Author/s:
Gonzalez Viejo, C;Mayorga-Martínez, AA;Harris, N;Villarreal-Lara, R;Fuentes, S

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Spaceward senses: examining retronasal aroma and mouthfeel perception in simulated space-microgravity environments

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Claudia Gonzalez Viejo[1,2] ✉, Arturo A. Mayorga-Martínez[3], Natalie Harris[1], Raul Villarreal-Lara[3,4] & Sigfredo Fuentes[1,2,3]

It has been reported that conditions in space missions alter the taste and perception of orthonasal aroma by astronauts. However, there is limited knowledge of the effects of space environments associated with the sensory perception of mouthfeel and retronasal aromas. This research aimed to study alterations in retronasal aromas and mouthfeel under an immersive space-simulated environment with a simulated microgravity seating position. A total of 12 well-trained panelists evaluated the intensity of different samples for retronasal aromas and mouthfeel using a neutral environment and a space-simulated environment. Non-invasive facial biometrics were also analyzed from participants' videos using the BioSensory© application. According to the results, in the space-simulated environment the retronasal aroma intensity was perceived to be significantly lower ($p < 0.05$) than in the neutral environment. The latter was also shown in the multivariate data analysis developed using self-reported and subconscious biometric variables. Regarding mouthfeel perception, the multivariate analysis showed that the intensity of mouthfeel samples was higher in the space-simulated environment. This study contributes to understanding the sensory requirements in space-simulated conditions to optimize and develop specialized food and beverages for long-term space exploration missions.

NASA's Artemis program plans to send crews to settle on the Moon by 2030 and Mars by 2040, laying the foundation for sustainable long-term space exploration[1,2]. Such missions must address critical challenges across diverse fields, including engineering, psychology, law, nutrition and health, and sensory science in space[3,4]. Astronauts in microgravity conditions face issues such as appetite loss and weight reduction due to menu fatigue and altered sensory perception[5–7]. Focusing on fresh, plant-based nutrition, including fruits, vegetables, and leafy greens, could be vital to overcoming these challenges. However, cultivating a wide variety of plants for balanced nutrition is impractical within space conditions. Genetic editing or modification techniques offer a solution by enhancing selected plant candidates with versatile traits to optimize their utility for food, materials, and pharmaceuticals while ensuring complete recyclability[8,9]. Beyond nutrition, it is essential to adapt sensory attributes, such as texture, aroma, and flavor, to suit the altered sensory experiences in space, thereby avoiding the drawbacks of relying solely on vitamin supplements, which degrade over time and can be toxic in high doses, and lack psychological benefits[10]. This holistic approach to plant-based sustenance is crucial for supporting human health and performance on these groundbreaking missions.

The Centre of Excellence in Plants for Space (CoE-P4S)[3,4], funded by the Australian Research Council from 2024 to 2030, addresses critical challenges such as mitigating sensory challenges astronauts face during long-term missions. It has been found that in unique space conditions, astronauts experience changes in their bodily responses, which affect their physical, physiological, sensory, and emotional well-being. Some critical changes reported include reduced heart rate, altered vision, taste, and aroma perception, bone mass loss, decreased appetite, weight loss, and lower nutrient absorption, among others[5,11–16]. Furthermore, due to the limited

[1]Digital Agriculture, Food and Wine Research Group. School of Agriculture, Food and Ecosystem Sciences. Faculty of Science, The University of Melbourne, Parkville, VIC, Australia. [2]Centre of Excellence in Plants for Space. Australian Research Council, The University of Melbourne Node. The University of Adelaide (Lead University), Adelaide, SA, Australia. [3]Tecnologico de Monterrey, School of Engineering and Science, Monterrey, N.L., México. [4]SensoLab Solutions, Monterrey, N.L., México. ✉e-mail: cgonzalez2@unimelb.edu.au

number of food choices that can be taken to Space, they must select specific menus that are repeated in cycles[5,7]. The latter, along with the processing methods required to bring food to space, such as freeze-drying, sterilization, and irradiation[17], may cause further menu fatigue due to the poor visual appeal and reduced palatability of available foods. Among the leading causes of reduced weight and low-calorie consumption of astronauts is the difference in basic senses perception (i.e., basic tastes, aromas, mouthfeel) in microgravity conditions[5,7,11,15].

It has been found that the taste and aroma perception of astronauts is altered in space conditions. Potential causes of taste alterations include microgravity, changes in atmospheric pressure, and motion sickness[15,18,19]. Similarly, a reduction in aroma perception has been attributed to shifts in body fluids in the nasal passages, which reduces the number of aroma molecules that reach the receptors[16,20]. A few studies have reported a reduced orthonasal aroma and an enhanced taste perception from participants under simulated microgravity positions[21–24]. Other authors found that sweet and salty tastes exhibited increased perceived intensity in both the supine position and real space conditions[18,20]. Discrepancies in findings from microgravity simulations on Earth may stem from trials that utilized a limited number of untrained panelists (fewer than six). More recent publications designed experiments with 12–14 well-trained panelists[11] and 51 consumers, enough to meet the conditions of a minimum power analysis of a minimum of 80%[25–27]. The former study focused on identifying specific alterations in orthonasal aroma, taste, and mouthfeel perception using reclining chairs to simulate microgravity, while the latter aimed to evaluate consumers' biometrics and acceptability of pick-and-eat leafy greens, collecting comprehensive digital data on self-reported, physiological, and emotional responses. Both studies used the aforementioned reclining chairs to simulate microgravity following Schroeder and Tuttle[15] findings, which reported similar results using the reclining position to those experienced in space.

