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Research article

Assessment of a virtual sensory laboratory for consumer sensory evaluations

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ABSTRACT

As technology advances in the field of food sciences, the sensory experience of food consumption remains complex and influenced by various factors. Traditional consumer testing, often conducted in isolated booth environments, presents challenges in terms of construct validity and user engagement for perception formation. The growing accessibility and sophistication of virtual reality (VR) technology offer a promising avenue for research. This study focuses on the assessment of a virtual sensory laboratory, seamlessly integrating traditional sensory practices into the virtual realm to explore disparities in consumer responses, especially in sensory analysis. The virtual laboratory, designed for compatibility with VR gear, closely resembles a sensory booth. The virtual environment enables the researchers to change the visual clues of the products being tested as well as the surroundings (e.g., colors, furniture, or even the environment). Additionally, the level of immersion can be enhanced by playing any type of music, if needed. One crucial question is to assess the opinions of the participants, if they feel comfortable in the created environment. Specific participant numbers are omitted, and the study engages participants. The success of this initiative could signify a substantial advance in analysis and cost savings, adding a layer of significance to the study's potential impact on optimizing research practices. The study lays the groundwork for optimal VR practices and anticipates further exploration with immersive elements to deepen our understanding of how virtual reality influences consumer behaviour in food selection compared to traditional sensory methods.

1. Introduction

Consuming food and beverages influence various sensory attributes based on contextual factors and acceptability. Sensory perception categorizes into intrinsic and extrinsic factors. Intrinsic factors encompass aroma, colour, taste, texture, and flavour, while extrinsic factors focus on packaging, labelling, price, and country of origin. These elements collectively contribute to the overall sensory perception of food and beverage qualities, considering preparation, cooking techniques, and consumption environments [1]. Eating environments, influenced by factors like eating site, ambient temperature, humidity, sound, and lighting, impact consumer preferences [2].

To introduce new products, food and beverage manufacturers invest significantly in consumer sensory research. However, despite this investment, only a small number of these products are commercially successful due to the inability of current methodologies to

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predict food-related behaviours and purchase decisions [3]. Traditional sensory testing panels often place consumers in isolated tasting booths in a controlled sensory laboratory setting, attempting to eliminate external influences. However, some argue that this environment does not accurately represent real-world circumstances in which consumers taste products [4].

Firstly, starting with the reality-virtuality continuum, proposed by Milgram and Kishino [5], serves as a foundational framework for understanding the spectrum between the real environment and virtual environments. Extended in 2019 to incorporate pure mixed reality, this continuum differentiates between the real environment, augmented reality, pure mixed reality, augmented virtuality, and the virtual environment [6]. This framework aids in categorizing different immersive environments, particularly within augmented reality analysis, focusing on the spectrum between the real environment and pure mixed reality [7].

Virtual reality (VR) refers to computer-generated simulations that users can interact with in a seemingly real way, creating environments that appear and feel similar to real-world objects and events [8]. VR technology provides users with a sense of presence, allowing interaction with the generated environment [9]. Distinguishing VR from other immersive technologies, augmented reality (AR) combines real-world elements with virtual ones in real time [10]. Mixed reality (MR) encompasses both AR and augmented virtuality, providing a comprehensive interaction between real and virtual components [11].

VR immerses users in a computer-generated virtual environment, offering a fully interactive and 360-degree immersive experience. In contrast, non-immersive VR systems lack this immersive quality, providing content without the full interactive experience [12]. VR differs from AR, which overlays normally invisible information onto real objects, and MR, which combines real and virtual components to create a partially built environment [11].

VR is making waves in the food industry, changing how it engages with consumers and even influencing the way consumers taste food through multi-sensory experiences [13]. The increasing popularity of immersive technologies, particularly VR, is noted for its potential in classrooms as a futuristic learning tool [14]. Utilizing VR in sensory tests can enhance consumer engagement and ecological validity by simulating real contextual environments [15]. While VR is viewed as a controlled experimental condition in lab settings, further research is needed to evaluate its performance in realistic environments [16].

1.1. *Virtual reality (VR) and sensory analysis*

In recent years, Virtual Reality (VR) studies have gained popularity in academic and business research, but there is a noticeable gap in the exploration of food sensory and food science studies. Some articles, including those by Gere et al. [17], Wang et al. [18], and Xu et al. [19], specifically reviewed food sciences and consumer behaviours. These authors concluded that future studies should focus on investigating the impact of providing more sensory modalities, employing multisensory stimuli, and using integrated measurement methods for more seamless experiences in food and consumer behaviour studies.

