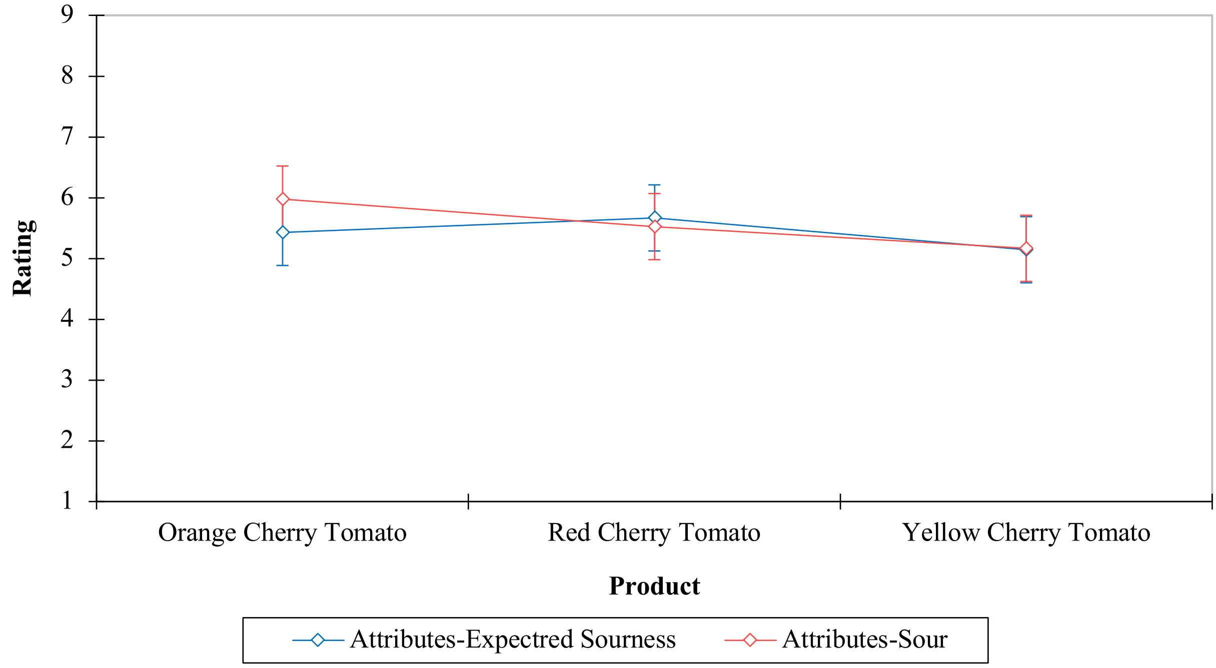


Figure 59: Mean expected vs preferred sourness ratings across cherry tomato types. Error bars represent standard errors.

Expected sourness for red tomatoes (5.67) was slightly higher than preferred (5.52), while orange tomatoes increased from 5.43 to 5.98, and yellow tomatoes remained nearly constant (5.14 to 5.17) (Figure 59). No significant difference was observed ($p = 0.527$), indicating that visual expectation had no measurable effect on sourness perception.

Table 18 presents the ANOVA results comparing expected and preferred ratings for various sensory attributes. No significant differences were found across liking, flavour, sweetness, or sourness, indicating that participants' perceptions closely matched their expectations.

Table 18: Summary of ANOVA Results on Expected vs Preferred Ratings

Attribute	Overall Mean Difference	p-Value	Significance	Interpretation
Liking	0.16	0.463	No	No significant difference between expected and preferred liking
Flavour	0.14	0.515	No	Perceived flavour aligned with expectations
Sweetness	0.25	0.280	No	Sweetness perception did not significantly differ from expectations
Sourness	0.14	0.527	No	No significant difference between expected and preferred sourness

5.6.2. Multivariate Analysis of Expected and Preferred Product Attributes.

Multiple Factor Analysis (MFA) was conducted to explore the relationships between the paired sensory attributes for each cherry tomato type. MFA helps to identify how well consumer expectations align with preferred sensory perception and whether the patterns are consistent across different product types.

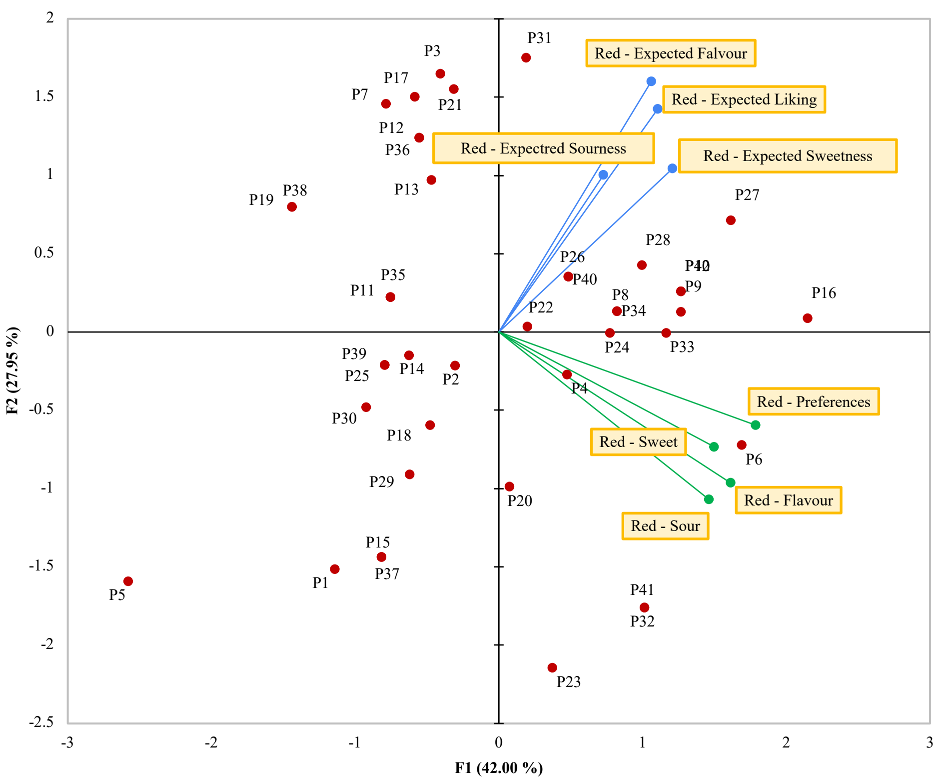


Figure 60: Multiple Factor Analysis (MFA) on Red Cherry Tomato

For red cherry tomatoes, the MFA (Figure 60) results showed that expected sweetness and sweetness had high loadings on Factor 1, confirming that sweetness perception was a major driver of consumer acceptance. Expected flavour and flavour were also strongly correlated, indicating that flavour expectations were consistent with preferred sensory experiences for red cherry tomatoes. The proximity between expected and preferred sourness on the MFA plot indicates that sourness perception played a secondary but meaningful role in shaping overall acceptance.

