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APPLICATION OF IMMERSIVE METHODS IN CONSUMER SENSORY SCIENCE

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1. BACKGROUND OF THE WORK AND ITS AIMS

The global sensory testing market is rapidly expanding, with a value of approximately USD 26.63 billion in 2024 projected to reach USD 47.5 billion by 2033. This growth underscores an escalating demand for advanced, high-fidelity sensory evaluation methods (Business Research Insight, 2024). Traditional laboratory sensory tests, while controlled, often fail to capture the dynamic, context-rich nature of real-world consumption. To bridge this gap, recent research has turned to immersive technologies. In particular, virtual reality (VR) and Augmented Virtuality (AV) allows creation of realistic simulated environments that mimic actual consumption contexts, thereby enhancing ecological validity without sacrificing experimental control. Eye-tracking (ET) adds an objective layer by capturing real-time visual attention to product features and labels. The dissertation synthesizes these advances: it integrates VR and ET to innovate consumer sensory testing, aiming to improve realism and predictive power of evaluations.

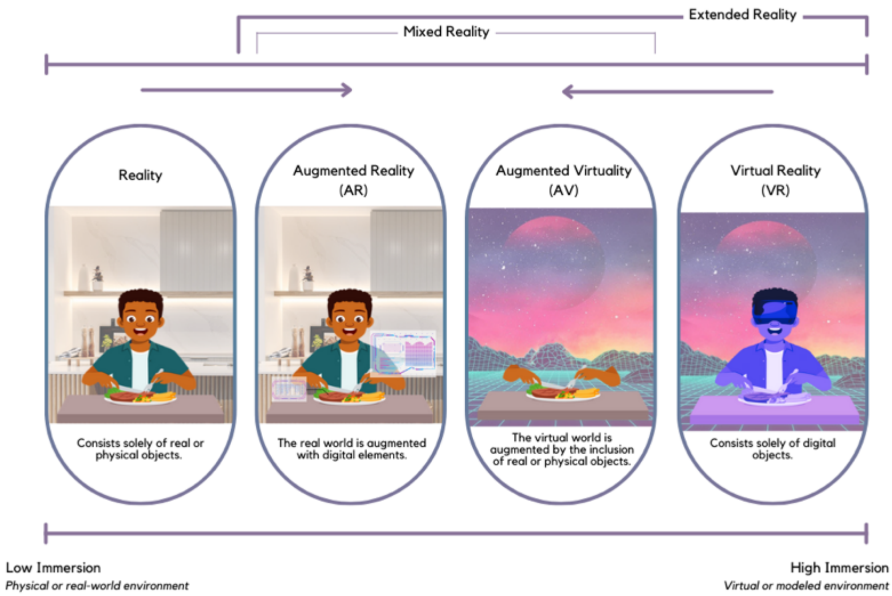


Figure 1: Illustration of Reality-Virtuality Continuum in a concept of sensory and consumer science inspired by Milgram & Kishino (1994).

The Reality–Virtuality continuum (Figure 1) situates sensory evaluation techniques on a spectrum from purely physical reality to fully virtual environments. Milgram and Kishino (1994) introduced this continuum to classify immersive experiences by degree of virtual content (Milgram & Kishino, 1994). In this framework, augmented reality (AR) blends digital enhancements into real settings, whereas augmented virtuality (AV) incorporates real-world elements into a virtual scene. Complete virtual reality (VR) provides purely computer-generated environments. Figure 1 illustrates these points: the far-left ("Reality") involves only physical objects, while the far-right ("VR") is entirely digital; intermediate stages include AR and AV. Defining this continuum guides the methodological choices of the thesis: it clarifies how immersive technologies (VR and AV) relate to traditional sensory testing.

In consumer sensory science, researchers seek to replicate authentic consumption contexts. Conventional sensory tests occur in white booths, lacking ecological validity (Gere et al., 2021). Immersive VR can simulate realistic settings (e.g. cafés, parks) to better match real-world conditions, controlling context while preserving experimental control (E. C. Crofton et al., 2019; Schouteten et al., 2024). VR can thus enhance reproducibility and ecological validity by standardizing stimuli presentation in convincing scenarios. When users interact in VR, their presence – the psychological sensation of "being there" – is critical. Presence is bolstered by real-time interaction and rich sensory immersion (Rubio-Tamayo et al., 2017). High immersion levels (e.g. with head-mounted displays and spatial audio) increase presence. Velichkovsky (2017) notes that stronger presence yields more natural sensory responses in VR. Specialized VR hardware (e.g. HTC Vive Pro Eye, Meta Quest 2) isolates users in digital worlds, enabling total sensory immersion and dynamic interactivity (Oyedokun et al., 2024). For example, calibrated VR booths can present virtual food items with controlled lighting and sound, mimicking a real tasting environment.