These studies can be categorized into two parts: sensory analysis of food and its psychological or physiological responses, as well as studies on purchasing products or behaviour [20–30]. Researchers found that creating new 3D food models and modifying their features, varying in complexity and difficulty, is essential for research involving food in VR. This process tends to be more complicated than context-based studies. Additionally, the virtualization of food using techniques like photogrammetry may be necessary to create more realistic food stimuli. The second part of studies focuses on enabling participants to engage with products, make choices, or buy them in real-time, requiring a high level of interactivity [14,31–37]. However, this involves a high level of specific programming and necessitates high-end VR headsets, especially for environments and products that demand intricate interactions. On the other hand, studies examining individual food preferences and behaviour after exposure to a pre-designed or pre-recorded VR setting with no interaction are relatively simpler.

Despite the potential of VR in sensory analysis, there are constraints and limitations. Issues such as the quality of visual stimuli, the level of immersion, and hand tracking on head-mounted displays (HMDs) have been highlighted in the cited papers. Despite technological advancements, these factors continue to pose challenges, especially in the field of computer science studies.

1.2. *Tools for assessment*

Based on our current knowledge, there are no specific assessment tools designed explicitly for VR and food science studies. Consequently, the tools available are adapted from the field of computer science. These tools encompass the Stimulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ).

The SSQ serves as a common tool for describing and evaluating simulator sickness, with participants rating 16 symptoms on a four-point scale (0–3). A factor analysis has identified three groups of symptoms: oculomotor, dizziness, and nausea [38]. Woo et al. [39] utilized the SSQ to determine recovery time from VR sickness. The VRSQ assesses various aspects of VR system performance, including headgear discomfort, system calibration, image lag, image blurriness, auditory surround, control of movement, ease of pointing and selection, and awareness of body location [40]. On the other hand, VRNQ combines elements of both the SSQ and VRSQ in a more concise form, evaluating the quality of VR software concerning user experience, game mechanics, in-game assistance, and virtual reality-induced symptoms and effects (VRISE) [41]. Researchers employing VRNQ include Brugada-Ramentol et al. [42], Tawil et al. [43], and Yeo et al. [44].

The use of these tools aids in understanding and developing guidelines, particularly for VR studies in sensory and consumer behaviour. Additionally, these tools contribute to the assessment of various factors. The current study has two primary aims: first, to evaluate the acceptability of a virtual sensory laboratory for the sensory evaluation of food, intended for future studies. This involves the initial step of creating VR neutral booths. The second aim is to assess the development of a sensory laboratory for consumer sensory evaluation, utilizing diverse assessment tools and providing recommendations for the duration of VR research in food science sessions.

2. Materials and methods

2.1. Participants

The participants in this study were students from the Hungarian University of Agriculture and Life Sciences (MATE). The sample comprised sixty (60) participants, with a distribution of 70 % females and 30 % males. This participant size aligns with the recommendations for acceptability tests, as indicated by Gacula and Rutenbeck [45], suggesting that the estimated number of participants should fall between 40 and 100 individuals. Notably, none of the participants had prior experience with or exposure to virtual reality (VR).

Before commencing the experiment, the study's aim was thoroughly explained to the participants to ensure a clear understanding of the methodology and the use of the VR headset. Participants provided informed consent through the statement "I am aware that my responses are confidential, and I agree to participate in this experiment," requiring an affirmative response for participation. Importantly, participants retained the right to withdraw from the experiment at any point, and they were not obligated to provide a reason if they felt uncomfortable. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the MATE internal ethics committee (approval number: MATE-BC/947-1/2023).

2.2. Place and measurement setup

The VR experiment took place in an empty and quiet classroom at the Hungarian University of Agriculture and Life Sciences (MATE), as illustrated in Fig. 1. The virtual sensory laboratory was created using Unreal Engine version 4.27.2 (Epic Games, Cary, North Carolina, US). The experiment utilized head-mounted displays (HMD), specifically the HTC VIVE Pro Eye from HTC Corporation in Xindian, New Taipei, Taiwan. To facilitate the smooth running of the experiment and guide participants through the process, two student assistants were recruited to assist with system setup and provide instructions to the participants.

2.3. Procedure

Fig. 2 outlines the procedural flow of the experiment. Participants were invited and provided their consent to partake in the study, receiving a comprehensive briefing on the study's expectations and objectives. The sequence of activities commenced with participants standing in a fixed position (starting point) and donning the head-mounted displays (HMDs) with the assistance of the laboratory assistant. Once the HMDs were in place, the VR environment initiated, revealing five (5) virtual sensory booths featuring different bakery items (pretzel, bread, croissant, baguette, and donut).

