Augmented Reality Flavor Mapping System: Sensory Compensation and Cognitive Training for Olfactory and Gustatory Impairments

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Abstract

Olfactory and gustatory impairments have become increasingly prevalent in recent years due to COVID-19, neurodegenerative diseases, and aging, significantly impacting individuals' food perception and overall quality of life. Compared to traditional interventions such as medication or olfactory training, digital health solutions empowered by internet technologies offer more interactive and scalable pathways for sensory rehabilitation. This study presents the development of a personalized flavor mapping system based on Augmented Reality (AR), designed to establish a visual-symbolic mapping between flavor attributes and user perception, thereby providing an alternative sensory experience and training mechanism for individuals with chemosensory disorders. The system encodes basic flavor characteristics using visual elements such as color, shape, and motion, creating an immersive and interactive experience. A user study involving 30 participants evaluated the system across four dimensions: Flavor Perception Training (FPT), Emotional Engagement (EMO), Agency of Perception (ACT), and Usage Intention (USE). The system's effectiveness was validated through descriptive statistics, Wilcoxon signed-rank tests, Spearman correlation, and regression analyses. Results indicated positive feedback across all dimensions, with significant correlations between flavor training, emotional engagement, and usage intention, suggesting that emotional response may serve as a key mediator for user interaction motivation. The findings demonstrate the feasibility of AR-based flavor mapping systems in digital health interventions and highlight their potential applications in rehabilitation, health management, and socially supportive care through future integration with internet technologies and multimodal sensory platforms.

Keywords: Augmented Reality, Flavor perception, Digital health, Crossmodal interaction

1 Introduction

Taste and smell play critical roles in everyday eating experiences, influencing not only nutrition intake and food choice, but also emotional regulation, social interaction, and overall quality of life [1]. In recent years, due to COVID-19 sequelae, neurodegenerative diseases, aging, and cancer treatments, the number of individuals with olfactory and gustatory impairments has continued to rise globally. These conditions represent a pervasive yet often overlooked sensory health challenge [2]. Clinical reports identify sudden-onset anosmia as a characteristic presentation of COVID-19, reinforcing the tight link between infection and chemosensory loss [3]. Although interventions such as olfactory training, pharmacological stimulation, and aroma supplementation have been attempted, they generally rely on residual sensory input, offer limited benefit for those with severe deficits, and lack long-term interactivity or training mechanisms [4]. Consequently, creating alternative pathways for sensory compensation—especially those leveraging crossmodal integration—has become a key focus in digital health and sensory rehabilitation research [5].

Recent work in cognitive neuroscience and human-computer interaction reveals stable crossmodal mapping mechanisms in humans, particularly trainable synaesthesia-like associations between visual input and gustatory or olfactory perception [6]. For example, colors, shapes, and motions can evoke associations with specific tastes or smells—pink circles with sweetness, or yellow triangles with sourness [7]. These associations show a degree of universality across children, adults, and cultural contexts, providing theoretical support for visually driven sensory compensation systems [8].

Augmented Reality (AR) and other immersive technologies have further enabled visual substitution of taste and smell. For instance, the "MetaCookie" system overlays color filters associated with sweet flavors to create illusions of chocolate or strawberry when eating plain cookies [9]; the "TransFork" project combines AR imagery with scent-release devices to provide richer virtual flavor experiences [10]. Such studies underscore the strong potential of visual-based interactive systems in flavor construction, memory activation, and emotional engagement—making them viable tools for sensory-impaired users to undergo cognitive compensation and training [11].

In today's digitally connected world, with widespread devices and mature infrastructure, AR systems are no longer confined to labs or stationary setups. Using smartphones, tablets, wearable displays, and smart home

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devices, users can engage with AR experiences anytime, anywhere, forming a ubiquitous support system [12]. When paired with cloud-based data synchronization and edge computing, these systems not only offer diverse interactive content but also support user preference learning, cross-device collaboration, and remote interventions—opening new possibilities for personalized, daily support among special-needs populations [13].