Augmented Virtuality (AV) further enhances realism by integrating actual sensory stimuli into virtual scenes (Zulkarnain, Moskowitz, et al., 2024). AV environments maintain precise experimental control while offering participants direct interaction with real food products embedded within digital contexts. This combination significantly improves ecological validity and sensory realism, addressing limitations inherent in purely virtual scenarios and conventional testing methods. AV thus represents an important intermediate step along the Reality–Virtuality continuum (Figure 1), optimizing sensory evaluation by blending the tangible experience of real-world objects with the flexibility and immersion offered by virtual technology.

Eye-tracking (ET) adds an objective layer by measuring gaze and attention in real time. In sensory studies, ET reveals which product features or labels capture consumers' focus (Motoki et al., 2021; Ye et al., 2020). For instance, eye-tracking identifies how packaging design (color, graphics) influences purchase intent by quantifying fixation duration on label elements. Effective packaging design aligns consumer expectations with product attributes, shaping sensory judgments (Álvarez-González et al., 2024). Eye-tracking data (fixation count, saccade patterns) can thus uncover subconscious preferences for label claims or imagery (Ye et al., 2020). In VR, embedded eye-tracking (VR ET) allows studying attention in rich virtual retail settings. In contrast to desktop ET, VR ET must account for head and body movement. Using both VR and ET together enables new insights into the cognitive load and emotional engagement of participants: psychometric instruments like the Simulator Sickness Questionnaire (Kennedy et al., 1993) and PANAS affect scales gauge users' comfort and involvement in VR (Watson et al., 1988).

The primary aim of the dissertation was to apply immersive VR and ET technologies in consumer sensory evaluations to improve ecological validity. In particular, the work sought to:

I. Assessing the acceptability and feasibility of a Virtual Sensory Laboratory for consumer sensory evaluation.
II. Comparing consumer sensory responses obtained in traditional laboratory settings and virtual sensory environments.
III. Evaluating the influence of immersive sensory methods and virtual environmental conditions on consumer perception.
IV. Exploring the role of Eye Tracking (ET) in VR for analysing visual attention and cognitive processing.
V. Investigating the potential of Augmented Virtuality (AV) in combining physical food stimuli with virtual environments for sensory evaluation.

2. MATERIALS AND METHODS

2.1. Research Design and Methodological Approach

This study's conceptual framework integrates immersive technologies, sensory science, and consumer behaviour through key mediators. The independent variables—Immersive Technologies (Virtual Reality and Augmented Virtuality), Eye-Tracking, and Sensory Stimuli—are hypothesised to influence outcomes via two mediating constructs: Cognitive Load and Immersion and Expectation Bias.

These mediators affect the dependent variables, namely Sensory Analysis (e.g., Just-About-Right scale, Check-All-That-Apply method, hedonic ratings) and Consumer Behaviour (e.g., decision-making, purchase intent). The framework highlights how immersive settings and visual attention mechanisms shape sensory perception and behavioural outcomes, enhancing ecological validity and methodological depth in consumer sensory research.