For their first task, participants spent at least three (3) minutes walking and identifying each product in the sensory booths. Following this, participants sat down (simultaneously in the virtual laboratory) on a chair, with the support of the student assistant to prevent any potential falls. Positioned at a virtual big table with an empty plate in front of them, participants proceeded to orally answer the Stimulator Sickness Questionnaire (SSQ) with the assistance of the laboratory assistant.

After completing the questionnaire, the second task involved participants smelling and identifying five scented sticks (Lemon, Strawberry, Cinnamon, Vanilla, and Caramel). The entire experiment was expected to take participants between seven (7) and ten (10) minutes. Following task two, participants' HMDs were removed, and they were asked to complete the Virtual Reality System Questionnaire (VRSQ) and Virtual Reality Neuroscience Questionnaire (VRNQ). As an incentive for their participation, each participant

Fig. 1. The place and the setup of the head-mounted displays.

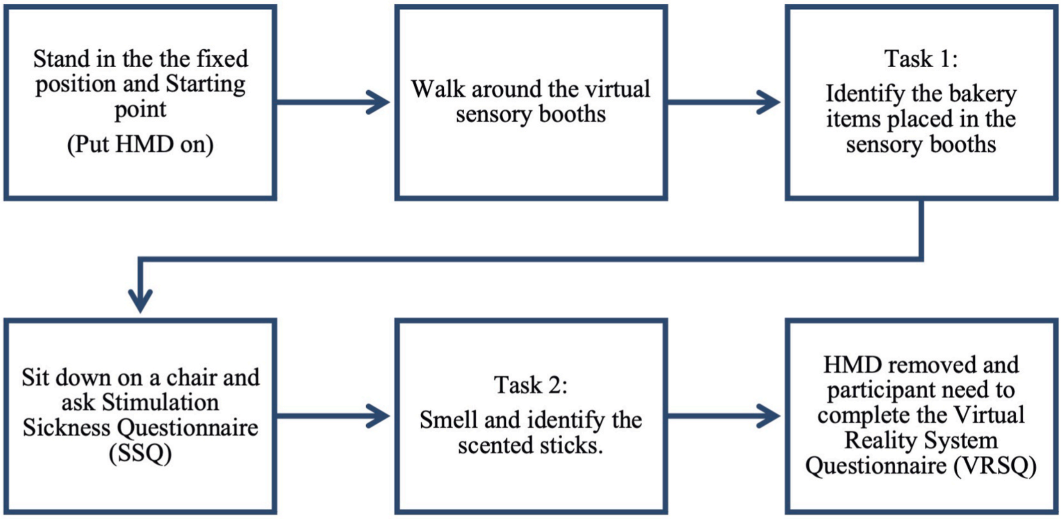

Fig. 2. Flow of the experiment and tasks for participants.

received a candy.

2.3.1. Task 1: Recognition of bakery items

In the virtual reality (VR) setting, five sensory booths were presented, each featuring a distinct bakery item (pretzel, bread, croissant, baguette, and donut). During the initial task, participants are required to spend a minimum of three (3) minutes navigating the VR environment to identify and familiarize themselves with each product within the sensory booths. Following the completion of this task, participants should promptly take a seat (simultaneously in the virtual laboratory), with assistance from a student assistant to prevent any potential falls.

2.3.2. Task 2: smelling test

Task two commences with a virtual table and an empty plate positioned in front of the participant. In this phase, participants are tasked with smelling and identifying five scented sticks (Lemon, Strawberry, Cinnamon, Vanilla, and Caramel). The student assistant will sequentially present the test tubes containing the concentrated scented sticks, recording the participant's responses provided verbally. In sensory analysis, identifying the scent correctly without the aid of word is one of the difficult sensory analysis methods. Each scent was also examined in detail to determine which ones were similar to or closely related to the one that was chosen. These are crucial responses that may reveal participants' preferences for particular scent attributes. The total time allocated for the participant to complete this olfactory test ranges from five (5) to seven (7) minutes.

Table 1
The questions in Virtual Reality System Questionnaire (VRSQ).

Virtual Reality 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 360° 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

2.4. Assessment tools

All the questionnaires were provided in both English and Hungarian to ensure the questions were easily understood by all participants. The SSQ followed the methodology outlined by Kennedy et al. [38], including 16 symptoms categorized into nausea, oculomotor, and disorientation.

The VRSQ, adapted from Kent L. Norman [40], focused on aspects related to the VR system. It consisted of 20 questions (refer to Table 1), 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.

In VRNQ, adapted from Kourtesis et al. [41], there were five primary categories: user experience, game mechanics, in-game assistance, and virtual reality-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 supplementary materials (S1).