The surrounding environment plays a crucial role in sensory analysis. For instance, consumer perceptions can vary significantly between immersive or virtual reality settings and traditional sensory booths; immersive conditions often reveal situational appropriateness[28–30]. Furthermore, physiological responses, such as lower heart rates in microgravity, are comparable to those observed in a supine position on Earth[12].

The most studied sense in Space conditions, especially in relation to seating position and reports from space exploration, has been the olfactory sense via orthonasal intake[11,16,20], followed by the oral sense via the basic tastes and, to a limited extent, the mouthfeel focusing on capsaicin[24,31]. However, it is important to understand the perception of other senses, such as retronasal aromas and mouthfeel. Retronasal aroma perception occurs when volatile compounds released in the mouth during mastication and swallowing travel through the nasopharynx to reach the olfactory epithelium during exhalation[32,33]. On the other hand, mouthfeel refers to the chemesthetic and tactile sensations in the oral cavity, mediated by the trigeminal nerve. Certain compounds in food and beverages interact with the trigeminal nerve, causing irritation and eliciting a sensation[34].

Therefore, this study aimed to investigate unknown alterations in retronasal aromas and mouthfeel under an immersive space-simulated environment with a simulated microgravity seating position, using a well-trained panel of 12 participants whose biometrics were recorded. This study expands the limited research on mouthfeel and retronasal aroma perception in space environments. It represents significant progress in understanding the essentials of sensory prerequisites for developing food and beverages that effectively support long-term space exploration missions. Furthermore, the findings from this study may also contribute to understanding food perception in the supine position for patients in hospitals who are unable to sit down for feeding or who have somehow lost sensorial perception, similar to changes described in space due to disease or trauma.

Results and discussion

Univariate data analysis

For retronasal aromas, the ANOVA did not find significant differences ($p > 0.05$) between environments for biometrics; however, there were significant differences ($p < 0.05$) for the perceived intensity. The latter was found to be significantly lower ($p < 0.05$) in the space-simulated environment compared to the neutral environment (Fig. 1A). These results coincide with those reported for orthonasal aromas in previous studies simulating microgravity seating positions[11,20,22,23] and in real space conditions[35]. On the other hand, mouthfeel did not present significant differences in intensity between the two environments but presented significant differences for some biometrics (Fig. 1B). It was found that panelists tended to tilt their heads back in the simulated microgravity position, which was expected due to the chair reclining. Furthermore, the head rotation was more directed to the left in the simulated space environment. For valence, panelists had a neutral response (mean value: 0.09) in the neutral environment. Besides, there were significantly higher values for smile and relaxed, and lower values for wink in the neutral environment.

Figure 2 shows more detailed results for the perceived intensities of the different samples tested in both environments. Although there were no significant differences ($p > 0.05$) in the interaction of sample × environment, it can be observed that there is a trend for lower intensity in retronasal aromas in the space-simulated environment (Fig. 2A), as suggested by the mean value of all samples (Fig. 1A). It can also be seen that, from the five aromas tested, coffee was the sample with the highest decrease in perceived retronasal aroma in a simulated environment, while coriander presented the lowest change. This larger decrease in coffee may be explained by its complex and highly volatile aromatic profile, which relies strongly on the efficient retronasal pathway of perception. Under simulated microgravity conditions, fluid shifts from the body towards the nasal passages, which can lead to nasal congestion, reduced airflow, and blockage of the aroma receptors, thereby impairing the transport of volatiles to the olfactory epithelium[16,20,36]. Coffee aroma consists of a wide range of compounds with low detection thresholds, including groups of aldehydes, furans, and pyrazines[37,38] and their combination, which may be more sensitive to changes in the nasal physiology. On the other hand, coriander is mainly composed of aromatic compounds such as (E)-2-decenal and linalool[39], which might have less impact under the aforementioned conditions, resulting in smaller perception differences.

For mouthfeel (Fig. 2B), although non-significant differences ($p > 0.05$) for the interaction of sample × environment, there was an observed increase in intensity perception in the space-simulated environment for all samples, except for astringent. Furthermore, the pungent sample presented the highest increase in perceived intensity in the space-simulated environment. It has been reported that astronauts crave pungent (spicy) food to enhance and improve the food palatability in space; therefore, this is a main ingredient in their diet while in the International Space Station (ISS)[40,41]. This is because the pungency from capsaicin provides a strong chemical stimulation to the trigeminal nerves, which is not affected by the fluid shifts explained earlier, compensating for the decrease in aroma perception intensity. The increase in pungency perception in space-simulated conditions may be explained by findings that reported a decrease in salivary secretion and its composition changes in microgravity[42], which might impact mucosal hydration, potentially being the cause of potentiated pungency perception.