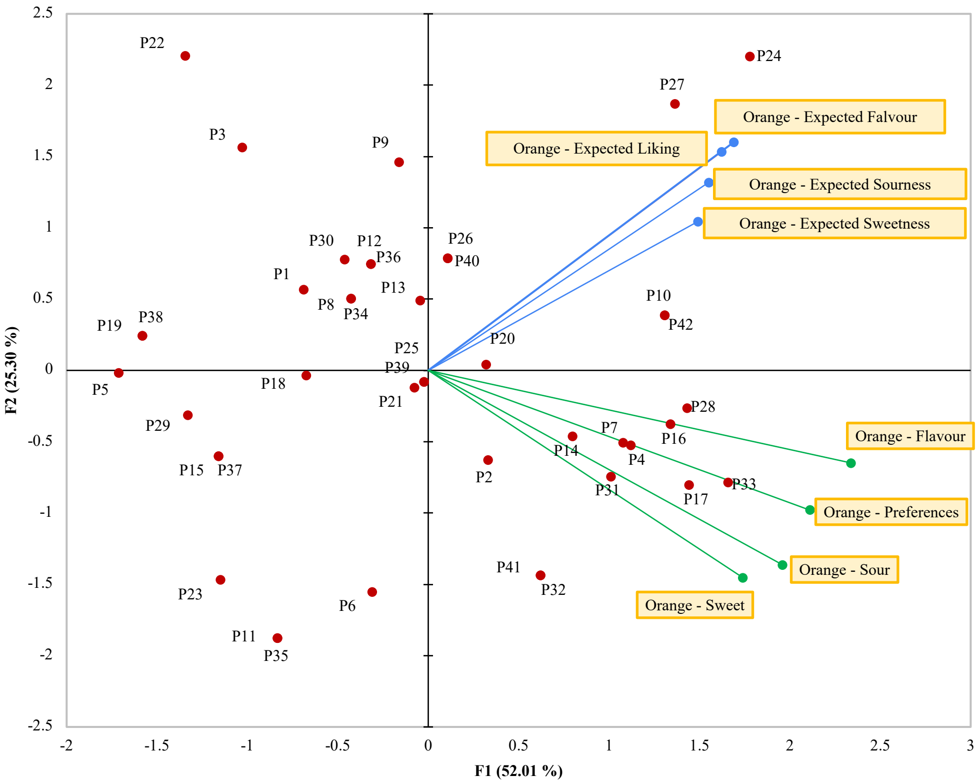


Figure 61: Multiple Factor Analysis (MFA) on Orange Cherry Tomato

For orange cherry tomatoes, the MFA (Figure 61) results showed that expected sweetness and sweetness clustered closely on Factor 1, indicating that sweetness perception was a key driver of acceptance. However, expected flavour and flavour were more widely spread, suggesting that flavour perception varied more among participants. The separation between expected and preferred sourness values indicates that sourness perception was less consistent for orange cherry tomatoes. Expected liking and preferences were also more dispersed, supporting the ANOVA finding that consumer preferences for orange cherry tomatoes were less predictable than for red or yellow tomatoes.

For yellow cherry tomatoes, the MFA (Figure 62) results showed a more balanced pattern, with sweetness and expected sweetness loading strongly on Factor 1, confirming that sweetness expectations influenced perception and acceptance. Expected flavour and flavour were positioned closer together, suggesting greater consistency between expected and preferred flavour perception. The relatively proximity between expected and preferred sourness also indicates that sourness perception was more stable for yellow cherry tomatoes, aligning with the ANOVA results showing no significant difference for this pair.

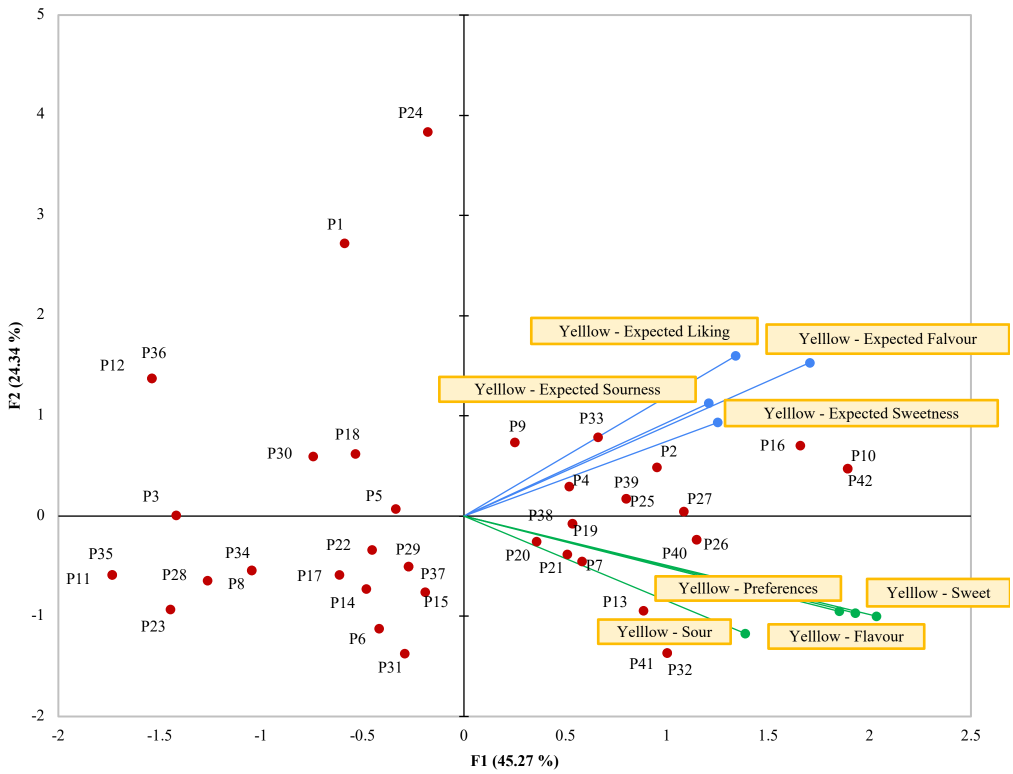


Figure 62: Multiple Factor Analysis (MFA) on Yelow Cherry Tomato

Table 19 summarises the MFA findings for each cherry tomato type. Red and yellow varieties showed strong alignment between expected and preferred perceptions, driven mainly by sweetness and flavour for red, and sweetness and sourness for yellow. The orange variety showed moderate alignment, with more variability observed in flavour perception.

Table 19: Summarisation of the MFA findings for each type of cherry tomato:

Cherry Tomato Type	Main Sensory Drivers	Alignment Between Expected and Preferred
Red	Sweetness and flavour	Strong alignment between expectations and perception
Orange	Sweetness and flavour	Moderate alignment, higher variability in flavour perception
Yellow	Sweetness and sourness	High consistency between expectations and perception

5.6.3. Discussion on the Product masking using Augmented Virtuality as an Initial Study.

The ANOVA and MFA results confirm that sweetness and flavour expectations are the strongest predictors of consumer acceptance across all cherry tomato types. For red cherry tomatoes, the significant alignment between expected and preferred sweetness and flavour indicates that consistency in taste perception drives higher product acceptance. The strong alignment for sweetness and flavour in the MFA plot reinforces this conclusion, suggesting that sweetness is the dominant sensory attribute influencing consumer satisfaction for red cherry tomatoes.