2.4.1. Determining the Stimulator Sickness Questionnaire (SSQ) score

The SSQ was determined using the formula developed by Kennedy et al. [38], wherein each category (nausea, oculomotor, and disorientation) has its specific SSQ symptoms that contribute to the severity score as shown in Table 2.

The SSQ score is considered negligible when it is lower than 5. A minimal score falls between 5 and 10, signifying a minor level of discomfort. A score of 10–15 is considered significant, indicating a notable level of discomfort. A score of 15–20 is regarded as concerning. Lastly, a score exceeding 20 is classified as severe.

2.4.2. Determination of the Virtual Reality System Questionnaire (VRSQ) and Virtual Reality Neuroscience Questionnaire (VRNQ) score

VRSQ and VRNQ scores were determined using Cronbach's alpha, α (or coefficient alpha), developed by Lee Cronbach [46]. Cronbach's alpha is employed to assess the reliability or internal consistency of a set of scale or test items [47]. The questionnaire score is based on a 7-point hedonic scale, where 1 represents the lowest and 7 represents the highest rating.

2.5. Data analysis

The analysis utilized data from three questionnaires: SSQ, VRSQ, and VRNQ. All data analysis was conducted using R-project version R-4.2.2 with RStudio 4.2.3 [48]. The results were statistically interpreted and presented in tabular and graphical formats, with mean or average values, minimum and maximum values, standard deviation, and coefficient of variance determined using the stats and ggplot2 libraries [49,50].

For the evaluation of VRSQ and VRNQ, Cronbach's Alpha from the psych library [51] was employed, and an acceptable score needed to be above 0.7 ($\alpha \geq 0.7$). Additionally, the Silhouette index and cluster analysis were performed using k-means clustering and Ward's agglomeration method from the cluster library [52] and based on Gere A [53]. script. Differences between clusters were analysed using Student's t-test from the stats library [49], ($\alpha = 0.05$).

Table 2
Determinations of the Stimulator Sickness Questionnaire (SSQ) symptoms belonging to categories (nausea, oculomotor, and disorientation).

Stimulator Sickness Questionnaire (SSQ) Symptoms	Categories		
	Nausea	Nausea	Nausea
General discomfort Fatigue	1	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.

3. Result and discussion

3.1. Software development

The software was developed using Unreal Engine version 4.27.2 (Epic Games, Cary, North Carolina, US) (Fig. 3). The created virtual sensory lab is freely available and downloadable from the following link: https://drive.google.com/drive/folders/1FmkE2vz1mnT4cN3an5VaE1kyoxZsPbjM?usp=share_link. According to the ISO 6658:2017 standard [54], a well-established sensory laboratory must utilize white (or light grey) colors, have good natural lighting (6500 K), and the air must be well-ventilated. In the virtual sensory laboratory, there are 8 booths, each equipped with a computer, monitor, chair, and food product (Figs. 4 and 5), with each booth measuring 1 m × 1 m × 2.5 m. In the center of the booths, there is a discussion table with four chairs. An example video of the procedure can be found in S2.

The development of the virtual sensory laboratory is based on the "EPI Cube," as described by Flavián et al. [6], and shown in Fig. 6(a). Specifically, it aligns with the planes numbered 4, 8, 2, and 6. In Fig. 6(b), this distinct virtual sensory lab can be categorized as a virtual try-on. As this virtual sensory lab is preliminary, it is crucial for consumers to try it out for their acceptance, especially considering the potential advancement toward more interactive devices that can lead to the classification of VR HMD with haptic devices on Fig. 6(b). As emphasized by Orús C. et al. [55], the use of VR experiences with real content and devices integrated with the human body (HMD) appears to yield better results. The combination of VR (real content with HMD) is more effective than other conditions (including AR) in generating successful experiences.

3.2. Questionnaires

3.2.1. Stimulator Sickness Questionnaire (SSQ)

Based on Table 3, 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.