Even though there is very limited research on mouthfeel perception in space environments, the finding of no significant differences between the environments for mouthfeel coincides with previous studies using other samples such as dark chocolate (astringent), chili flakes (pungent), refreshing (mint drops), ice (cold), and popping candy (popping)[11], and solutions with pure capsaicin[24].

Multivariate data analysis

Figure 3A shows that the principal component one (PC1) represented 33.02% of data variability for retronasal aromas. In comparison, principal component two (PC2) accounted for 26.14%, adding up to a total of 59.16%, which is close enough to the cutoff point of 60% for a PCA to be significantly represented by the main PCs[43]. According to the factor loadings (FL), PC1 was mainly represented by pitch (FL = 0.30),

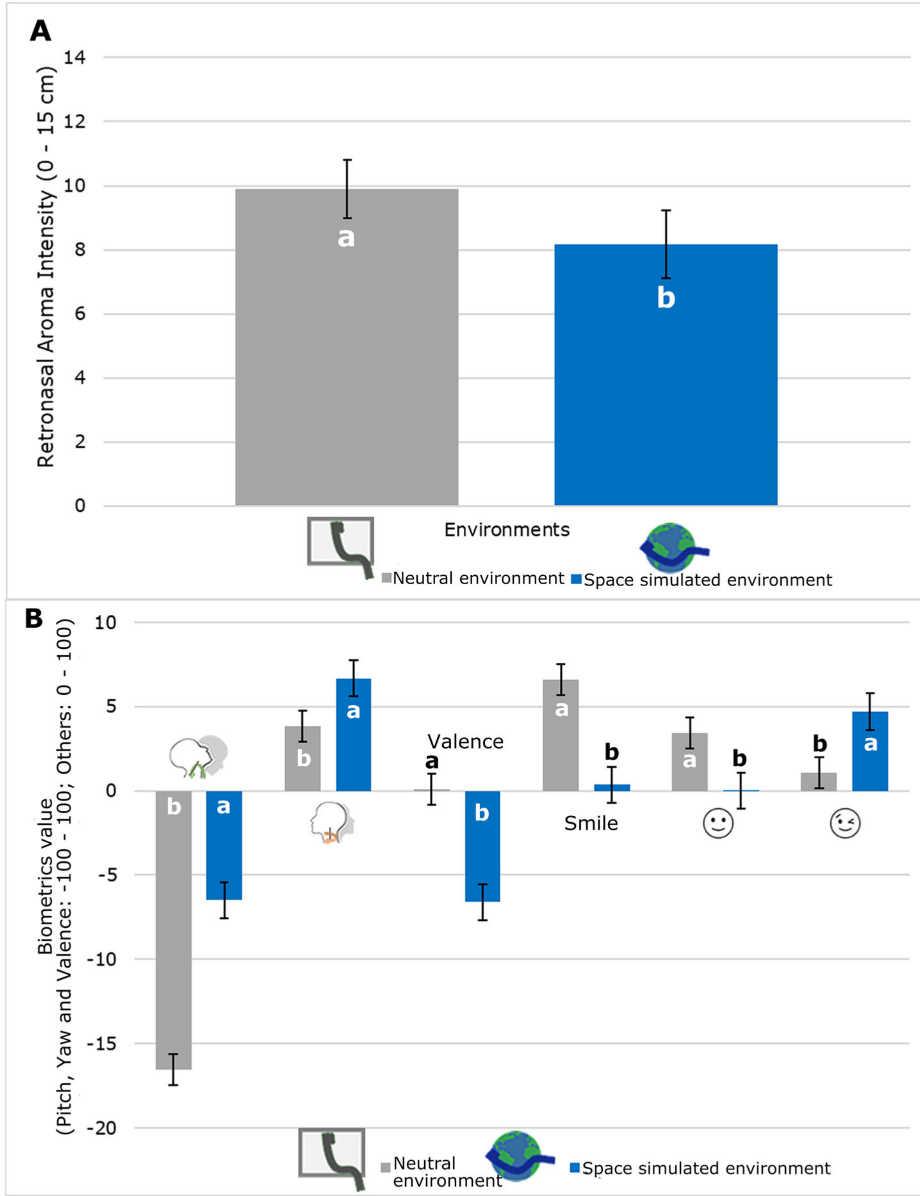


Fig. 1 | Figures representing the mean values and ANOVA results for the two immersive environments. Graphs showing the mean values and error bars (standard error; $n = 12$) in the two different environments for (**A**) the perceived intensity of the retronasal aromas and (**B**) the biometric responses for mouthfeel. Letters a-b represent significant differences according to ANOVA ($p < 0.05$) and the least significant differences (LSD; $\alpha = 0.05$) test. represents the neutral environment with normal seating position, while represents the simulated space environment with microgravity position. Figures , and represent jaw, pitch, and roll head movements, respectively.