For orange cherry tomatoes, the weaker alignment between expected and preferred sensory attributes suggests that variability in flavour perception may reduce overall acceptance. The significant difference in expected sweetness vs sweetness ($p = 0.013$) indicates that sweetness perception remains important, but the moderate alignment in MFA suggests that further refinement of flavour consistency is needed to enhance product acceptance.

For yellow cherry tomatoes, the consistent alignment between expected and preferred sweetness and flavour suggests that consumers experienced a more balanced sensory profile. The lack of significant differences for expected flavour vs flavour and expected sourness vs sourness indicates that yellow cherry tomatoes have greater consistency between sensory expectations and preferred taste experience.

The use of Augmented Virtuality (AV) contributed to the alignment between expected and preferred sensory perception by masking colour differences among the cherry tomato types. Colour is known to influence taste expectations, with red products typically associated with higher sweetness and flavour intensity. By masking these visual cues using greyscale rendering, AV allowed participants to focus more directly on intrinsic sensory attributes such as taste and texture, leading to more accurate evaluations. This was supported by the Multiple Factor Analysis (MFA), which showed stronger alignment between expected and preferred ratings in the AV condition.

Although the red tomato's colour in the traditional setting could have influenced participants' expectations, this does not present a flaw in the experiment. On the contrary, it highlights the very type of perceptual bias that AV is designed to address. The more pronounced discrepancy observed for the red tomato in the traditional condition underscores how strong visual cues can distort flavour perception. The AV condition effectively removed this bias, demonstrating its value as a methodological tool for enhancing the objectivity of sensory data. Therefore, rather than being a weakness, the red tomato's visual influence serves as a justification for the use of AV in future sensory evaluations.

6. CONCLUSIONS AND RECOMMENDATIONS

Eye-tracking (ET) and Virtual Reality (VR) technologies have independently emerged as transformative tools within sensory science, providing innovative solutions to overcome traditional methodological limitations in sensory evaluations.

Eye-tracking significantly advances sensory research by objectively measuring consumer visual attention, cognitive processes, and subconscious expectation biases. Precise ET metrics, such as fixation duration, gaze distribution, and pupil dilation, allow sensory researchers to interpret consumer responses beyond subjective self-reports, enabling accurate predictions of consumer preferences and purchasing decisions. ET's capability to objectively assess visual interactions with product packaging, labelling, and sensory cues provides valuable insights, enhancing sensory evaluations.

Virtual Reality represents a significant advancement in sensory science by providing highly immersive, realistic, and contextually rich environments. VR technology enables controlled yet authentic scenarios, substantially improving the ecological validity of sensory tests by closely replicating real-world consumer experiences. VR enhances sensory perception studies by allowing systematic manipulation of environmental and contextual variables, significantly influencing emotional responses, cognitive engagement, and decision-making processes. This facilitates richer data collection, increases participant engagement, and enhances predictive accuracy concerning real-world consumer behaviours.

Although primarily utilized independently, the limited integration of VR and ET (VR ET) presents specific opportunities for understanding visual attention within immersive environments. Challenges such as gaze-tracking accuracy in VR, technological variability, cognitive load, simulator sickness, and user comfort underscore the importance of methodological refinement and empirical validation.

To effectively leverage ET, VR, and their limited integration within sensory science, several key recommendations are proposed. Firstly, establish standardized methodological protocols independently for VR experiments, clearly defining optimal calibration, stimuli presentation, and environmental scenarios. Standardizing VR methodologies will ensure methodological reliability and reproducibility across sensory studies.
Secondly, future research should explore the impact of VR environments on multisensory interactions and sensory perceptions. Specifically, studies should identify how different virtual environments systematically influence sensory evaluation outcomes, emotional engagement, and cognitive load.

Thirdly, advanced analytical frameworks should be developed and validated separately for each technology to manage, analyse, and interpret the complex sensory data generated. Statistical techniques like Principal Component Analysis (PCA), Multiple Factor Analysis (MFA), and cluster analysis should be adapted specifically for ET and VR contexts to accurately interpret relationships between sensory data and consumer behaviour.

Fourthly, targeted studies should explore the limited integration of VR and ET (VR ET) to clarify how immersive virtual environments affect visual attention patterns and related sensory outcomes. Lastly, in exploring AV technology independently, implementing specialized questionnaires such as the Extended Reality Sickness Questionnaire (XRSQ) will effectively capture nuanced symptoms related to XR experiences, particularly enhancing the realism and accuracy of AV sensory studies. Systematic evaluations of methodological factors affecting accuracy, ecological validity, and user comfort within VR, AV, and integrated VR ET setups are recommended. This includes addressing technological limitations, managing cognitive load, minimizing simulator sickness, and optimizing user experiences through validated questionnaires such as SSQ, PANAS, VRNQ and VRSQ.

By clearly differentiating and individually refining ET and VR, selectively integrating VR ET, and separately enhancing AV, sensory researchers can improve the ecological validity, predictive accuracy, and practical applicability of consumer sensory evaluations. These methodological advancements will significantly support informed, consumer-driven product optimization strategies and substantially contribute to the evolution of sensory science.

7. NEW SCIENTIFIC RESULTS

I. I developed and established a Virtual Sensory Laboratory and sensory booth for conducting immersive Virtual Reality (VR) sensory evaluations, enabling participants to move freely within the virtual environment, significantly enhancing ecological validity and user engagement beyond traditional laboratory setups.

> **Zulkarnain, A. H. B.**, Kókai, Z., & Gere, A. (2024). Assessment of a virtual sensory laboratory for consumer sensory evaluations. *Heliyon*, *10*(3), e25498. [https://doi.org/10.1016/j.heliyon.2024.e25498] – **IF_{2023} 3.4, Q1**
>
> **Zulkarnain, A. H. B.**, Radványi, D., Szakál, D., Kókai, Z., & Gere, A. (2024). Unveiling aromas: Virtual reality and scent identification for sensory analysis. *Current Research in Food Science*, *8*, 100698. [https://doi.org/10.1016/j.crfs.2024.100698] – **IF_{2023} 6.2, D1 (Food Science)**
>
> **Zulkarnain, A. H. B.**, Kókai, Z., & Gere, A. (2024). Immersive sensory evaluation: Practical use of virtual reality sensory booth. *MethodsX*, *12*, 102631. [https://doi.org/10.1016/j.mex.2024.102631] – **IF_{2023} 1.7, Q2**

II. I identified significant differences in sensory perceptions and emotional responses between traditional sensory testing and immersive VR-based evaluations, highlighting VR potential in replicating authentic consumer consumption contexts. I also evaluated the influence of different immersive virtual environments (e.g., park and food court) on consumer sensory perceptions, demonstrating contextual influences on product acceptance and sensory attribute ratings.

III. I was the first to systematically assess consumer cognitive load and emotional engagement within immersive VR contexts using validated psychometric instruments (PANAS, VRNQ, SSQ, and XRSQ), providing comprehensive understanding of user comfort and engagement during sensory evaluations.