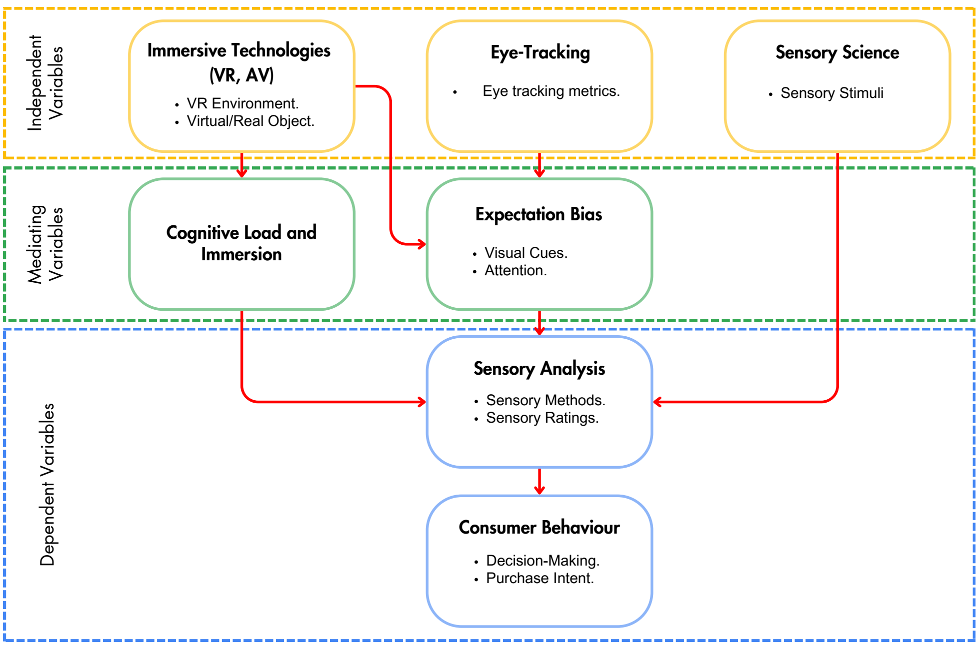


Figure 2: Study Framework and Rationale – The framework illustrates the relationship between independent variables, mediating variables, and dependent variables.

2.2. Experimental Setup, Instruments Used and Participants

Five experiments were conducted using different combinations of head-mounted displays and software platforms, each designed to explore specific aspects of consumer sensory evaluation in immersive environments. The technologies included HTC Vive Pro Eye, Meta Quest 2, and Pico Neo 3 Pro Eye, paired with either Unity or Unreal Engine software, depending on the visual and interactive requirements of the virtual setting. A summary of the hardware, software, environments, products, and sensory methods used in each experiment is presented in Table 1.

Table 1: Study setup, technology and virtual environment for each experiment.

Experiment	Head-mounted Display (HMD)	Software	Virtual Environment	Product	Sensory Methods
1	HTC Vive Pro Eye	Unreal Engine	Virtual Sensory Laboratory	3D bakery items and aroma sticks	Bakery identification and smelling test
2	HTC Vive Pro Eye	Unity	Sensory Booth	Lemonades (10%, 20%, 30% sugar)	9-point hedonic scale
3 (Methods)	Meta Quest 2	Unity	Sensory Booth	Biscuits and orange juice	Just-About-Right scale, Check-All-That-Apply, Preference ranking
3 (Environment)	Meta Quest 2	Unity	VR Park and VR Food Court	Same as above	Same as above
4	Pico Neo 3 Pro Eye + Tobii Pro Nano	Unity + Ocumen + Tobii Pro Lab	Empty Canvas	Food packages with sustainability labels	Eye-tracking, fixation metrics, purchase intent
5	Meta Quest 2	Unity	Café Environment	Red, orange, and yellow cherry tomatoes	Expectation vs. sensory preference testing

In Experiment 1, a virtual sensory laboratory (Figure 3) was developed using Unreal Engine and the HTC Vive Pro Eye. Participants idetify 3D bakery items within individual and guess the aromas using smelling sticks VR booths (Figure 4).

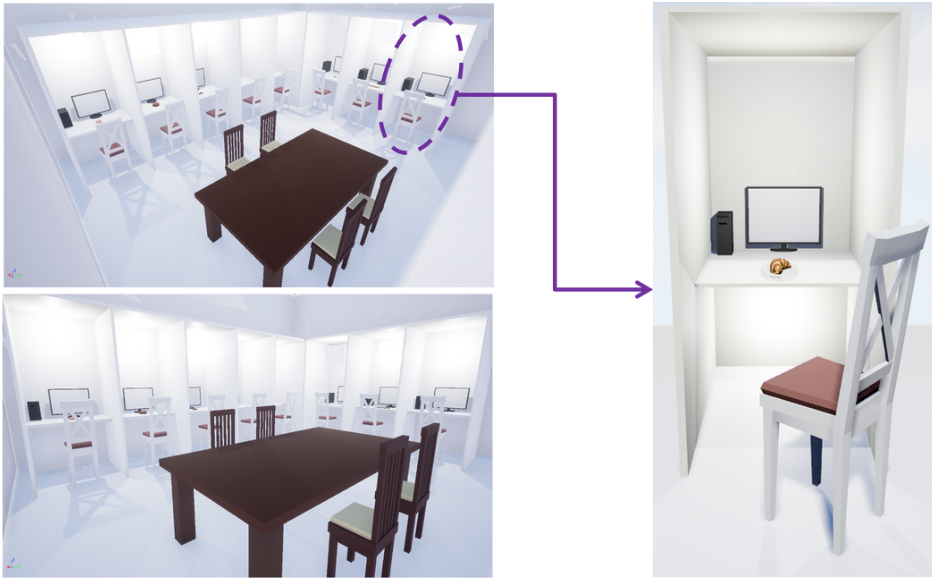
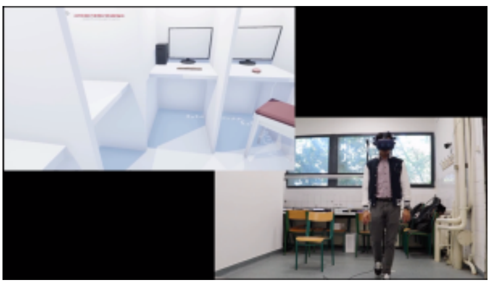


Figure 3: The virtualized sensory lab overview of sensory booths and a discussion table based on ISO 8589:2007 standard using Unreal Engine.