disgust, laughing, and smirk (FL = 0.28) on the positive side of the axis, and by valence (FL = −0.26) and roll (FL = −0.23) on the negative side. On the other hand, PC2 was mainly characterized by sadness (FL = 0.35) and smile (FL = 0.30) on the positive side of the axis and by pitch (FL = −0.11) on the opposing side. Samples were found to be mainly separated into two groups according to the environment in which they were tested. Samples in neutral environments were positively related to higher perceived retronasal aroma intensity, heart rate, emotions such as joy, surprise, and sadness, and roll head movements. In contrast, the opposite was found for the samples tested in the simulated space environment. The latter group of samples was positively related to pitch head movement, meaning that participants tilted their head upwards in the simulated microgravity position. This finding may be explained since it has been reported that tilting the head upwards is often a sign of memory recollection[11,44], which may be due to two factors (i) participants recall more their memory since the intensity perception is lower, and (ii) the reclining position, which forces participants to lean backwards. The head movements in food tasting are often related to appealing and rejection of products, which has been reported in other studies. For example, in studies with newborns, it was found that participants turned their head to the left and backwards (retraction) as a rejection response to bitter taste[45,46]. A similar response was reported for humans when tasting beer[47].

A sample that stood out from the others was coriander seeds tested in the space-simulated environment, which was not grouped with any other samples but had positive associations with emotions such as anger, laughing , smirk , and contempt. Results found for retronasal aromas coincide with those reported in previous studies for orthonasal aromas, which showed a decreased perceived intensity in real space conditions while in the ISS, as well as in simulated microgravity seating positions or at bed rest; these changes have been attributed to fluid shifts that occur in the head and that block the nasal passage, affecting the aroma receptors[11,16,20,22,23].

Figure 3B shows that for mouthfeel, the PCA represented a total of 62.55% of data variability (PC1 = 38.31%; PC2 = 24.24%), which is above the cutoff of 60% required for a PCA to be representative[43]. On the positive side of the x-axis, the PC1 was mainly characterized by smile (FL = 0.30) and joy (FL = 0.29), and on the negative side by pitch (FL = −0.28), and yaw and wink (FL = −0.27). Besides, PC2 was mainly represented by smirk (FL = 0.38) and contempt (FL = 0.34) on the positive side of the axis and by scared (FL = −0.22) and attention (FL = −0.19) on the negative side. It was found that samples were mainly separated into two