Oculomotor cybersickness includes symptoms such as blurred vision, difficulty focusing, and eyestrain. The oculomotor system

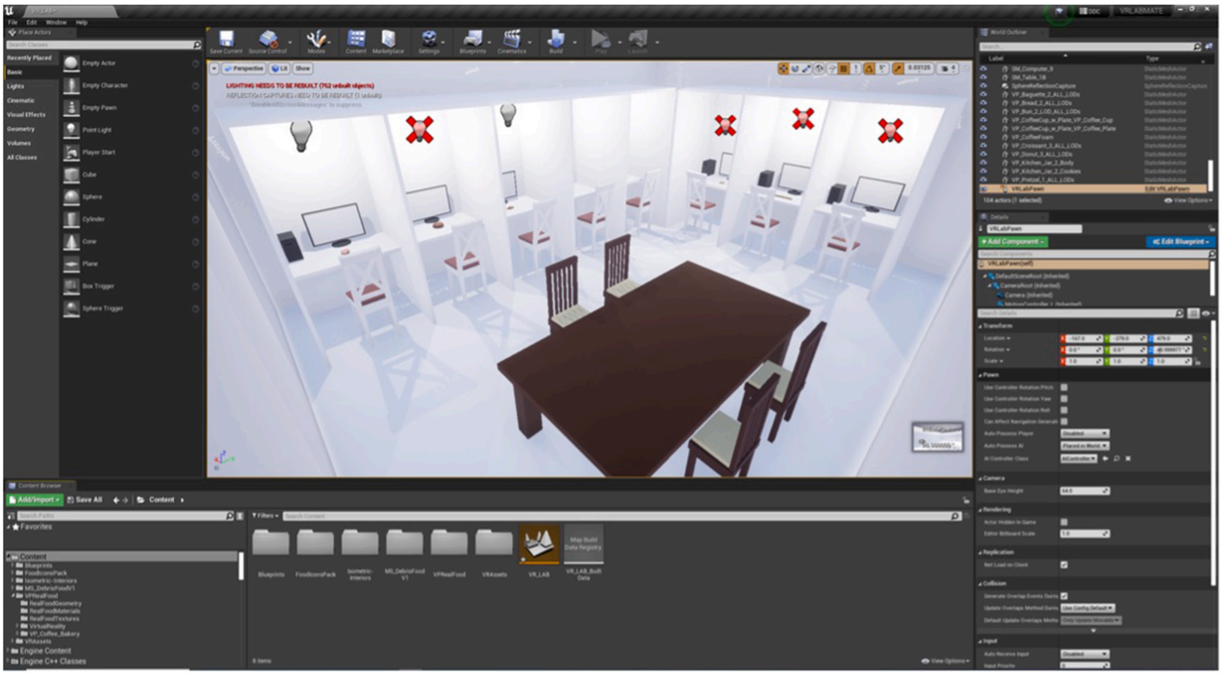

Fig. 3. The Unreal Engine Software for the development of the virtual sensory laboratory.

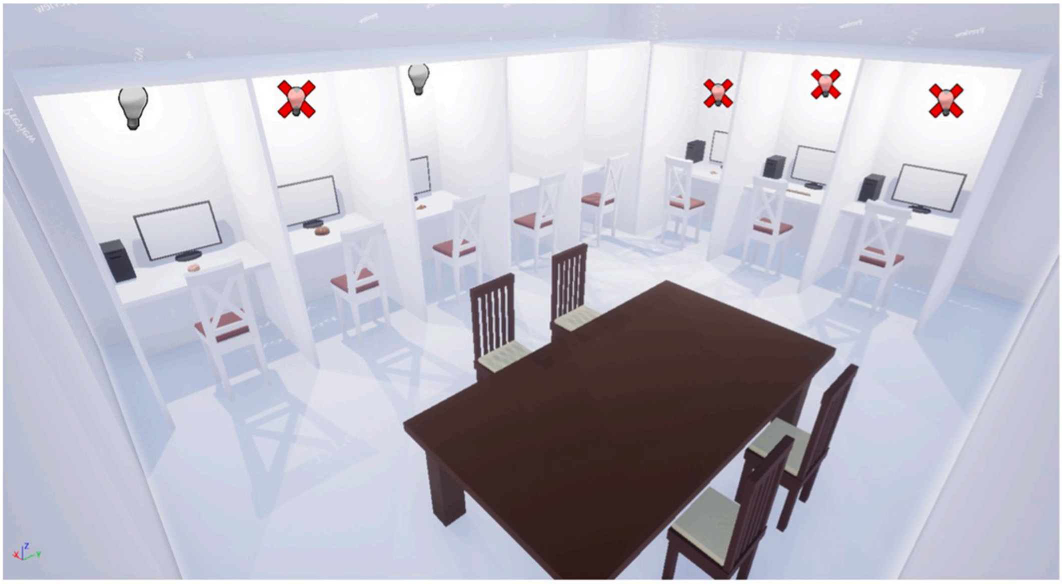

Fig. 4. The virtual environment of the sensory laboratory. Some lightbulbs are crossed due to some interference with other lighting.