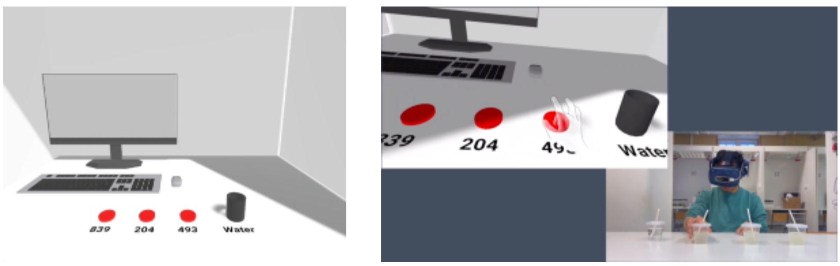
(A)

(B)

Figure 4: (A) Point-of-view (POV) while standing, (B) POV while sitting down.

Experiment 2, built with Unity, recreated a traditional sensory booth in a virtual environment (Figure 5) where participants assessed three lemonade samples with sugar concentrations of 10%, 20%, and 30% using a 9-point hedonic scale (Figure 6).

Figure 5: The virtualized sensory lab overview of sensory booth based on ISO standard using Unity.



(A) (B)

Figure 6: (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.

Experiment 3 (Figure 7) was divided into two parts. The first examined the performance of different sensory evaluation methods—Just-About-Right (JAR) scale, Check-All-That-Apply (CATA), and preference testing—using biscuits and orange juice (Figure 8) inside a VR sensory booth. The second focused on the influence of immersive environmental context, presenting the same products in two distinct virtual settings: a park and a food court. Both parts of Experiment 3 used Meta Quest 2 headsets and were built in Unity.

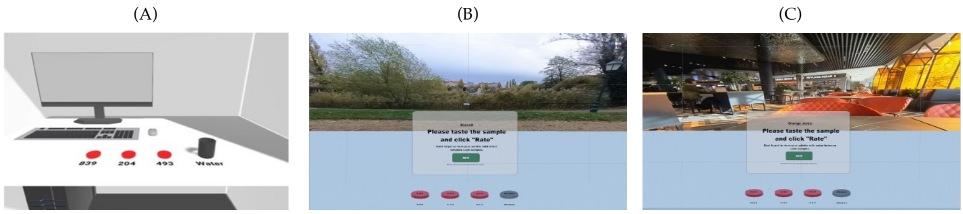


Figure 7: Virtual environments used in the study: (A) Virtual Sensory Booth based on ISO 6658:2017 standards, replicating MATE sensory laboratory; (B) Park, recorded in a Budapest public park; (C) Food Court, captured in a Budapest shopping mall.

Figure 8: 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.

(A) (B)

Figure 9: (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.

Experiment 4 integrated virtual and desktop eye-tracking technologies to study consumer attention to sustainable food labels (Figure 9). Using the Pico Neo 3 Pro Eye and Tobii Pro Nano, participants viewed food packages within an Empty Canvas VR environment, allowing clear observation of visual attention patterns through fixation duration, sequence, and pupil dilation. This experiment was developed using Unity, Ocumen, and Tobii Pro Lab software platforms.

Experiment 5 examined expectation bias by presenting colour images of red, orange, and yellow cherry tomatoes in a virtual café (Figure 10), followed by the tasting of real, desaturated samples while still in VR. This allowed assessment of how visual expectations influenced actual sensory perceptions of taste and preference.