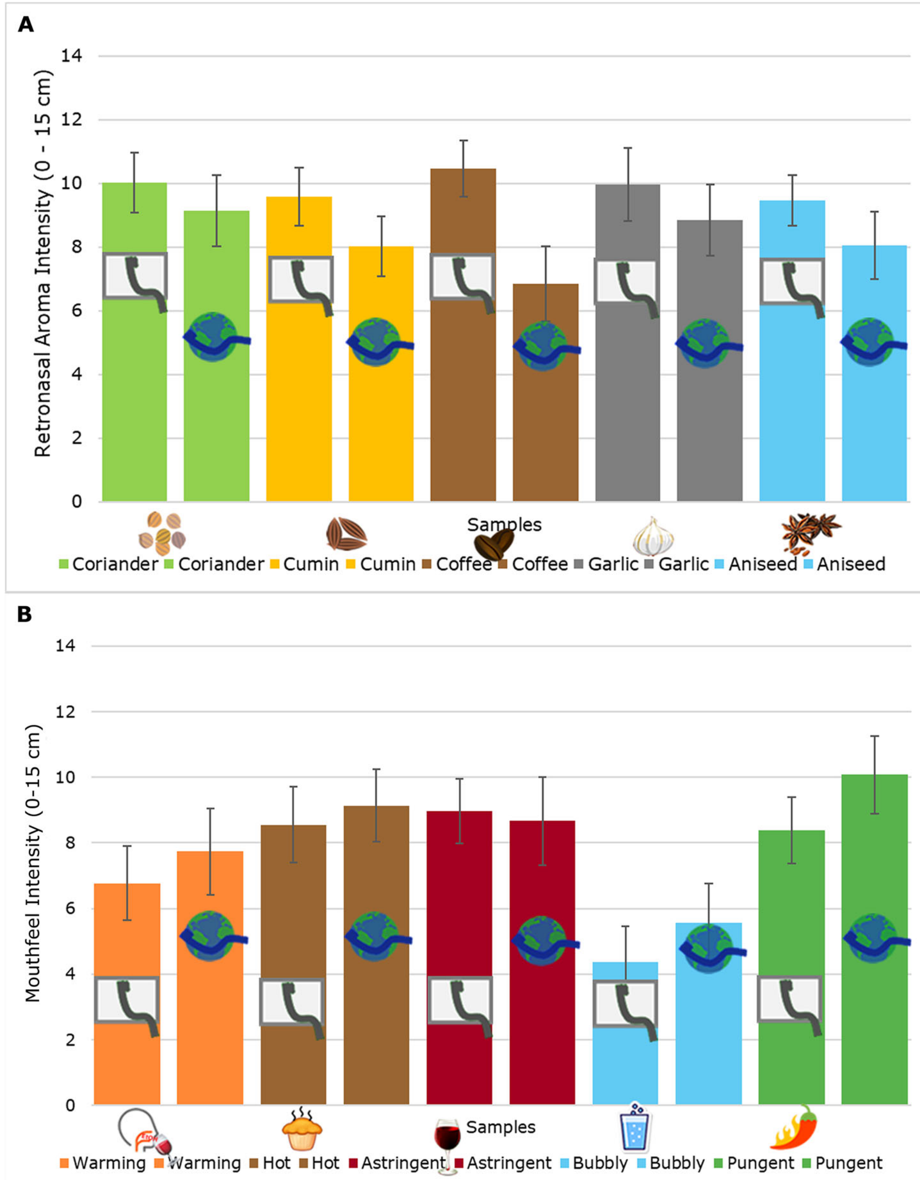


Fig. 2 | Figures representing the mean values and ANOVA results for the self-reported responses. Graphs showing the mean values and error bars (standard error; $n = 12$) for samples tested in the two different environments for (**A**) the perceived intensity of the retronasal aromas and (**B**) the perceived intensity of mouthfeel. represents the neutral environment with normal seating position, while represents the simulated space environment with microgravity position.

groups according to the environments (neutral and space). Samples tested in the space-simulated environment were positively related to higher perceived mouthfeel intensity, engagement, heart rate, pitch, and surprise, while those tested in a neutral environment were positively associated with blood pressure (systolic and diastolic), attention, and valence. A sample that was separated from the rest was the physical hot (muffin) tested in a neutral environment, which was positively related to laughing. smiley, but negatively associated with the same sample tested in the simulated space environment. Pungency was the only sample that had been previously tested by other authors[24] using a solution with capsaicin with participants in bed rest position using hospital beds and found no significant differences between the bed rest and the normal position; however, the authors did not conduct any multivariate analysis, focusing only on univariate statistics, which does not consider the effects of the autonomic nervous system and emotional responses from humans. As can be observed in Fig. 3B, the pungent sample tasted in the simulated space environment was separated (opposite quadrant) from that tasted in the normal environment. In the former environment, it was more related to mouthfeel intensity. Even though both capsaicin (pungent) and ethanol (warming) have an effect on the TRPV1 receptor, their effects differ, as the TRPV1 is activated by capsaicin and temperature, while ethanol modulates it[48]. When consuming both capsaicin and ethanol together, the latter potentiates the pungency of capsaicin[49]. These differences in their mechanisms explain the separation of these samples in the PCA, especially in the space-simulated environment. On the other hand, even though in the univariate analysis (ANOVA), the astringency had lower perceived intensity values in the space-simulated environment, when evaluating multiple variables, including the emotional and physiological responses, this sample was associated with higher intensity within the space environment, with the opposite results for the same sample in the neutral environment. In a previous study[11], researchers used dark chocolate as the astringent sample, and results from multivariate analysis showed that astringency in that sample was not perceived differently. However, in the present study using wine, which creates a more intense astringency, results differed.

The negative association between heart rate and the space-simulated environment when evaluating retronasal aromas coincides with what has been reported to occur in a supine position on Earth and in microgravity in space[12], as well as found in previous studies assessing orthonasal aromas[11]. However, when assessing mouthfeel, the opposite response was found; this may be due to the effects of mouthfeel that irritate the trigeminal nerves, which may elicit different responses from the autonomic nervous system (ANS).