> **Zulkarnain, A. H. B.**, Cao, X., Kókai, Z., & Gere, A. (2024). Self-Assessed Experience of Emotional Involvement in Sensory Analysis Performed in Virtual Reality. *Foods*, *13*(3), 375. [https://doi.org/10.3390/foods13030375] – **IF_{2023} 4.7, Q1**

IV. I was the first to applied Virtual Reality Eye Tracking (VR ET) and compare them with desktop-based ET to investigate consumer visual attention patterns toward sustainable food labelling, providing empirical insights into how sustainability claims impact visual engagement and purchasing decisions in virtual retail scenarios.

V. I introduced and demonstrated a novel methodological framework for Augmented Virtuality (AV) based sensory evaluations, effectively integrating real-world food stimuli into controlled virtual scenarios to maintain sensory realism, standardizing calibration, environmental setup, and stimuli presentation procedures to enhance reproducibility and reliability, and demonstrated that AV effectively isolates visual effects such as color, reducing bias and improving the accuracy of sensory research outcomes.

Zulkarnain, A. H. B., Moskowitz, H. R., Kókai, Z., & Gere, A. (2024). Enhancing consumer sensory science approach through augmented virtuality. *Current Research in Food Science*, *9*, 100834. [https://doi.org/10.1016/j.crfs.2024.100834] – **IF$_{2023}$ 6.2, D1 (Food Science)**

8. SUMMARY

This research investigated the application of immersive technologies in consumer sensory evaluations, with the aim of enhancing ecological validity, emotional realism, and methodological robustness. Conventional sensory evaluation methods conducted in controlled laboratory environments often fail to replicate the complexity and contextual factors influencing real world consumer behaviour. To address this limitation, the study introduced immersive technologies to simulate lifelike consumption contexts and more accurately capture consumer responses.

The initial phase focused on the development and validation of a virtual sensory laboratory. Compared to traditional sensory booths, the virtual environment demonstrated greater participant engagement, increased realism, and improved sensory immersion. Subsequent experiments examined the impact of distinct virtual environments such as food courts, parks, and home dining settings on sensory perception and emotional responses. Results revealed that environmental context plays a critical role in shaping product acceptance, perceived liking, and emotional intensity.

Virtual reality eye tracking (VR ET) and eye tracking (ET) were employed to assess visual attention toward sustainability labels in both immersive and traditional conditions. These technologies enabled the capture of real time gaze data in contextually rich settings, offering novel insights into how consumers engage with visual elements that influence purchase intent and product evaluation. The findings confirmed the value of ET and VR ET in identifying attention drivers and quantifying decision-making processes.

An innovative application of augmented virtuality (AV) was also explored, wherein participants evaluated real food samples, specifically cherry tomatoes, within a virtual café. This technique allowed the visual masking of colour cues while preserving the physical attributes of taste and texture. The results demonstrated a closer alignment between expected and actual sensory perceptions, particularly by reducing bias introduced by visual expectations. This highlights the potential of AV to enhance the validity of consumer sensory data where visual influence is a confounding factor.

The methodological contributions of this research include the formulation of standardised protocols for immersive sensory studies, encompassing calibration procedures, environmental control, stimulus delivery, and participant interaction. Cognitive load and user experience were systematically evaluated using validated psychometric tools including the Simulator Sickness Questionnaire (SSQ), Positive and Negative Affect Schedule (PANAS), Virtual Reality Neuroscience Questionnaire (VRNQ), and Virtual Reality System Questionnaire (VRSQ).

In conclusion, this research illustrates the significant benefits of integrating immersive technologies into sensory science. The integrated use of virtual reality (VR), virtual reality eye tracking (VR ET), eye tracking (ET), and augmented virtuality (AV) provides a comprehensive methodological toolkit that improves the realism, reliability, and interpretability of sensory data. These advancements offer valuable guidance for sensory scientists, product developers, and industry practitioners aiming to create more consumer relevant and context aware sensory evaluation frameworks.

9. LIST OF PUBLICATION IN THE FIELD OF STUDY

9.1. Publications in Journal

First Author Publications

Zulkarnain, A. H. B., Szakál, D., Boncsarovszki, B., Tao, C., Kókai, Z., & Gere, A. Next-Generation Virtual Sensory Analysis: The Evolving Role of Virtual Reality and Eye Tracking in Food Science—A Graphical Perspective – Under Review (2025)

Zulkarnain, A. H. B., Kókai, Z., & Gere, A. Sick from Virtual Reality Sensory Testing? The Role of the Simulator Sickness Questionnaire in Virtual Sensory Analysis – Under Review (2025)

Zulkarnain, A. H. B., Kókai, Z., & Gere, A. Application of Different Sensory Methods in Virtual Reality Sensory Analysis: Evaluating the Impact of Immersive Environments on Food Perception – Under Review (2025)

Zulkarnain, A. H. B., Kókai, Z., & Gere, A. Comparing Realities: Bridging Traditional Sensory Testing to Virtual Reality – Under Review (2025)

Zulkarnain, A. H. B., & Gere, A. (2025). Virtual reality sensory analysis approaches for sustainable food production. *Applied Food Research*, *5*(1), 100780. [https://doi.org/10.1016/j.afres.2025.100780] – **IF$_{2023}$ 4.5, Q1**

Zulkarnain, A. H. B., Moskowitz, H. R., Kókai, Z., & Gere, A. (2024). Enhancing consumer sensory science approach through augmented virtuality. *Current Research in Food Science*, *9*, 100834. [https://doi.org/10.1016/j.crfs.2024.100834] – **IF$_{2023}$ 6.2, D1 (Food Science)**

Zulkarnain, A. H. B., Kókai, Z., & Gere, A. (2024). Immersive sensory evaluation: Practical use of virtual reality sensory booth. *MethodsX*, *12*, 102631. [https://doi.org/10.1016/j.mex.2024.102631] – **IF$_{2023}$ 1.7, Q2**

Zulkarnain, A. H. B., Cao, X., Kókai, Z., & Gere, A. (2024). Self-Assessed Experience of Emotional Involvement in Sensory Analysis Performed in Virtual Reality. *Foods*, *13*(3), 375. [https://doi.org/10.3390/foods13030375] – **IF$_{2023}$ 4.7, Q1**

Zulkarnain, A. H. B., Kókai, Z., & Gere, A. (2024). Assessment of a virtual sensory laboratory for consumer sensory evaluations. *Heliyon*, *10*(3), e25498. [https://doi.org/10.1016/j.heliyon.2024.e25498] – **IF$_{2023}$ 3.4, Q1**

Zulkarnain, A. H. B., Radványi, D., Szakál, D., Kókai, Z., & Gere, A. (2024). Unveiling aromas: Virtual reality and scent identification for sensory analysis. *Current Research in Food Science*, *8*, 100698. [https://doi.org/10.1016/j.crfs.2024.100698] – **IF$_{2023}$ 6.2, D1 (Food Science)**