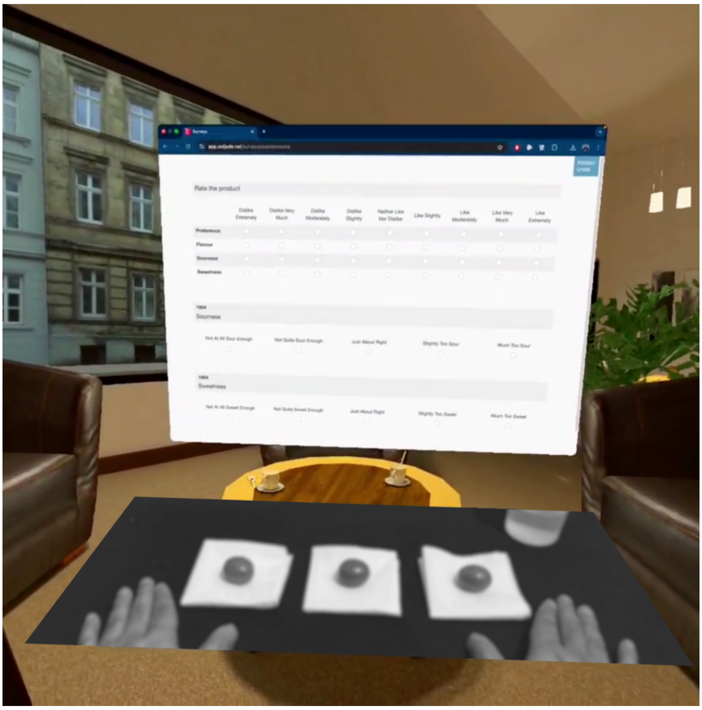


Figure 10: Virtual café environment in Augmented Virtuality (AV), where samples were evaluated in monotone colour while maintaining real-world interaction during sensory testing.

To enhance ecological validity, all virtual environments were carefully calibrated in terms of scale, lighting, and realism. The VR sensory laboratory in Experiment 1 adhered to ISO 6658:2017 standards, and the immersive scenes in Experiment 3 were created using 360° footage of real public locations. All experiments took place in a controlled room measuring 3×4×2.8 metres, with constant ambient conditions. Visual and auditory immersion was maintained using headphones, and sample presentation in VR was synchronised with real food tasting. Trial sequences were counterbalanced to reduce fatigue and order effects, and eye-tracking systems were calibrated using a standard 9-point procedure with practice runs to ensure data reliability.

2.3. Experimental Procedures for Sensory Evaluations

Each experiment followed a crossover or within-subject design. In Experiment 1 (VR Lab Acceptability), participants first explored the virtual sensory lab freely (~3 min) to familiarize, then sat to identify and rate five aroma sticks (lemon, strawberry, cinnamon, vanilla, caramel) while wearing the VR headset. Simulator Sickness Questionnaire (SSQ) was administered before and after, and post-VR surveys (Virtual Reality Sickness Questionnaire, VRSQ; Virtual Reality Neuroscience Questionnaire, VRNQ) assessed comfort and presence.

In Experiment 2 (Traditional vs VR), subjects evaluated three lemonades (10%, 20%, 30% sugar) using a 9-point hedonic scale first in a standard booth and then (or vice versa) in the VR sensory booth. This crossover design balanced order effects. The same panel of attributes (sweetness, sourness, overall liking) was rated under each condition.

Experiment 3 (Sensory Methods and Environments) had two parts. Experiment 3 Methods (M) tested biscuits and juice inside the VR sensory booth using JAR scales, CATA questions, and preference ranking (each product had three variants). Experiment 3 Environment (E) repeated these tests in two immersive scenarios (Park vs Food Court) on separate days (with identical stimuli and protocols). Emotional state (PANAS) and any VR-induced discomfort (SSQ) were recorded after each session.

Experiment 4 (ET on Sustainability Labels) employed a randomized crossover. Participants viewed 20 product packages bearing various sustainability claims (organic, Fair Trade, etc.) on a computer screen (desktop ET) and then in a virtual reality eye tracking (VR ET). Gaze data captured fixation counts and durations on each label. After both sessions, questionnaires measured purchase intent and perceived sustainability. The goal was to see if attention and acceptance differed between real and virtual presentations.

Experiment 5 (Augmented Virtuality Colour Masking) evaluated how visual expectation alters taste. In a virtual café, subjects first saw colour images of red, orange, and yellow tomatoes and rated expected liking, sweetness, sourness. Then the same real tomato samples (now desaturated/grey) were tasted under VR (participants still wearing the HMD). Post-tasting, actual sensory ratings were collected. This design tested whether masking colour in VR could nullify colour-driven expectation bias.