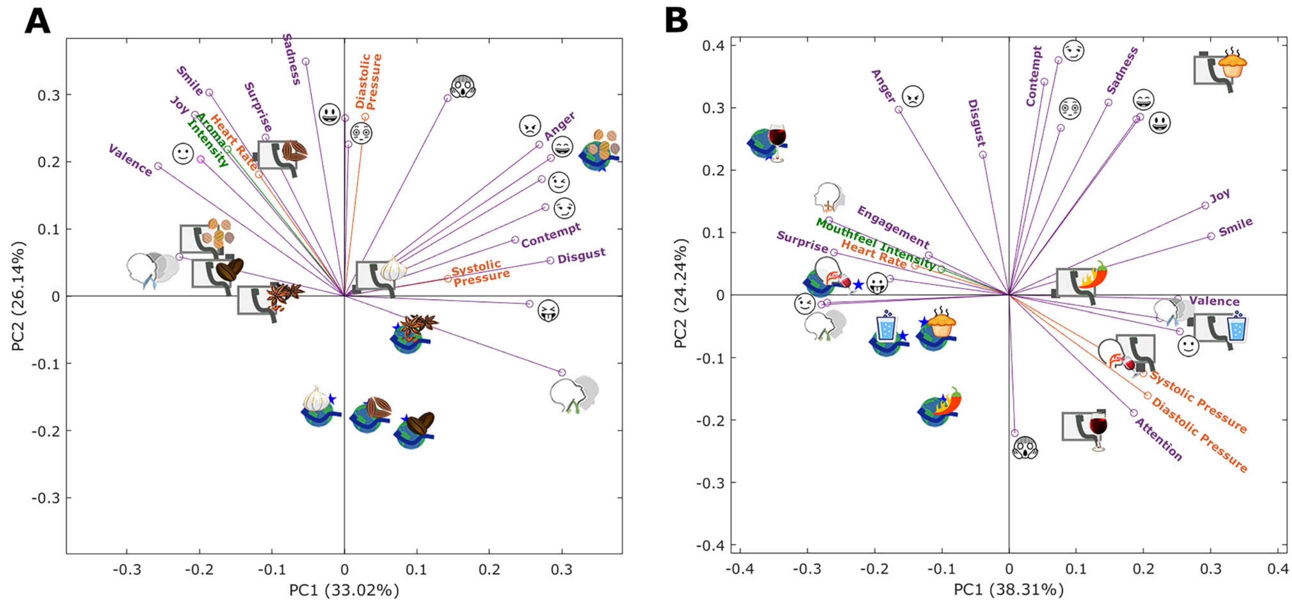


Fig. 3 | Principal component analysis of self-reported and biometric responses. Principal components analysis (PCA) from the two sensory sessions for (**A**) retronasal aromas and (**B**) mouthfeel using variables from the self-reported and subconscious biometrics from trained panelists (*n* = 12). represents the neutral environment with normal seating position, while represents the space simulated environment with microgravity position. Samples corresponding to the images represented in the figures can be found in Table 1.

The sensory science research conducted in space-simulated environments plays a pivotal role in enhancing the understanding of how human senses and perceptions adapt to the unique conditions of space. This study has yielded significant insights into the alteration of sensory perception, particularly within an immersive space-simulated setting that mirrors the challenges astronauts will face, including a simulated microgravity seating position. Notably, findings showed that global aroma intensity is perceived as less intense in space-simulated environments compared to neutral (normal) conditions. Additionally, the multivariate analysis revealed that mouthfeel intensities are experienced as more pronounced in these space-simulated conditions. Some limitations of this study were the inability to achieve a complete microgravity environment that simulates free movement on Earth, such as with parabolic flights from NASA Airbus 310. Another limitation is that the study should be narrowed to trained panelists who possess the physical fitness of astronauts and psychological training for microgravity and confined spaces, as these factors may alter their perception of food and beverages. However, trained astronauts for future missions, such as Artemis, are limited. However, some studies have been planned with NASA to conduct sensory experiments on board the International Space Station using our biometric technologies.

This research highlights the critical role of sensory experiences in long-term space missions. As we plan journeys to the Moon and Mars, understanding how sensory perception changes in space is key to developing food systems that support astronauts' nutrition, enjoyment, and psychological well-being. These findings emphasize the need for continued research into the behavioral and physiological impacts of spaceflight on sensory responses to optimize food design for mission success.

Methods

Samples description

Samples for session one (S1) consisted of five spices that provide familiar retronasal aromas found in foods; furthermore, these are spices that would be easy to take to space for astronauts to enhance or improve their food, as they already do as part of their Tex-Mex menu for the ISS[41]. These samples consisted of (i) coriander seeds, (ii) aniseed, (iii) coffee beans, (iv) garlic flakes, and (v) cumin seeds. They were selected due to their plant source and as common spices used in foods that may be produced in space. All participants received the same amount of each sample, as shown in Table 1, and no further preparation was required.

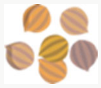
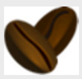
Session two (S2) consisted of five samples that elicited different mouthfeel (trigeminal) sensations, as shown in Table 2. These were selected based on typical trigeminal sensations commonly found in many foods and beverages, which will likely be found in space meals. The products used to test each mouthfeel were selected because they serve as the best references, aligning with their main descriptors, making it easier for the panelists to focus on the specific mouthfeel. Besides, the panelists have been trained in general senses using these samples. No further preparation was required, except for the muffin (physical hot), which was microwaved for 10 s right before each participant started the tasting.

Sensory sessions and biometric analysis

Two sessions were conducted over two days (one session per day). These consisted of (i) S1: retronasal aromas and (ii) S2: mouthfeel. A total of 12 panelists who have been trained for over two years in basic senses (orthonasal and retronasal aromas, basic tastes, and texture/mouthfeel) and different food and beverages using the Quantitative Descriptive Analysis (QDA®) method with a 15-cm non-structured scale, participated in both sessions. All participants were healthy and had been previously screened for any physiological impediments (e.g., anosmia, ageusia) as required by the International Organization for Standardization (ISO) Sensory Analysis—General Guidance for the Selection, Training, and Monitoring of Assessors—Part 1: Selected Assessors[50]. Various references to elicit specific descriptors had been used for the basic senses training, following the mentioned ISO regulation standard. This study was validated and approved by the Human Ethics Committee from The University of Melbourne (UoM; ID: 1953926.6). All participants were required to sign a consent form.