Fig. 5. The view of a single virtual sensory booth and the point of view of the participants when viewing inside the sensory booth.

involves the third cranial nerve (CN III), which controls eye muscle movement, pupil constriction, eye focusing, and upper eyelid position [56]. It's noteworthy that experienced VR users tend to have significantly fewer overall cybersickness symptoms and oculomotor symptoms than inexperienced users [57].

3.2.2. Virtual Reality System Questionnaire (VRSQ)

As shown in Table 4, all 20 questions had a Cronbach's α greater than 0.7. This indicates that there are minimal issues with the software and the environment. The overall VR experience was excellent, and participants accepted the virtual sensory laboratory, providing promising prospects for future studies.

The average scores of the VRSQ are illustrated in Fig. 5. 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

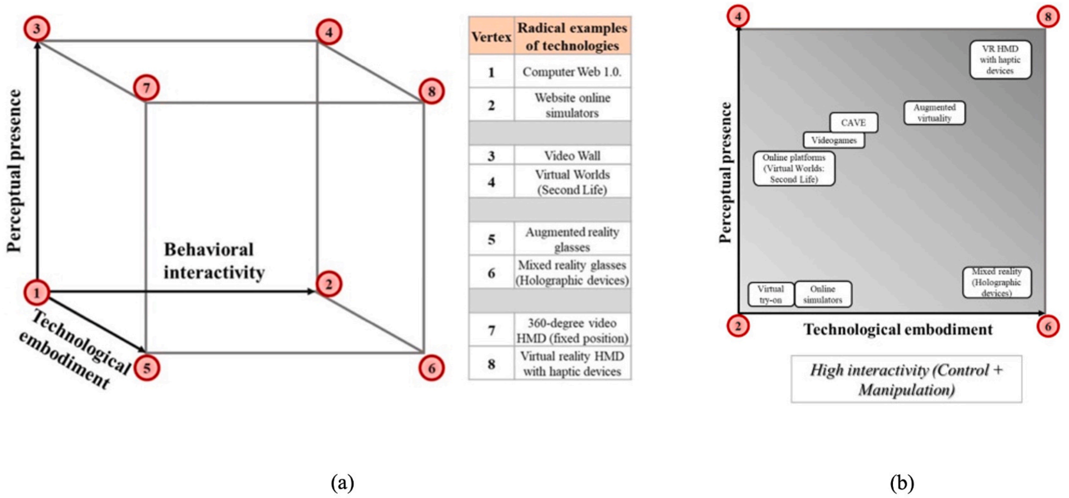

Fig. 6. (a) The "EPI Cube" and the corresponding extreme examples of technologies; (b) Technologies positioned on the faces of the "EPI Cube" (Extreme levels of behavioral interactivity). The figures were adapted from Flavián et al. [6].

Table 3
Stimulator Sickness Questionnaire (SSQ) Score based on the symptoms.

Stimulator 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

Table 4
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 360° 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

blurred areas, especially when participants are looking at the product on the table. This issue may be related to oculomotor symptoms reported in the SSQ score, indicating challenges in coordinating eye movement during motion.

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 [57]. Given that participants experienced sickness symptoms in the SSQ after 10 min in the VR environment, the time it takes for users to adapt to the environment can be an influential factor in cybersickness [58].

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 Tables 3 and is an important factor in determining overall acceptability in a virtual sensory laboratory.

3.2.3. Virtual Reality Neuroscience Questionnaire (VRNQ)

In validating both VRSQ and SSQ, VRNQ emerges as the most fitting questionnaire, offering comprehensive coverage of all relevant aspects. As indicated in Table 5, 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 5 shown 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 in Table 4, 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 min for testing, as an extended duration may impact results.

3.2.4. Combination of Stimulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ) for each participant

The combination of SSQ, VRSQ, and VRNQ was conducted using cluster analysis. Since all the questionnaires had scores on different scales, normalization was necessary. The number of clusters was determined using the Silhouette index [59] shown in Fig. 7. As the highest number in the silhouettes determines the number of clusters (Fig. 8), the number of clusters should be two (2). Silhouette indices show an interesting pattern. While the highest value is seen for two clusters, the index drops and slightly increases between cluster numbers 3 and 6. After 6 clusters, the index drastically drops, which is expected as the number of participants to be clustered is 60.

A k-means clustering by Ward's method had been used to cluster the data of SSQ, VRSQ, and VRNQ questionnaires. Following the results of Fig. 8, there are two clear clusters. The first cluster consists of 36 participants, and the second cluster consists of 24 participants.

From the two clusters, mean and standard deviations had been calculated to determine the difference between the two clusters (Table 6).

According to Table 6, the differences between Cluster 1 and Cluster 2 were examined, and distinctions for each item were identified through a heteroscedastic *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.