2.4. Data Collection and Statistical Methods

Data collection included raw sensory ratings, questionnaire responses, and eye-tracking metrics (fixation durations and counts on predefined Areas of Interest). Motion and physiological metrics (e.g. simulator sickness questionnaire, SSQ) were also recorded for VR sessions. Statistical analysis was conducted in R, XLSTAT, Tobii Pro Lab, and Ocumen SDK (Python). Sensory scores were analyzed using analysis of variance (ANOVA) with repeated measures, considering factors such as condition (VR vs. control) or environment. Associations between expected and preferred product attributes were examined via Multiple Factor Analysis (MFA). Cluster analysis (hierarchical clustering) was used to identify consumer segments (e.g. those preferring VR vs. booth). Eye-tracking data were aggregated across participants to generate heatmaps and summary metrics (e.g. first fixation, total dwell). The significance threshold was set at $p<0.05$.

2.5. Ethical Considerations

All participants provided informed consent after a full explanation of procedures. Experiments followed ethical guidelines (Declaration of Helsinki) and were approved by the institutional review board. Anonymity and data privacy were maintained throughout. The SSQ and PANAS surveys were used to monitor for adverse effects, and no participants withdrew due to discomfort.

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

3. RESULTS AND DISCUSSION

3.1. Experiment 1: Virtual Sensory Laboratory Acceptability

Experiment 1 validated the basic VR lab experience. The VR sensory booth was modelled according to ISO standards. Participants evaluated 3D virtual bakery items while smelling corresponding fragrance sticks. Results showed high acceptability of the VR environment: in a post-VR questionnaire all mean scores were above 7 on a 1–9 Likert scale. In particular, "overall VR experience" averaged 8.17±1.21, indicating strong user comfort, whereas the most challenging task ("grasping/place virtual items") still averaged a positive 7.10±1.95. These scores (Zulkarnain, Kókai, et al., 2024) demonstrate that participants received the virtual sensory booth favourably.

On the sensory task, vanilla aroma was identified most reliably: 52% of participants detected the vanilla scent correctly, whereas detection rates for lemon, strawberry, cinnamon, and caramel were below 20%. This likely reflects both the familiarity of vanilla in bakery contexts and priming from the visual task. Indeed, prior studies have shown that immersive context and prior exposures can bias odour identification (Brengman et al., 2022; Flavián et al., 2021). In this case, identifying virtual bakery items may have altered expectations for the subsequent smelling task, similar to cross-modal effects noted by Brianza et al. (2022). Nevertheless, the VR test produced clear data: products and odours were evaluated without major technical issues.

Overall, Experiment 1 established a performance baseline in VR. The results suggest that a VR sensory booth can be implemented reliably and is well accepted by consumers (mean acceptability >7/9). Participants quickly adapted to the HMD and controllers, and measured simulator sickness was minimal. In sum, the VR lab provided realistic visual cues for the next experiments, with negligible negative effects on comfort.

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

In Experiment 2, participants evaluated the same lemonade samples in two conditions: a traditional sensory booth and a VR sensory booth. The goal was to compare ratings between the real and virtual settings. No statistically significant differences were found in overall liking or sweetness perception between conditions (F-test, $p>0.05$). In other words, participants' hedonic scores in VR closely matched those from the traditional booth. This replicates findings from Zulkarnain et al. (2024) and validates that VR does not distort basic sensory judgments. It suggests that VR can faithfully reproduce key aspects of product tasting, supporting its use in place of conventional tests.

Subjectively, participants reported similar flavour experiences in both conditions. The Visual Analog Scales for sweetness and tartness overlapped almost completely. These parallel results indicate that the immersive VR environment was capable of evoking authentic sensory perceptions. Principle Component Analysis (PCA) across conditions confirmed high correlation between VR and real ratings. Thus, any novelty or immersion did not systematically bias the evaluations. This consistency supports the claim that VR allows "more authentic sensory experiences" without losing experimental control.

The SSQ data showed only mild discomfort in this study, confirming that participants could comfortably undergo both VR and real testing. In practice, this means researchers and product developers could interchange VR for some routine tests. As indicated by our results, VR offers practical advantages (e.g. easily changing booth settings) while yielding comparable sensory data. This comparability aligns with the literature suggesting that VR can match real-world contexts in consumer testing without compromising accuracy (Zulkarnain, Radványi, et al., 2024).

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

Experiment 3 was divided into two parts. Experiment 3(M) evaluated biscuit and orange juice samples in a VR sensory booth using three methods: Just-About-Right (JAR) scaling, Check-All-That-Apply (CATA), and preference ranking. Part B then repeated these tastings in two immersive contexts (VR Park and VR Food Court) to see how setting influenced perception.