Co-authored Publications

Szakál, D., **Bin Zulkarnain, A. H.**, Cao, X., & Gere, A. (2023). Odors Change Visual Attention. A Case Study with Stawberry Odor and Differently Flavoured Yoghurts. *Meat Technology*, *64*(2), 17–24. [https://doi.org/10.18485/meattech.2023.64.2.3] – **IF$_{2023}$ 0.5, Q4**

Szakál, D., Fekete-Frojimovics, Z., **Zulkarnain, A. H. B.**, Rozgonyi, E., & Fehér, O. (2023). Do we pay more attention to the label that is considered more expensive? Eye-tracking analysis of different wine varieties. *Progress in Agricultural Engineering Sciences*, *19*(1), 35–50. [https://doi.org/10.1556/446.2023.00069] – **IF$_{2023}$ 1.68, Q2**

Gere, A., **Zulkarnain, A. H. B.**, Szakál, D., Fehér, O., & Kókai, Z. (2021). Virtual reality applications in food science. Current knowledge and prospects. *Progress in Agricultural Engineering Sciences*, *17*(1), 3–14. [https://doi.org/10.1556/446.2021.00015] – **IF$_{2021}$ 0.74, Q3**

9.2. Conferences

Conference Proceedings

Totorean, A., Lancere, L., Horsak, B., Simonlehner, M., Stoia, D. I., Crisan-Vida, M., Moco, D., Fernandes, R., Gere, A., Sterckx, Y., **Zulkarnain, A.**, Gal-Nadasan, N., & Stoia, A. (2024). Heart Rate and Surface Electromyography Analysis to Assess Physical Activity Using a Virtual-Reality Exergame. In N. Herisanu & V. Marinca (Eds.), *Acoustics and Vibration of Mechanical Structures—AVMS-2023* (Vol. 302, pp. 139–146). Springer Nature Switzerland. [https://doi.org/10.1007/978-3-031-48087-4_15]

Oral Presentations

Zulkarnain, A H.B., Kókai Z., Gere A. (2024, May 3 - 5). Enhancing the Practical Application of Virtual Reality Sensory Evaluations. Tavaszi Szél Konferencia 2024/Spring wind conference 2024, Budapest, Hungary.

Zulkarnain, A. H. B., Kókai Z., Gere A. (2023, November 16). Revolutionizing Sensory Evaluation with VR Sensory Booth: Implementing Different Sensory Methods. Lippay János - Ormos Imre - Vas Károly (LOV) Conference 2023, Budapest, Hungary.

Zulkarnain, A. H. B., Kókai Z., Gere A. (2023, June 9). Comparison of traditional and virtual reality sensory testing. 5th BiosysFoodEng 2023, Budapest, Hungary.

Zulkarnain, A H. B., Kókai Z., Gere A. (2023, May 5 - 7). Consumer's positive and negative affects on virtual reality sensory analysis. Tavaszi Szél Konferencia 2023/Spring wind conference 2023, Miskolc, Hungary.

Zulkarnain, A. H. B., Kókai Z., Gere A. (2022, November 5 - 6). Testing acceptability of the virtual reality sensory laboratory. Postgraduate Research Colloquium 2022, Subang Jaya, Selangor, Malaysia.

Poster Presentations

Zulkarnain, A H.B., Moskowitz H. R., Kókai Z., Gere A. (2024, September 8 - 11). Exploring the Potential of Augmented Virtuality in Enhancing Sensory Science. EUROSENSE 2024: A Sense of Global Culture, Dublin, Ireland.

Gere A., **Zulkarnain, A H.B.**, Cao X., Szakál D., Radványi D. (2024, September 8 - 11). Eye-tracking insights: predicting food choices in virtual reality environments. EUROSENSE 2024: A Sense of Global Culture, Dublin, Ireland.

Gere A., **Zulkarnain, A. H. B.**, Cao X., Radványi, D. (2023, June 29 - 30). Citizen Science applications in sustainable food systems. Possibilities for food scientists. E³UDRES² Citizen Science Conference, Setúbal, Portugal.

Zulkarnain, A. H. B., Kókai Z., Gere A. (2022, June 10 - 11). Bringing the conventional sensory laboratory into virtual reality (VR) for food sensory evaluation. 4th FoodConf 2022, Budapest, Hungary.

Zulkarnain, A. H. B., Totorean A., Gere A., Cruz E., Horsak B., Lancere L., Schoeffer L., Simonlehner M., Crișan-Vida M., Fernandes R., Sterckx Y. (2022, June 10 - 11). Development of a social inclusive immersive virtual reality exergame to promote physical activity. 4th FoodConf 2022, Budapest, Hungary.

Zulkarnain, A. H. B., Kókai Z., Gere A. (2022, May 6 - 8). Introducing the virtual sensory laboratory for food sensory evaluation. Tavaszi Szél Konferencia 2022/Spring wind conference 2022, Pécs, Hungary.

10. APPENDICES

10.1. Bibliography

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10.2. Further appendices

10.2.1. Questionnaire

10.2.1.1. Simulator Sickness Questionnaire

STIMULATOR SICKNESS QUESTIONNAIRE

Name:
(Név)

Age: *(Életkor)*

Gender: *(Neme)*

Instruction: Choose (X) how much each symptom below is affecting you **right now**.
(Feladat: Válassza ki (X-el), hogy az alábbiakban felsorolt egyes tünetek jelenleg mennyire befolyásolják Önt.)

	None *(Nincs)*	Slight *(Enyhe)*	Moderate *(Mérsékelt)*	Severe *(Súlyos)*
1. General Discomfort *(Általános rossz közérzet)*	☐	☐	☐	☐
2. Fatigue *(Fáradtság)*	☐	☐	☐	☐
3. Headache *(Fejfájás)*	☐	☐	☐	☐
4. Eye Strain *(Szem megerőltetés)*	☐	☐	☐	☐
5. Difficulty Focusing *(Fókuszálási nehezség)*	☐	☐	☐	☐
6. Salivation Increasing *Fokozódó nyáladzás)*	☐	☐	☐	☐
7. Sweating *(Izzadás)*	☐	☐	☐	☐
8. Nausea *(Hányinger)*	☐	☐	☐	☐
9. Difficulty Concentrating *(Koncentrációs nehézség)*	☐	☐	☐	☐
10. "Fullness of Head" *(Fej telítettség)*	☐	☐	☐	☐
11. Blurred Vision *(Homályos látás)*	☐	☐	☐	☐
12. Dizziness with Eyes Open *(Szédülés nyitott szemmel)*	☐	☐	☐	☐
13. Dizziness with Eyes Closed *(Szédülés csukott szemmel)*	☐	☐	☐	☐
14. Vertigo* *(Szédülés)*	☐	☐	☐	☐
15. Stomach Awareness** *(Gyomor rossz érzete)*	☐	☐	☐	☐
16. Burping *(Böfögés)*	☐	☐	☐	☐

* Vertigo is experienced a loss of orientation with respect with vertical upright.
(A szédülés a függőlegesen felfelé irányuló tájékozódás elvesztését jelenti)
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short nausea.
(A gyomorérzetet általában a kellemetlen érzés jelzésére használják, ami csak rövid ideig tartó hányinger)

Thank you for participating!
(Köszönjük a részvételt!)