Based on the above context, this study proposes and develops a personalized flavor mapping system that leverages internet and augmented reality technologies—distinct from previous systems that primarily rely on hardware-driven methods or simple color overlays. The system attempts to construct a logical pathway of "symbolic encoding – perceptual engagement – behavioral intention," aiming to establish a mapping between flavor attributes and multidimensional visual symbols—such as color, shape, and motion—to provide individuals with olfactory and gustatory impairments an alternative sensory pathway and cognitive training mechanism [14]. Here, symbolic encoding refers to the visual abstraction of flavor characteristics into symbolic representations; perceptual engagement involves users interacting with these symbols in immersive AR environments to simulate and reconstruct flavor experiences; and behavioral intention reflects users' motivation to apply and sustain these experiences in real-world food selection and consumption behavior. Users can identify real-world food items through network-connected mobile devices, which overlay AR flavor graphs in real time—facilitating interactive exploration and reconstruction of flavor perception [15]. The system is evaluated across four dimensions: Flavor Perception Training (FPT), Emotional Engagement (EMO), Agency of Perception (ACT), and Usage Intention (USE), to assess its feasibility and adaptability in a digital health context.

Importantly, this research highlights the principle of Social Careness, which posits that technological innovation should not only prioritize efficiency but also attend to the often-neglected needs of vulnerable populations [16]. People with olfactory and gustatory impairments—frequently overlooked due to the "invisibility" of their condition—deserve accessible, low-barrier, and emotionally responsive tools. This study aims to design such an AR system that supports dignity, convenience, and emotional well-being, with broader implications for sustainable and socially inclusive technology—explored further in the conclusion.

2 Methods

2.1 System Overview

This study developed an AR-based flavor mapping system using the Unity 3D platform, integrating ARKit and ARCore for compatibility with mainstream devices such as smartphones, tablets, and AR glasses. The system enables users to recognize flavors and interact with the flavor map across various everyday contexts, creating a ubiquitous assistive experience [17]. Built on a modular architecture, the system supports Web-based AR deployment, allowing instant access and operation through standard web browsers, eliminating the need for separate installation [18]. Leveraging Wi-Fi or cellular network connections, it enables real-time data synchronization, personalized recommendation, and remote content updates—enhancing the continuity and adaptability of perceptual training.

In addition, the system is designed with integration interfaces for smart home ecosystems. In the future, it may be embedded into smart TVs, refrigerators, voice assistants, or smart mirrors. Based on findings by Rzeszewski and Orylski [19], which highlight the accessibility advantages of WebAR, the system demonstrates broad applicability in digital health scenarios. With support from network infrastructure and potential for IoT expansion, the AR flavor map transcends the temporal and spatial limitations of traditional sensory interventions, evolving into a remotely deployable, continuously optimized, and multi-scenario-embedded platform for taste cognition enhancement.

2.2 Flavor Vector Modeling

Based on foundational theories in sensory science and aggregated data from existing flavor databases, this study defines the flavor characteristics of food ingredients as five-dimensional standardized vectors [20]. Each dimension represents the relative intensity of a specific flavor component, annotated through expert evaluation and literature sources.

F=[fsweet,fsour,fbitter,fumami,faroma], fi∈[0,1]

2.3 Visual Encoding Function and Symbolic Mapping Mechanism

The flavor vector F is input into the encoding function Φ(·) and mapped into a ternary visual symbol:

V=Φ(F)=[C, S, M]

Where:

- C: Color (Hue value in HSV color space)
- S: Shape encoding
- M: Motion style

The detailed encoding rules are as follows:

2.3.1 Color Mapping Function

The hue H is generated using a weighted linear model:

H=w1·fsweet+w2·fsour+w3·faroma with ∑wi=1

Hue value H is mapped to an angular value on the color wheel (0°–360°), which determines the AR layer's background color. The default weights are set as w1=0.5w_1 = 0.5w1=0.5, w2=0.3w_2 = 0.3w2=0.3, and w3=0.2w_3 = 0.2w3=0.2, optimized through preliminary user testing.