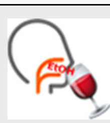
Each study was conducted using two treatments, which consisted of (i) a neutral environment (white background) with a normal seating position (Fig. 4A), and (ii) a space-simulated environment with a simulated microgravity seating position (Fig. 4B). Both environments were simulated using immersive rooms with a 180° screen, and each participant tested the samples individually, meaning that they were alone in the room to avoid distraction and suggestion bias; furthermore, the initial environment for each participant was randomized, therefore, half of participants started on the neutral and half on the space-simulated environments to avoid bias.

Table 1 | Samples and serving sizes used for the retronasal aromas session

Sample	Image[a]	Brand/Manufacturer	Serving size	Active aromatic compound(s)	Threshold
Coriander seeds		Hoyts (Hoyts Food Industries, Moorabbin, VIC, Australia)	3 seeds	(E)-2-decenal Linalool	0.35 ppb 7.4 ppb[59]
Aniseed			10 seeds	Anethole	NR
Garlic flakes			5 flakes	Diallyl disulfide Allyl methyl sulfide	0.22 ppb 0.14 ppb[60]
Cumin seeds			10 seeds	Cuminaldehyde	0.02 ppb[61]
Coffee whole beans		BunCoffee Byron Bay (Bun Coffee, Byron Bay, NSW, Australia)	2 beans	2-Furfurylthiol	0.01 ppb[62]

[a]Image used to depict the samples. *NR* Not reported.

Table 2 | Samples and serving sizes used for the mouthfeel session

Sample	Mouthfeel	Image[a]	Brand/Manufacturer	Serving size	Serving temperature	Active trigeminal compound	Threshold
Hot muffin	Physical hot		Mr Brownie (Magdalenas Lazaro, Alfamen, Zaragoza, Spain)	¼ of a muffin	Heated in microwave ~45 °C	Thermal stimulation (physical)	NA
Carbonated water	Carbonation		Capi (Capi, Melbourne, VIC, Australia)	30 mL	Room temperature (~20 °C)	Carbon dioxide	5.3% v/v[63]
Chili flakes	Pungent (spicy)		Hoyts (Hoyts Food Industries, Moorabbin, VIC, Australia)	5 seeds and 5 flakes	Room temperature (~20 °C)	Capsaicin (in water)	0.80 ppm[64]
Red wine	Warming		St. Erth Shiraz (C & J Wines Pty Ltd, Heathcote, VIC, Australia)	30 mL	Room temperature (~20 °C)	Ethanol	8% v/v[65] (perception of warming)
Red wine	Astringent		St. Erth Shiraz (C & J Wines Pty Ltd, Heathcote, VIC, Australia)	30 mL	Room temperature (~20 °C)	Tannins (in water[b])	23.8 ppm[66]

[a]Image used to depict the samples. [b]Non-significant changes have been reported in threshold for solutions in ethanol[67].

For the seating positions, reclining chairs (Timber Ridge; Westfield Outdoors®, Indianapolis, IN, USA) were used, and participants were placed in a 90–270° for the normal position and 0–170° for the simulated microgravity position as described by Gonzalez Viejo, et al.[11]. The latter position has been reported as effective in simulating microgravity on Earth as this position allows the distribution of body weight evenly, similar to the effects caused by microgravity, providing a weightless sensation[51]. Other researchers have found that a reclining position delivers similar results to those in space microgravity when conducting cognitive and motor activities[15].

A stand holding a Samsung Tab S 10.5-inch (Samsung Electronics, Suwon-si, South Korea) was placed in front of the participant. The tablet displayed the BioSensory© application (App; The University of Melbourne, Parkville, VIC, Australia)[52]. This App showed the sensory questionnaire, which consisted of a single question per sample to rate the intensity of the specific aroma (S1) or mouthfeel (S2) on a 15-cm non-structured scale (absent—intense). While displaying the question, the BioSensory App recorded the participants' faces to obtain their biometrics, including emotional responses, heart rate, and blood pressure (Table 3). For the tasting sessions (S1 and S2), participants were given the following instructions (i) fit the clip (Fig. 4) on your nose, (ii) take the sample and insert it in your mouth (solid samples: chew the sample for 3–5 s; liquids: swirl through the mouth for 3–5 s), (iii) close your mouth and remove the nose clip, and (iv) release your breath through your nose. The latter allowed to experience better the retronasal aromas and the mouthfeel or trigeminal sensations. This method was successfully tested previously with the panel during training sessions. All 12 participants evaluated the samples in the two treatments