Experiment 3 (M): The JAR and CATA analyses revealed that using multiple sensory methods in VR successfully captured product attributes. In the VR booth, participants applied more negative descriptors to certain samples (e.g. "bitter," "dry") and more positive descriptors to others (e.g. "sweet," "refreshing"), consistent with classical sensory profiles. For example, Juice C (the "thick, bitter" sample) was mainly tagged as "bitter" and "syrupy" in CATA, and its sweetness was rated below optimal in JAR. These method results provided a rich picture of each product's profile. Importantly, all three methods functioned effectively in VR and showed patterns compatible with those from static testing, demonstrating methodological robustness.

Experiment 3 (E): In the VR Park and VR Food Court, environmental context altered participants' impressions. The JAR data (Fig. 52) show that immersive backgrounds tended to enhance positive attributes: for instance, Biscuit A's sweetness and softness ratings improved in the VR Park, while Biscuit C (initially too hard in the booth) was perceived as sweeter and more balanced in the park setting. Similarly, Juice A (initially too bitter) received slightly higher sweetness ratings in the VR Food Court, and Juice C (thick/bitter) was described as more refreshing in the Food Court. These shifts suggest that the pleasant, familiar contexts (particularly the Food Court) focused attention on favourable aspects. CATA results mirrored this trend: juices in the booth were often labelled with negative terms like "bitter" and "astringent," whereas in the Food Court participants chose more positive terms ("sweet," "refreshing"). This indicates that a novel environment can bias evaluations toward positivity – an effect noted in prior studies of VR food context (Torrico et al., 2021).

Participants also completed a post-VR immersion questionnaire. Consistently, the VR Food Court was rated highest for immersion (mean 7.55±2.07), followed by the VR booth (6.88±1.73) and the VR Park (6.73±1.88). In other words, the most elaborate environment (Food Court) elicited the strongest sense of presence. Clustering analysis of preferences revealed two sub-groups: one group showed higher liking and arousal for the immersive park/food court settings, whereas the other preferred the controlled booth. These findings align with Crofton et al. (2021), Schouteten et al. (2024) and Torrico et al. (2021), who likewise reported that more realistic virtual contexts enhance engagement and positive perception. In summary, Experiment 3 demonstrated that VR contexts can influence sensory ratings: immersive scenes tend to amplify desirable attributes, while a plain booth encourages critical evaluation. This has important implications for designing VR studies and interpreting consumer data, and it confirms that context is a key factor in sensory science (Schouteten et al., 2024; Torrico et al., 2021).

3.4. Simulator Sickness Questionnaire (SSQ) in Experiments 1–3

All VR sessions were followed by the standardized Simulator Sickness Questionnaire (SSQ) to assess discomfort. Across Experiments 1–3, SSQ scores remained low, indicating good user tolerance. A principal component analysis of SSQ items revealed that Experiments 1 and 2 produced mostly mild symptoms, whereas Experiment 3 had varied profiles. In detail, Experiment 1 (basic booth and laboratory tasks) was mainly associated with cognitive/visual strain symptoms (difficulty concentrating, eye strain), reflecting the newness of VR locomotion. Experiment 2 (simple tasting in VR) showed slightly more autonomic symptoms (headache, nausea) than Experiment 1, suggesting some vestibular conflict in extended drinking tasks. Experiment 3 split into two parts: the version set in familiar environments (VR Park/Food Court) yielded minimal SSQ scores, whereas the variant with more complex tasks (longer tasting with movement) showed moderate vestibular and ocular strain.

The PCA plots illustrates these patterns: Exp 2 loaded on gastrointestinal symptoms (nausea, stomach awareness), while Exp 3 in immersive mode had higher dizziness scores. Importantly, however, no participant reported severe sickness, and most effects resolved quickly. These results agree with Zulkarnain, Kókai, et al. (2024) and other VR studies showing that simulator sickness in food-tasting VR is generally low (often “somewhat discomfort” at most) when users stand/sit and do not engage in vigorous motion. Proper calibration and breaks (as used here) can minimize sickness. Overall, the SSQ findings support the usability of VR for sensory testing: discomfort was limited and manageable.

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

Experiment 4 examined how eye-tracking (ET) findings compare between a desktop display and an immersive VR headset when evaluating sustainability labels. Participants viewed images of food packages featuring various eco-label logos, under two conditions: (a) a computer screen with a Tobii tracker, and (b) the same task in VR with an integrated Ocumen eye tracker. The fixation heatmaps revealed remarkably similar attention patterns across modes. The "GMO-Free" logo consistently captured the highest fixation intensity in both desktop and VR conditions. In the screen setting, fixations on this label were tightly clustered (bright red), whereas in VR the gaze pattern was more spread but still clearly focused on the label. Other logos (Fair Trade, Rainforest Alliance, UTZ, Euro Leaf) also attracted attention in both modes, but with more diffuse fixations in VR. For example, the Euro Leaf logo produced a sharp fixation cluster on-screen, whereas VR viewing showed a broader distribution around the logo. These results indicate that salient labels draw users' attention regardless of test mode, but that the immersive environment adds visual complexity, leading to a wider scan path.