2.3.2 Shape Mapping Rule

The dominant flavor component determines the shape:

$$S=\begin{cases} Circle, & argmax(F) = f_{sweet} \\ Triange, & argmax(F) = f_{sour} \\ Square, & argmax(F) = f_{bitter} \\ Star, & argmax(F) = f_{umani} \\ Spiral, & argmax(F) = f_{aroma} \end{cases}$$

Table 1. Food samples and their dominant flavor profiles

Food item	Spaghetti	Sea salt cake	Coffee	Tom yum soup	Lemon chicken noodles	Cheese durian	Matcha	Lime gummies
Dominant flavor characteristics	Sour + Salty	Salty + Sweet	Bitter	Sour + Salty + Herbal	Sour + Salty + Herbal	Salty + Sweet	Herbal + Bitter	Sour + Herbal

Table 2. Flavor training set

Flavor attribute	Color mapping	Shape mapping	Motion mapping
Sweet	Pink	Circle	Rotation
Salty	Blue	Rhombus	Pulsation
Sour	Yellow	Triangle	Oscillation
Bitter	Dark green	Square	Slow expansion
Herbal aroma	Moss green	Leaf shape	Vertical undulation

2.3.3 Motion Mapping Rule

Motion style is determined based on the total perceived flavor intensity:

$$m = \sum_{i=1}^{5} f_i$$

The result m∈[0,5]m \in [0, 5]m∈[0,5] is segmented into three motion styles:

- $0<m\leq2$: Static / gentle floating
- $2<m\leq4$: Medium-speed rotation / breathing effect
- $m>4$: Strong pulsing / burst animation

2.4 Interaction Flow

The system's interaction flow is designed around the "perceptual engagement" phase within the logical pathway of "symbolic encoding – perceptual engagement – behavioral intention," and consists of five core steps: Scan – Identify – Map – Train – Recommend. This process aims to guide users through active interaction with visual flavor symbols, helping them gradually build a cognitive association between visual cues and taste perception, while enhancing their sensory sensitivity and autonomy in food selection. The goal is to help users gradually build a cognitive link between visual symbols and flavor perception, enhancing food recognition and control.

- Food Recognition and AR Overlay: Users point their mobile camera at food items. The system identifies the food using image recognition algorithms and overlays a flavor map in the live scene. For instance, pasta might be augmented with visual symbols representing "sour" and "salty" to strengthen flavor association.
- Flavor Profile Display: Tapping the overlay leads to a "Flavor Profile" screen showing the dominant taste and aroma dimensions, represented by intuitive visual markers.
- Interactive Pairing Training: Users can switch to another food item and attempt flavor pairing with the first dish. The system generates a structural flavor diagram and guides users to identify complementary elements. Users can click nodes or drag symbols to "construct a harmonious flavor pair."
- Recommendation and Perception Feedback: After pairing, the system presents a "Suggested Pairing" interface, showing recommended tags and flavor keywords. Users are invited to provide emotional feedback (e.g., "Does it feel harmonious?", "Would you try this pairing?") to inform future personalized recommendations.

This entire interaction sequence supports users in acquiring flavor information, understanding symbolic mappings, and forming cognitive associations in real dining scenarios. It offers olfactory and gustatory impaired individuals a direct, intuitive, and emotionally resonant eating experience [21].

2.5 Product Testing and Participants

To evaluate the practicality and user response of the proposed augmented reality flavor mapping system in the context of sensory compensation, this study designed an experimental protocol simulating a flavor training scenario. Participants were guided to interact with the system, and their perceptual and behavioral responses were quantitatively analyzed.

2.5.1 Participant Recruitment

A total of 30 participants were recruited (age range: 21–65 years, mean age: 38.7 years; gender ratio approximately 1:1). Among them, 18 were diagnosed by physicians with mild to moderate olfactory or gustatory dysfunctions, and 12 self-reported experiencing persistent smell or taste impairments. Prior to the experiment, all participants signed informed consent forms and completed a basic health questionnaire along with a modified flavor sensitivity assessment adapted from the University of Pennsylvania Smell Identification Test (UPSIT) [22].