10.2.1.2. Virtual Reality System Questionnaire

VIRTUAL REALITY SYSTEM QUESTIONNAIRE

Name:
(Név)

Age: Gender:
(Életkor) *(Neme)*

Instruction: Rate (X) each of the following.
(Feladat: Értékelje (X-el) az alábbiak mindegyikét.)

									NA
1.	Head gear is *(Fejvédő felszerelés)*	Very Uncomfortable *(Nagyon kellemetlen)* ☐	☐	☐	☐	☐	☐	Very Comfortable *(Nagyon kényelmes)* ☐	☐
2.	Calibrating the system and tracking *(Rendszer követése)*	Very Difficult *(Nagyon nehéz)* ☐	☐	☐	☐	☐	☐	Very Easy *(Nagyon könnyű)* ☐	☐
3.	Image lags when head is turned slowly *(A kép késik,ha a fejet lassan forgatjuk)*	Very Much *(Nagyon sokat)* ☐	☐	☐	☐	☐	☐	Not at all *(Egyáltalán nem)* ☐	☐
4.	Image lags when head is turned quickly *(A kép késik, ha a fejet gyorsan forgatjuk)*	Very Much *(Nagyon sokat)* ☐	☐	☐	☐	☐	☐	Not at all *(Egyáltalán nem)* ☐	☐
5.	Image is blurred in some areas *(A kép egyes területeken elmosódott)*	Very Much *(Nagyon sokat)* ☐	☐	☐	☐	☐	☐	Not at all *(Egyáltalán nem)* ☐	☐
6.	All the image blurred *(Minden kép elmosódott)*	Very Much *(Nagyon sokat)* ☐	☐	☐	☐	☐	☐	Not at all *(Egyáltalán nem)* ☐	☐
7.	Image skips or break up at times *(A kép időnként ugrik vagy szétesik)*	Very Often *(Nagyon gyakran)* ☐	☐	☐	☐	☐	☐	Never *(Soha)* ☐	☐
8.	Image covers 360° surround *(A kép 360°-os környezetet fed le)*	Incomplete *(Hiányos)* ☐	☐	☐	☐	☐	☐	Complete *(Teljes)* ☐	☐
9.	Trying to locate source of sounds *(A hangok forrását próbálja lokalizálni)*	Very Difficult *(Nagyon nehéz)* ☐	☐	☐	☐	☐	☐	Very Easy *(Nagyon könnyű)* ☐	☐
10.	Trying to aim or point at targets using head position *(Próbájon célozni vagy célpontokra mutatni a fej helyzetével)*	Very Difficult *(Nagyon nehéz)* ☐	☐	☐	☐	☐	☐	Very Easy *(Nagyon könnyű)* ☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
11. Trying to aim or point at targets using hand/controller *(A kézzel/vezérlővel történő célzás vagy célzásra való törekvés)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
12. Moving through space using head orientation *(A térben való mozgás a fej tájékozódásával)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
13. Orienting one's self in the space *(A térben való tájékozódás)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
14. Trying to turn and see what is to the left and right *(Próbáljon elfordulni és megnézni, mi van jobbra és balra)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
15. Trying to turn and see what is behind *(Próbáljon megfordulni és megnézni, mi van mögötte)*	☐	☐	☐	☐	☐	☐	☐	☐

	Confusing *(Zavaros)*						Very Clear *(Nagyon egyértelmű)*	NA
16. Awareness of body location *(A testhelyzet elhelyezkedése)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Poor *(Nagyon gyenge)*						Very Good *(Nagyon jó)*	NA
17. Location of hands and arms *(A kezek és karok elhelyezkedése)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
18. Physically move in the virtual environment *(Fizikai mozgás a virtuális környezetben)*	☐	☐	☐	☐	☐	☐	☐	☐

	Very Difficult *(Nagyon nehéz)*						Very Easy *(Nagyon könnyű)*	NA
19. Pick up and/or place items in the virtual environment *(Tárgyak felvétele vagy elhelyezése a virtuális környezetben)*	☐	☐	☐	☐	☐	☐	☐	☐

	Negative *(Negatív)*						Positive *(Pozitív)*	NA
20. Overall experience with VR *(Általános tapasztalat a VR-rel kapcsolatban)*	☐	☐	☐	☐	☐	☐	☐	☐

Comments*(Megjegyzés)*:

Thank you for participating!*(Köszönjük a részvételt!)*

10.2.1.3. Virtual Reality Neuroscience Questionnaire

VIRTUAL REALITY NEUROSCIENCE QUESTIONNAIRE

Code:
*(*Kód:*)*

Age: *(Életkor)*	Gender: *(Nem)*

Instruction: Rate by circle each of the following.
*(*Utasítás: Karikával értékelje az alábbiakat*)*

<u>User Experience</u>

What is the level of immersion you experienced?
*(*Milyen szintű elmélyülést tapasztalt?*)*

1	2	3	4	5	6	7
Extremely Low *(*Rendkívül alacsony*)*	Very Low *(*Nagyon alacsony*)*	Low *(*Alacsony*)*	Neutral *(*Semleges*)*	High *(*Magas*)*	Very High *(*Nagyon magas*)*	Extremely High *(*Nagyon magas*)*

Please write below any additional comments and/or suggestions relevant to the question above:
*(*Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:*)*

What was your level of enjoyment of the VR experience?
*(*Milyen szinten élvezte a VR élményt?*)*

1	2	3	4	5	6	7
Extremely Low *(*Rendkívül alacsony*)*	Very Low *(*Nagyon alacsony*)*	Low *(*Alacsony*)*	Neutral *(*Semleges*)*	High *(*Magas*)*	Very High *(*Nagyon magas*)*	Extremely High *(*Nagyon magas*)*

Please write below any additional comments and/or suggestions relevant to the question above:
*(*Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:*)*

How was the quality of the graphics?
(Milyen volt a grafika minősége?)

1	2	3	4	5	6	7
Extremely Low (Rendkívül alacsony)	Very Low (Nagyon alacsony)	Low (Alacsony)	Neutral (Semleges)	High (Magas)	Very High (Nagyon magas)	Extremely High (Nagyon magas)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How was the quality of the sound?
(Milyen volt a hangminőség?)

1	2	3	4	5	6	7
Extremely Low (Rendkívül alacsony)	Very Low (Nagyon alacsony)	Low (Alacsony)	Neutral (Semleges)	High (Magas)	Very High (Nagyon magas)	Extremely High (Nagyon magas)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How was the quality of the VR technology overall (i.e. hardware & peripherals)?
(Összességében milyen volt a VR technológia minősége (azaz a hardver és a perifériák)?)

1	2	3	4	5	6	7
Extremely Low (Rendkívül alacsony)	Very Low (Nagyon alacsony)	Low (Alacsony)	Neutral (Semleges)	High (Magas)	Very High (Nagyon magas)	Extremely High (Nagyon magas)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Game Mechanics

How easy was to use the navigation system (e.g. teleportation) in the virtual environment?
(Mennyire volt egyszerű a navigációs rendszer használata (pl. teleportálás) a virtuális környezetben?)