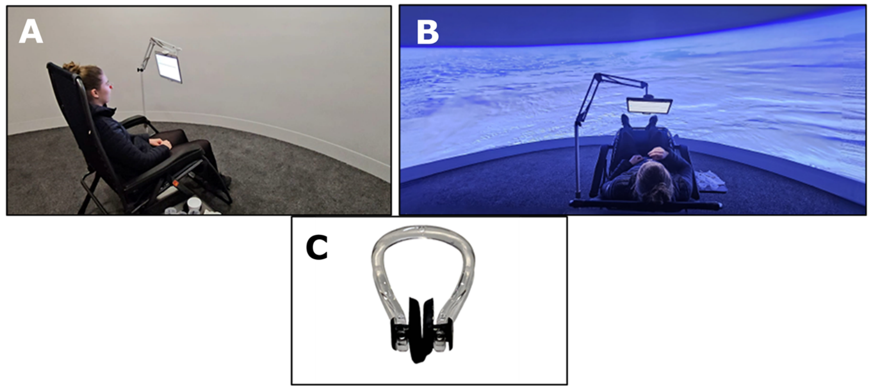
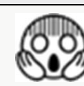
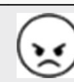
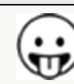
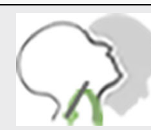
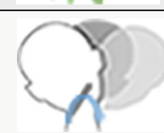
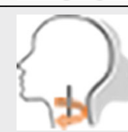


Fig. 4 | Immersive environments and nose clip used for the study. Images show the immersive environments with **A** a neutral room with a white background and normal seating position, and **B** a space-simulated environment with the Earth seen from space in a 180° screen and microgravity seating position. Additionally, **C** shows the nose clip used in the sensory sessions to experience the senses better.

Table 3 | Variables used for statistical analyses of each sensory session for emotional and physiological responses

Variable	Session	Label[a]	Variable	Session	Label[a]
Joy	S1 S2	Joy	Laughing	S1 S2	
Contempt	S1 S2	Contempt	Wink	S1 S2	
Disgust	S1 S2	Disgust	Scared/Scream	S1 S2	
Surprise	S1 S2	Surprise	Rage	S1 S2	
Sadness	S1 S2	Sadness	Smirk	S1 S2	
Anger	S1 S2	Anger	Stuck out tongue with winking eyes	S1	
Engagement	S2	Engagement	Stuck out tongue	S2	
Attention	S2	Attention	Pitch	S1 S2	
Valence	S1 S2	Valence	Roll	S1 S2	
Smile	S1 S2	Smile	Yaw	S2	
Relaxed	S1 S2		Heart rate	S1 S2	HR
Smiley	S1 S2		Systolic pressure	S1 S2	SP
Flushed	S1 S2		Diastolic pressure	S1 S2	DP

S1 and S2 stand for sessions one and two.
[a]Emojis shown were obtained from the open-source Noto Color Emoji Font from Google for publication purposes. Images shown for head movements were created by the authors.

(environment × position), allowing for a 20–30 min break between sessions. Furthermore, samples were labeled with different three-digit random codes for each room and tasted in random order to avoid bias.

Videos recorded during the sessions were analyzed for emotions using an automated software developed by the Digital Agriculture Food and Wine Group from UoM (DAFW-UoM) based on the Affectiva software development kit (Affectiva, Boston, MA, USA). This software can assess emotions, dimensions, head movements, and emojis that resemble facial expressions through video analysis and deep learning trained on over 14 million videos from 90 countries[53–57]. Furthermore, videos were analyzed for physiological responses such as heart rate and blood pressure using computer vision algorithms developed by the DAFW-UoM based on the photoplethysmography (PPG) principle in the green channel of the RGB color code[58]. Physiological and emotional variables used for the statistical analyses for each session are shown in Table 3.

Statistical analysis

Variables shown in Table 3, along with the intensity of each sample, were analyzed using ANOVA ($p < 0.05$) and Fisher's least significant difference (LSD) *post hoc* test ($\alpha = 0.05$) to assess significant differences between environments and the interaction of environment × samples using XLSTAT ver. 2024.4.0 (Lumivero, New York, NY, USA). Furthermore, biometrics and intensities were analyzed using multivariate data analysis based on principal components analysis (PCA) based on covariance to assess relationships between variables and their association with samples. This analysis was developed using the Matlab® R2021a code (Mathworks Inc., Natick, MA, USA) written by the DAFW-UoM group.

Data availability

Data and intellectual property belong to The University of Melbourne; any sharing needs to be evaluated and approved by the authors and the University.

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Author contributions
C.GV.: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, project administration; funding acquisition; Writing— original draft, writing—review and editing, visualization; A.A.M-M: Methodology, validation, investigation, writing—original draft, writing—review and editing, visualization; N.H.: Methodology, validation; writing—review and editing, visualization; R.V-L: Methodology, validation, investigation, formal analysis, writing —original draft, writing—review and editing, visualization; S.F.: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, funding acquisition; writing—original draft, writing—review and editing, visualization.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Claudia Gonzalez Viejo.