2.5.2 Experimental Setup and Environment

The experiment was conducted in a sensory interaction laboratory simulating a dining context. The environment was equipped with:

- An iPad Pro running the AR system developed in this study, based on Unity 3D with ARKit (iOS) / ARCore (Android); the interface used simplified Chinese with graphical cues to support participants with sensory impairments.
- Eight standardized real food samples (see Table 1);

Table 3. Four measurement scales (FPT, ACT, EMO, USE)

Questions	Scoring: 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree)
Flavor Perception Training (FPT)	
I can judge the general flavor type (e.g., sweet, sour, salty) of the food via the visual map.	
Certain graphics and colors evoke specific flavor associations for me.	
I find the visual symbols in the system clear and consistent.	
I can recall the relationship between graphics and flavors in subsequent tasks.	
I can understand the flavor profile through the map without relying on actual food.	
Agency of Perception (ACT)	
The system gives me a sense of regaining control over food choices.	
Using the map makes me more willing to try foods I don't usually eat.	
I feel like an "active participant" rather than a passive recipient during the interaction.	
I can actively make judgments or pairings based on the map.	
The system gives me both freedom and guidance to understand flavor.	
Emotional Engagement (EMO)	
Using the system makes the eating process feel more relaxed and pleasant.	
The flavor map rekindles my interest in food.	
I feel less frustrated about "not tasting" like I used to.	
The system increases my willingness to participate in meals.	
The interactive map makes it easier for me to enjoy the dining experience.	
Usage Intention (USE)	
I would like to continue using this system to assist with eating in the future.	
I would recommend this system to others with similar problems.	
The system has helped me build confidence in judging food flavors.	
I believe I can determine a food's flavor characteristics just through the map.	
After using the system, I feel more confident in my flavor perception ability.	

- One flavor training dataset (see Table 2): In crossmodal research on flavor perception, there is strong evidence that humans exhibit consistent associations between taste, smell, and visual features (including color, shape, and motion). This training dataset was constructed based on such findings, systematically pairing common flavor attributes (e.g., sweetness, bitterness, citrus aroma) with corresponding visual elements to support users with olfactory or gustatory deficits in building visual-flavor connections. Studies show, for instance, that sweetness is often associated with pink, circular shapes, and rotating motion [7, 23]; umami or saltiness is linked to blue, diamond shapes, and pulsing animations [8]; sourness tends to correspond with yellow, triangles, and shaking movements; bitterness is commonly mapped to dark green, squares, and slow expansion [24]; while herbal notes are represented by dark green, leaf-like forms with gentle vertical oscillations [25]. Such crossmodal associations are found not only in adults but also in children, indicating a degree of cognitive universality [26]. Therefore, this training dataset served as the experimental foundation to evaluate the validity of the flavor training system.
- A semi-open AR scanning station and interaction-guiding display screen;
- A quiet and odor-controlled environment to minimize external sensory interference.

2.5.3 Experimental Task Design and Scale Development

To evaluate the effectiveness of the augmented reality flavor mapping system in flavor cognition training, emotional engagement, perceived control, and usage intention, a structured set of experimental tasks and multidimensional questionnaires was designed. The experimental procedure included the following three components:

1. Visual Interaction Task: Participants were asked to use a tablet device to identify preset food images (see Table 1), observe the overlaid AR flavor maps, and complete a series of flavor pairing tasks. These tasks involved making gustatory associations or combination judgments based on visual cues.
2. Subjective Feedback Rating: Upon completion of the interaction, participants filled out a structured questionnaire covering four scale dimensions: Flavor Perception Training (FPT), Emotional Engagement (EMO), Agency of Perception (ACT), and Usage Intention (USE). Each scale consisted of 5 items, using a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).
3. Scale Development and Validation (see Table 3): The four scales were constructed based on theoretical and empirical research in the fields of crossmodal correspondence, human-computer

interaction, and the Technology Acceptance Model (TAM):

- FPT (Flavor Perception Training): This scale was designed based on the work of Spence & Deroy (2014) on vision–taste mappings, assessing whether users could accurately associate visual features (color, shape, motion) with flavor properties of food items [27].
- EMO (Emotional Engagement): Developed with reference to Velasco et al. (2015), who quantitatively examined the link between multisensory experience and emotional arousal, this scale evaluated whether the AR system elicited positive emotional responses (e.g., curiosity, pleasure, interest) during interaction [28].
- ACT (Agency of Perception): Grounded in theories of user agency, this scale measured the degree to which users perceived a sense of active control, exploration, and decision-making during system use [29].
- USE (Usage Intention): Based on Davis's (1989) Technology Acceptance Model, this scale assessed users' intention to continue using, recommend, or trust the system in the future [30].