1	2	3	4	5	6	7
Extremely Difficult *(Extrém nehéz)*	Very Difficult *(Nagyon nehéz)*	Difficult *(Nehéz)*	Neutral *(Semleges)*	Easy *(Könnyű)*	Very Easy *(Nagyon könnyű)*	Extremely Easy *(Rendkívül könnyű)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How easy was to physically move in the virtual environment?
(Mennyire volt könnyű fizikailag mozogni a virtuális környezetben?)

1	2	3	4	5	6	7
Extremely Difficult *(Extrém nehéz)*	Very Difficult *(Nagyon nehéz)*	Difficult *(Nehéz)*	Neutral *(Semleges)*	Easy *(Könnyű)*	Very Easy *(Nagyon könnyű)*	Extremely Easy *(Rendkívül könnyű)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How easy was to pick up and/or place items in the virtual environment?
(Mennyire volt egyszerű a tárgyakat felvenni és/vagy elhelyezni a virtuális környezetben?)

1	2	3	4	5	6	7
Extremely Difficult *(Extrém nehéz)*	Very Difficult *(Nagyon nehéz)*	Difficult *(Nehéz)*	Neutral *(Semleges)*	Easy *(Könnyű)*	Very Easy *(Nagyon könnyű)*	Extremely Easy *(Rendkívül könnyű)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How easy was to use items in the virtual environment?
(Mennyire volt egyszerű az egyes tárgyak használata a virtuális környezetben?)

1	2	3	4	5	6	7
Extremely Difficult (Extrém nehéz)	Very Difficult (Nagyon nehéz)	Difficult (Nehéz)	Neutral (Semleges)	Easy (Könnyű)	Very Easy (Nagyon könnyű)	Extremely Easy (Rendkívül könnyű)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How easy was the 2-handed interaction e.g., grab the item with the one hand, and push the button with the other hand?
(Mennyire volt egyszerű a kétkezes interakció, pl. egy kézzel fogd meg a tárgyat , a másikkal nyomd meg a gombot?)

1	2	3	4	5	6	7
Extremely Difficult (Extrém nehéz)	Very Difficult (Nagyon nehéz)	Difficult (Nehéz)	Neutral (Semleges)	Easy (Könnyű)	Very Easy (Nagyon könnyű)	Extremely Easy (Rendkívül könnyű)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

In-Game Assistance

How easy was to complete the tutorial(s)?
(Mennyire volt egyszerű az oktatóprogram(ok) befejezése?)

1	2	3	4	5	6	7
Extremely Difficult (Extrém nehéz)	Very Difficult (Nagyon nehéz)	Difficult (Nehéz)	Neutral (Semleges)	Easy (Könnyű)	Very Easy (Nagyon könnyű)	Extremely Easy (Rendkívül könnyű)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How helpful was/were the tutorial(s)?
(Mennyire volt(ak) hasznosak az oktatóanyag(ok)?)

1	2	3	4	5	6	7
Extremely Unhelpful (Rendkívül haszontalan)	Very Unhelpful (Nagyon haszontalan)	Unhelpful (Nem segítőkész)	Neutral (Semleges)	Helpful (Hasznos)	Very Helpful (Nagyon hasznos)	Extremely Helpful (Rendkívül hasznos)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How did you feel about the duration of the tutorial(s)?
(Hogyan vélekedik az oktatások időtartamáról?)

1	2	3	4	5	6	7
Extremely More Time Needed (Rendkívülien több időre van szükség)	Much More Time Needed (Sokkal több időre van szükség)	More Time Needed (Több időre van szükség)	Neutral (Semleges)	Enough Time Available (Elég idő áll rendelkezésre)	Much Time Available (Sok idő áll rendelkezésre)	Plenty of Time Available (Rengeteg idő áll rendelkezésre)

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How helpful were the in-game instructions for the task you needed to perform?
(Mennyire voltak hasznosak a játékon belüli utasítások az elvégzendő feladathoz?)

1	2	3	4	5	6	7
Extremely Unhelpful *(Rendkívül haszontalan)*	Very Unhelpful *(Nagyon haszontalan)*	Unhelpful *(Nem segítőkész)*	Neutral *(Semleges)*	Helpful *(Hasznos)*	Very Helpful *(Nagyon hasznos)*	Extremely Helpful *(Rendkívül hasznos)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

How helpful were the in-game prompts e.g. arrows showing the direction, or labels?
(Mennyire voltak hasznosak a játékon belüli felszólítások, például az irányt mutató nyilak vagy a címkék?)

1	2	3	4	5	6	7
Extremely Unhelpful *(Rendkívül haszontalan)*	Very Unhelpful *(Nagyon haszontalan)*	Unhelpful *(Nem segítőkész)*	Neutral *(Semleges)*	Helpful *(Hasznos)*	Very Helpful *(Nagyon hasznos)*	Extremely Helpful *(Rendkívül hasznos)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

VR Induced Symptoms and Effects (VRISE)

Did you experience nausea?
(Hányingert tapasztalt?)

1	2	3	4	5	6	7
Extremely Intense *(Rendkívül intenzív)*	Very Intense *(Nagyon intenzív)*	Intense *(Erős)*	Moderate *(Mérsékelt)*	Mild *(Enyhe)*	Very Mild *(Nagyon lágy)*	Absent *(Nem tapasztalt)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Did you experience disorientation?
(Dezorientációt tapasztalt?)

1	2	3	4	5	6	7
Extremely Intense *(Rendkívül intenzív)*	Very Intense *(Nagyon intenzív)*	Intense *(Erős)*	Moderate *(Mérsékelt)*	Mild *(Enyhe)*	Very Mild *(Nagyon lágy)*	Absent *(Nem tapasztalt)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Did you experience dizziness?
(Érzett szédülést?)

1	2	3	4	5	6	7
Extremely Intense *(Rendkívül intenzív)*	Very Intense *(Nagyon intenzív)*	Intense *(Erős)*	Moderate *(Mérsékelt)*	Mild *(Enyhe)*	Very Mild *(Nagyon lágy)*	Absent *(Nem tapasztalt)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Did you experience fatigue?
(Fáradtságot tapasztalt?)

1	2	3	4	5	6	7
Extremely Intense *(Rendkívül intenzív)*	Very Intense *(Nagyon intenzív)*	Intense *(Erős)*	Moderate *(Mérsékelt)*	Mild *(Enyhe)*	Very Mild *(Nagyon lágy)*	Absent *(Nem tapasztalt)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Did you experience instability?
(Instabilitást tapasztalt?)

1	2	3	4	5	6	7
Extremely Intense *(Rendkívül intenzív)*	Very Intense *(Nagyon intenzív)*	Intense *(Erős)*	Moderate *(Mérsékelt)*	Mild *(Enyhe)*	Very Mild *(Nagyon lágy)*	Absent *(Nem tapasztalt)*

Please write below any additional comments and/or suggestions relevant to the question above:
(Kérjük, írja le alább a fenti kérdéssel kapcsolatos további megjegyzéseit és/vagy javaslatait:)

Thank you for participating!
(Köszönjük a részvételt!)