3.3. Smelling task

Fig. 9 here.

Fig. 9 illustrates the outcomes of the smelling test, a component that can be conveniently executed in VR to explore its applicability in sensory science analysis. The scents of lemon, strawberry, cinnamon, and vanilla from the smelling sticks were aligned with the ISO 5496:2006 standard [60]. According to the results, a majority of participants struggled to identify the smells of lemon, strawberry,

Table 5
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

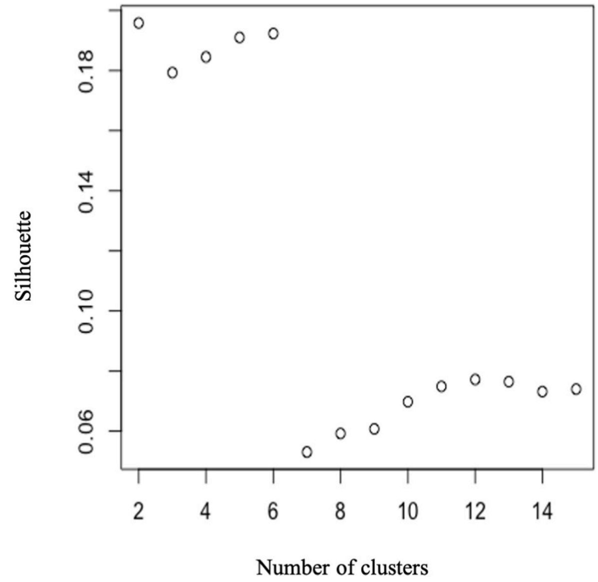

Fig. 7. Silhouettes indices of the different cluster numbers.

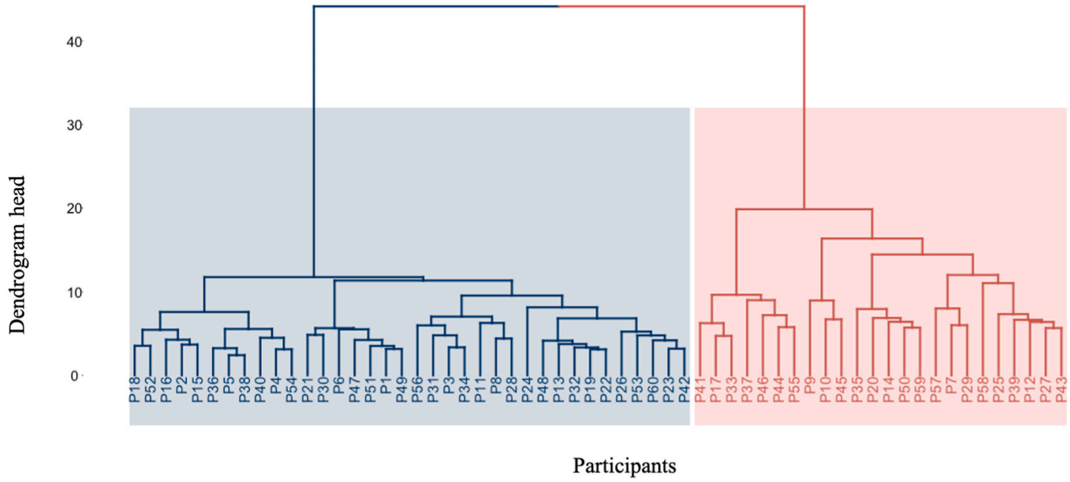

Fig. 8. Dendrogram obtained after running k-means clustering with Ward's method on the data of the Stimulator Sickness Questionnaire (SSQ), Virtual Reality System Questionnaire (VRSQ), and Virtual Reality Neuroscience Questionnaire (VRNQ) questionnaires. Blue background shows cluster 1, while the red background shows the members of cluster 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cinnamon, and caramel. However, more than half of the participants successfully recognized the aroma of vanilla.

This finding aligns with studies by Brengman et al. [61] and Flavián et al. [62] that delved 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.

3.4. 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

Table 6
Score or mean on each cluster with Stimulator 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 360° 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

Stimulator 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 and 10 is minimal, between 10 and 15 is significant, between 15 and 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.

"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.

3.5. Implications

Considering the Stimulator 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 valuable implications 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 [68].

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 [63]. The virtual sensory laboratory stands out as a pioneering tool, allowing researchers to delve 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 [64]. 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 [65]. 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 [66].