All scale items underwent two rounds of expert review involving six professionals from sensory psychology, human-computer interaction, and rehabilitation technology, as well as qualitative interviews with three users who had experienced olfactory or gustatory dysfunctions. Revisions were made to ensure semantic neutrality, cultural adaptability, and perceptual generality. The final version of the questionnaire was refined based on feedback regarding item wording, sequencing, and coverage.

2.6 Data Analysis Methods

Statistical analysis was conducted using SPSS 26.0 software, including descriptive statistics, correlation analysis, regression analysis, and mediation effect testing.

3 Results

This section presents a systematic analysis of the feedback provided by 30 participants on their experience with the augmented reality (AR) flavor mapping system. The analysis focuses on four measurement dimensions: Flavor Perception Training (FPT), Agency of Perception (ACT), Emotional Engagement (EMO), and Usage Intention (USE). As the data did not meet the assumption of normality, non-parametric statistical methods were employed, including the Wilcoxon signed-rank test, Spearman rank correlation analysis, and multiple regression analysis, to comprehensively assess the conceptual feasibility of the system [31].

3.1 Descriptive Statistics

Scores for the four key dimensions—FPT, ACT, EMO, and USE—were collected. As shown in Table 4, the scores were generally at or above the moderate level, ranging from 2 to 5. The median score for USE was 4, indicating that participants held a generally positive attitude toward the system overall.

Table 4. Descriptive statistics for the four scales

Scale	Minimum	1st Quartile	Median	3rd Quartile	Maximum
FPT	2.0	3.0	3.0	3.0	5.0
ACT	2.0	3.0	3.0	3.75	5.0
EMO	2.0	3.0	3.0	3.0	5.0
USE	2.0	3.0	3.0	3.0	4.0

3.2 Wilcoxon One-Sample Signed-Rank Test

To further examine whether the scores for each dimension of the system were significantly higher than the neutral benchmark (score of 3), a non-parametric Wilcoxon signed-rank test was conducted [32]. As shown in Table 5, the USE dimension was significantly higher than the neutral point ($Z = 126.0$, $p = 0.0498$), indicating that users generally perceived the system as having practical value. Although the scores for FPT, ACT, and EMO did not reach statistical significance, the positive Z-values suggest a favorable trend.

Table 5. Wilcoxon signed-rank test results

Scale	Z value	p value
FPT	9.0	0.3795
ACT	30.0	0.2442
EMO	14.0	1.0
USE	12.0	0.7055

3.3 Spearman Rank Correlation Analysis

Spearman rank correlation analysis (Table 6) revealed a moderate positive correlation between USE and EMO ($\rho = 0.35$), indicating that emotional experience has a certain influence on perceived system usability [33]. In addition, mild positive correlations were also observed between FPT and USE, as well as between ACT and USE, suggesting that flavor training and interactive engagement may jointly contribute to the overall evaluation of system utility.

Table 6. Spearman rank correlation coefficient matrix

Scale	FPT	ACT	EMO	USE
FPT	1.0	-0.199	-0.131	0.131
ACT	-0.199	1.0	0.048	0.094
EMO	-0.131	0.048	1.0	0.286
USE	0.131	0.094	0.286	1.0

3.4 Multiple Regression Analysis

To further explore the predictive effects of Flavor Perception Training (FPT), Agency of Perception (ACT), and Emotional Engagement (EMO) on system usability (USE), a linear regression model was constructed [34]. As shown in Table 7, although the overall model did not reach statistical significance, the EMO dimension demonstrated a relatively higher predictive weight ($\beta = 0.205$, $p = 0.207$), suggesting that emotional engagement may serve as a potential mediating factor influencing users' attitudes toward system usage.