10.2.2. Code Metadata

Current code version	V 1.0
Permanent link to code/repository used for this code version	https://github.com/MATESensoryVR/VRSensoryBooth_V1.2023.git
Permanent link to Reproducible Capsule	-
Legal Code License	MIT License https://github.com/MATESensoryVR/VRSensoryBooth_V1.2023/blob/main/LICENSE.md
Code versioning system used	git version 2.39.3
Software code languages, tools, and services used	C++, Unity 2022.3.10f1, OpenXR Plugin 1.8.2, Oculus Integration 57.0, Oculus SDK 1.3.2
Compilation requirements, operating environments & dependencies	Oculus Quest 2, Unity 2022.3.10f1, OVRBuild APK (optional)
If available Link to developer documentation/manual	https://github.com/MATESensoryVR/VRSensoryBooth_V1.2023/blob/main/README.md
Support email for questions	abdulhannanphd@gmail.com; gere.attila@uni-mate.hu

ACKNOWLEDGEMENT

Belajar jauh ke bumi Hungary,
Membawa harapan meniti hari,
Tekun menimba ilmu di MATE,
Akhirnya PhD menjadi realiti.

With a heart full of gratitude and emotion, I reflect on this journey with deep appreciation for every soul who made it meaningful. I thank God for the strength, patience, and guidance that carried me through. To Him belongs the words: “Kun Faya Kun” — ‘Be, and it is’. Reaching this milestone is not merely an academic achievement, but a tribute to the love, support, and belief that made it possible. Most people say a PhD is a lonely journey, but that has never felt completely true to me. This chapter, though deeply personal, has never been mine alone. It belongs to every person who stood beside me, cheering me on, holding me up, and reminding me who I am even when I forgot.

This journey has been more than academic. It has been a mirror into who I am, who I want to become, and the kind of resilience I did not know I had. At the centre of it all, I have been incredibly fortunate to be guided by two mentors who truly represent what every PhD student hopes for: supportive, insightful, and genuinely invested in my success.

To Dr Attila Gere, I am deeply and sincerely grateful for your exceptional mentorship. You were not only a supervisor but also a guide, a motivator, a friend, and most of all, a constant supporter throughout this entire journey. Your expertise and your commitment to excellence were instrumental to the success of my research. What stood out most was your willingness to invest in me as a person. You believed in me even during moments when I doubted myself. You were always there with time, encouragement, honest feedback, and genuine care. You challenged me to go further, to think more deeply, and to aim higher, while also reminding me to find balance as a human being. This path felt less lonely and more meaningful because of you. I will carry your influence with me for the rest of my life. Thank you for being a mentor in the truest sense, and a friend I shall always be grateful for.

To Dr. Kókai Zoltán, thank you for your guidance, support, and steady presence throughout this journey. You have always been supportive and have been there whenever I needed help or direction. Your trust in my work, your gentle nudges in the right direction, and your unwavering support meant more than words can say. I have grown under your mentorship, and I am truly grateful for the role you have played in both my academic and personal journey.

To my PhD mates and lab colleagues (Dr. Barbara Lovasné Bíró, Dorina Szakál, Xu Cao (Jeremy), Balázs Boncsarovszki and Chengfang Tao), thank you for being a constant source of support, inspiration, and camaraderie. From brainstorming sessions to long lab hours and shared laughter in between, you’ve made this journey memorable and fulfilling. Our collaborations and friendship have shaped not only my academic path but also my personal growth. I am grateful to walk this journey with such an incredible team.

To the Hungarian University of Agriculture and Life Sciences (MATE), thank you for becoming my academic home. Within these walls, I found not only knowledge but a community of scholars, mentors, and friends who have left a lasting impact on my life. The Institute of Food Science and Technology provided the space to pursue meaningful research and personal growth. I am also deeply thankful to the International Coordinators who helped me adapt in my early days at MATE. Your patience, support, and kindness made a world of difference as I adjusted to a new academic and cultural environment. The faculty, staff, and students created a space where ideas flourished and where I could truly grow.

Realistically, pursuing a PhD and my Master's degree - particularly overseas - wouldn't be possible without solid financial support. Therefore, I am very grateful to the Tempus Public Foundation and the Stipendium Hungaricum Scholarship Programme, thank you for making this journey possible. The support enabled me to pursue both my Master's and PhD studies in Hungary. I am also grateful to the Embassy of Hungary in Kuala Lumpur and the Embassy of Malaysia in Budapest for their assistance and support throughout the process.

To my Malaysian and Hungarian family, my constants. My mother, my grandparents, my uncle, my best friends who became sisters, and those who treated me as their own. Mrs Nurul Atiqah Binti Abdul Rahman (Mother), Hj Abdul Rahman Bin Abdul (Grandfather), Hjh Norkiah Binti Ariffin (Grandmother), Mr Ezry Bin Abdul Rahman (Uncle), Ms Nurul Atiqah Binti Mohd Yunus (best friend and sister), Mrs Nur Ain Sharmira and family (best friend), Vaskó Maria (Hungarian Mother), Pelády Tamás Szabolcs (Hungarian Brother), Mr Ameerul Aqim Bin Mohd Azmi (best friend in Hungary), Mrs. Vanitha Gopalakrishnan (Embassy of Malaysia), Mrs. Nor Afzan Jemburi (Embassy of Malaysia) and family, Dr Daniela Horváth Selvam and Mr. Bálint Horváth, Dr Wendy Lim Pek Kui (Mentor, Taylor's University) and all members of the Hj Mohamed and Abdul Clan. Your love, prayers, sacrifices, and unwavering belief in me have been the foundation of this journey.

To those in Hungary and Malaysia who stood by me, through struggle, and in the moments when I felt most down and stressed, you are not forgotten. Thank you for being there when everything felt heavy. Your quiet presence made me feel seen, your kindness made me feel cared for, and your strength made me feel loved. You helped carry me through my lowest points, and for that, I will always be deeply grateful.

To all my Malaysian and Hungarian friends, and to everyone in Hungary whether friends, colleagues, educators, or members of the communities that have been part of my journey — thank you for being present through the many seasons of my life. I am especially grateful to the MATE Sensory Lab team, my students, DOSZ Ambassadors System, SEARA, MASIH, MAIH, EUDRES, SH HOOK Mentor, and to all my professors, lecturers and friends at the University of Debrecen, Taylor's University, the Food Institute of Malaysia, as well as my teachers during my school years. Each of you has contributed to who I am today. Thank you for the friendships, guidance, collaboration, inspiration, and education that have shaped not only my academic path, but also the person I have become. Your impact reaches far beyond the classroom or lab, it lives in the way I think, create, care, and carry myself through life.

All of this is not merely a completion, but a commencement.
Thank you very much for being a part of this extraordinary journey.

Segala jasa, sokongan, dan kasih sayang akan sentiasa terpahat dalam ingatan dan tidak akan dilupakan. Terima Kasih!

Finally, To myself

For not giving up even when the path seemed impossible.

For believing in my own story, pushing through the struggles, and proving that resilience leads to greatness.

♫ **"Hold on to the memories, they will hold on to you."** – *New Year's Day*, *Taylor Swift*

Now, see yourself—**You are a PhD Doctor!**