Total fixation counts and dwell times were consistent between conditions: most participants eventually fixated every logo, and the top three ranked labels (by engagement) were the same. Importantly, no significant differences in purchase intent or label recall were found between screen and VR tests. In other words, the VR-ET setup yielded equivalent measures of consumer attention to sustainability claims. This confirms VR-based ET as a valid method: immersive shopping simulations can replicate the insights from traditional eye-tracking, with the added benefit of realistic context. Notably, this was the first application of VR eye-tracking to sustainable labelling (Zulkarnain & Gere, 2025). In summary, Experiment 4 showed that while VR induces a more distributed gaze, the overall patterns of visual engagement with product labels are comparable to conventional ET.

3.6. Experiment 5: Introductory Use of AV for Colour Masking in Sensory Evaluation

The final experiments explored Augmented Virtuality (AV), in which real food items are integrated into a virtual scene to mask visual cues. This approach aims to isolate non-visual sensory attributes. Experiment 5 applied AV to colour: participants saw real cherry tomatoes in grayscale while in a VR café. First, they gave expected liking, sweetness, sourness and flavour intensity based on coloured images of red, orange and yellow tomatoes. Then they tasted the preferred tomatoes (in random order) but all samples were viewed in grayscale through VR.

The results (analysed by MFA) showed that expected and preferred sensory ratings followed consistent patterns. For red tomatoes, both expected and preferred sweetness were closely aligned and were the main drivers of liking. Expected flavour and preferred flavour were also correlated. Sourness had a smaller role (its expected vs preferred values were close, indicating a secondary influence). For orange tomatoes, expected and preferred sweetness remained key, but flavour perceptions were more variable: expected flavour did not map as closely to preferred flavour, and expected vs preferred sourness showed greater scatter. This resulted in more dispersion in liking and preference scores – indeed, ANOVA showed consumers were less consistent in their preferences for orange tomatoes. In contrast, for yellow tomatoes the expected and preferred ratings were tightly clustered on all attributes. Sweetness again dominated but expected flavour, preferred flavour, and even sourness all aligned closely between expectation and preferred, reflecting the lowest variance among the three types.

These findings demonstrate that AV successfully decoupled visual expectation from taste: by presenting samples in grayscale, participants' colour-based biases were minimized, revealing the true influence of sweetness and flavour. The patterns also suggest that colour does impact expectations differently by type: for example, red and yellow varieties had more predictable effects on liking than orange. This proof-of-concept supports Zulkarnain, Moskowitz, et al. (2024) thesis that AV can control visual cues in sensory tests. In practical terms, AV could be used to mask branding or color when assessing intrinsic taste attributes.

4. CONCLUSION AND RECOMMENDATIONS

This thesis validated Virtual Reality (VR), Augmented Virtuality (AV), and Eye Tracking (ET) as effective methodologies in consumer sensory evaluation. The experiments demonstrated that VR offers sensory ratings consistent with traditional methods, significantly enhancing ecological validity and capturing contextual influences. Eye Tracking provided objective measures of consumer visual attention, deepening insights into subconscious behaviours and decision-making processes.

Augmented Virtuality successfully integrated real sensory stimuli within immersive contexts, effectively reducing visual expectation biases and improving sensory realism. Collectively, these immersive methods enhanced realism, methodological robustness, and predictive accuracy in sensory testing.

Key recommendations include broadening the adoption of VR and AV in routine sensory evaluations to ensure ecological validity, systematically integrating Eye Tracking for richer behavioural insights, and expanding AV methods to address sensory biases comprehensively.
Based on these findings, several practical recommendations are offered:

1. **Expand the application of VR and AV** in industry-standard sensory testing to ensure ecological validity and realistic product evaluation, especially for context-sensitive products.
2. **Routinely integrate Eye Tracking** within sensory studies to obtain objective and nuanced insights into consumer behaviour, visual biases, and subconscious preferences.
3. **Implement AV methodologies** to systematically investigate and control sensory biases arising from visual attributes, thereby enhancing consumer perception accuracy.

Future research should further refine the integration of immersive technologies, expanding their application to diverse food categories and consumer segments, and exploring long-term consumer adaptation to virtual sensory environments.

5. 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)**

6. LIST OF PUBLICATION IN THE FIELD OF STUDY

I. 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**

II. 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.

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