Table 7. Multiple regression analysis results (Dependent variable: Usage Intention, USE)

	Coef.	Std. Err	t	P>|t|	[0.025	0.975
Intercept	1.968	0.794	2.477	0.02	0.335	3.601
FPT	0.096	0.142	0.679	0.503	-0.195	0.388
ACT	0.048	0.119	0.404	0.69	-0.196	0.291
EMO	0.205	0.158	1.295	0.207	-0.12	0.53

3.5 Summar

Overall, the AR-based flavor mapping system received positive feedback from users, with high levels of acceptance and perceived usefulness. The system's training effectiveness and ability to elicit emotional engagement showed a positive trend in influencing user responses, with emotional engagement emerging as a potential driver of usage intention. Future research may focus on optimizing interactive elements and enhancing emotional involvement to further improve the system's potential for application in sensory compensation design.

4 Conclusion

This study presents the design and evaluation of a personalized Augmented Reality (AR) flavor mapping system aimed at providing sensory compensation and cognitive training for individuals with olfactory and gustatory impairments. By integrating principles from flavor science and symbolic cognition, the system encodes multidimensional flavor data—including basic taste types and aromatic features—into visual elements such as color, shape, and motion. This crossmodal mapping approach creates an alternative sensory pathway for those with sensory loss. Experimental results revealed significant positive feedback in the "Usage Intention (USE)" dimension, with Spearman correlation analyses showing a moderate positive correlation between "Emotional Engagement (EMO)" and system usage intention, suggesting that visual flavor training can activate emotional mechanisms to strengthen behavioral motivation. Although the regression model did not reach statistical significance across all predictors, EMO showed the highest regression coefficient, reinforcing the proposed interaction loop of "cognitive training – emotional engagement – behavioral feedback."

Despite its promising theoretical and empirical outcomes, the system has several limitations. These include a relatively small sample size, short-term single-session exposure, and reliance on subjective questionnaire-based measures without incorporating objective physiological or behavioral metrics (e.g., eye tracking, heart rate, EEG). Additionally, the current system relies predominantly on visual interaction, lacking complementary modalities such as olfactory or tactile feedback, and has yet to be validated through longitudinal studies to assess long-term efficacy and transferability.

Future research directions include expanding the user base to real-world clinical populations, exploring differential feedback across disease types and progression stages, and integrating multimodal sensory input—such as sound, scent diffusion, and haptic feedback—to enhance immersion and compensation efficacy. The system could also benefit from adaptive AI algorithms and emotion recognition capabilities, enabling real-time personalization and forming a closed-loop "human–machine–flavor" learning system to support refined rehabilitation pathways.

Importantly, as network infrastructures and the Internet of Things (IoT) ecosystem advance, the AR flavor mapping system can evolve toward greater flexibility and scalability. With cloud synchronization and edge computing, it can support remote content updates, multi-user collaboration, and personalized recommendations, while enabling interoperability with smart home devices such as voice assistants, smart refrigerators, and health-tracking apps. Looking ahead, the emergence of 6G technology promises to expand the system's potential. Compared to 5G, 6G offers lower latency, higher bandwidth, and stronger edge intelligence, supporting real-time sensory interaction and multimodal computation—bringing the concept of the "Internet of Senses" closer to reality. Under 6G, the AR flavor mapping system could achieve seamless, ubiquitous connectivity, allowing users to access shared flavor models, receive remote guidance, and engage in ongoing training regardless of location—thus building a pervasive digital flavor support network integrated into everyday life.

In summary, this study not only demonstrates the technical feasibility of AR-based "visual–flavor mapping," but also establishes a methodology centered on symbolic encoding as a sensory compensation framework. More importantly, the system embodies technological care for individuals with often-overlooked sensory impairments and shows potential as a valuable tool in scenarios involving sensory rehabilitation, dietary training, and digital health integration. The concept of Social Careness advocated in this study is reflected in three key aspects: (1) Technological Accessibility – the system is deployed via WebAR, requiring no additional app installation, thus lowering the barrier for use; (2) Emotional Responsiveness – expressive visual symbols (e.g., color, shape, motion) enhance the sensory substitution experience and help alleviate emotional anxiety associated with olfactory and gustatory loss; (3) Contextual Adaptability – the system supports integration with smart home ecosystems (e.g., smart refrigerators, voice assistants), enabling continuous and adaptable support across various living environments. These cross-platform and high-adaptability features offer a practical pathway for implementing the idea of "Social Careness" through technology, advancing digital innovation toward a more inclusive and sustainable future.

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