The virtual sensory laboratory plays a dual role in education, serving as both a research tool and a training platform [15]. 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

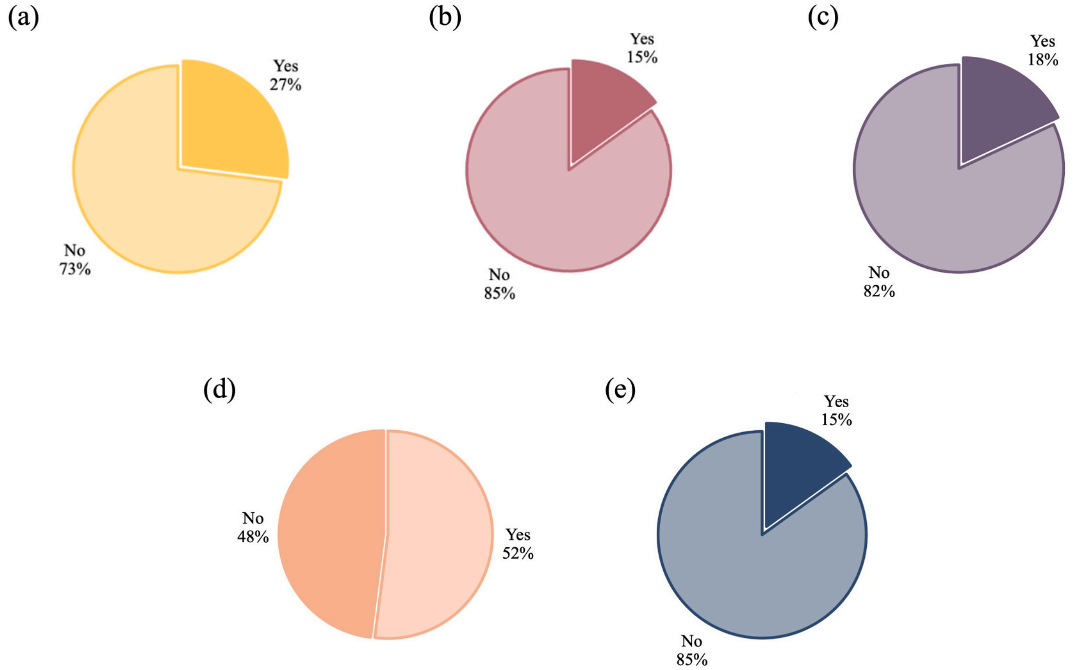

Fig. 9. The results of the participants that can identify the sensory sticks with five aromas: (a) Lemon, (b) Strawberry, (c) Cinnamon, (d) Vanilla, and (e) Caramel.

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 [67]. 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 behavior in a virtual environment provides a unique perspective on product preferences, purchasing decisions, and overall consumer experiences [65]. 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 [17,68]. 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.

This study emphasizes that the virtual sensory laboratory was well-received by the participants and provides evidence of its suitability for consumer sensory testing. It is recommended to use the Virtual Reality Neuroscience Questionnaire (VRNQ) questionnaire.

4. Conclusion

This virtual sensory laboratory serves as a valuable resource for sensory scientists and consumers interested in exploring the emerging opportunities provided by VR. The application of the virtual laboratory in the food industry, especially in sensory science, demonstrates its potential. The development of the virtual sensory environment underscores the limited scientific data on utilizing VR to uncover the relationships influencing food choices, indicating a research gap in this VR realm. Further research and software development are necessary, particularly to enhance the quality and smoothness of the virtual sensory laboratory.

Distinguishing itself from conventional sensory booths, the virtual sensory laboratory replicates an environment, and the extent to which VR can be employed in food consumer behavior research should be determined based on evidence from studies utilizing VR. Despite some feedback addressing issues such as image quality and the smoothness of the virtual environment, this study provides evidence supporting the methodology's validity and highlights the significant benefits of using VR in sensory science studies. This approach can aid in understanding consumer behavior and optimizing product design. Overall, considering the SSQ, VRSQ, and VRNQ scores, the virtual sensory laboratory proves suitable for consumer sensory evaluation.

Given that these were preliminary studies in the domain of VR and sensory analysis, future investigations should focus on comparing traditional and virtual sensory testing. Exploring potential differences and consumer perceptions in such a comparative study would be intriguing. Additionally, incorporating physical interaction in the virtual sensory laboratory merits attention. The scarcity of research on integrating hand gestures to mimic reality without using hand controllers accompanying headsets presents an avenue for further exploration. Future studies should delve into comparing different sensory tests in varied environments to expand the understanding of the potential applications of VR in sensory analysis.

CRediT authorship contribution statement

Abdul Hannan Bin Zulkarnain: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zoltán Kókai:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Attila Gere:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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