

The Effect of Microgravity and Space Flight on the Chemical Senses

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ABSTRACT: The effect of space flight and microgravity on the chemical senses is reviewed. Skylab-4 and Soyuz 30-31 studies revealed changes in taste thresholds while no effect was found in a Canadian investigation (41-G) and conflicting results were obtained on another Soyuz mission. Two simulated microgravity studies found no effect on taste or smell sensitivity; while 5 other studies found an effect. Microgravity induces physiological changes including an upward shift of body fluids toward the head, which may lead to an attenuation of the olfactory component in the flavor of foods. Chemosensory changes may also relate to space sickness, Shuttle atmosphere, stress, radiation, and psychological factors.

Keywords: microgravity, space flight, taste, smell, chemosensory

INTRODUCTION

FLYING IN SPACE HAS BEEN A CHALLENGING dream for human beings all over the world. Presently, being in space has become a routine type of task for a certain privileged group of the population called astronauts or cosmonauts. Although the fascination with being in space may fill the astronauts with a sense of fulfillment, many other physiological and psychological effects come into play. The physiological effects are quite varied in nature and include changes in energy requirements, body composition, fluid homeostasis, protein utilization, calcium/bone metabolism and hematopoiesis (Lane and Smith 1999). Physiological adaptation to microgravity can result in loss of red blood cells, bone loss, and changes in gastrointestinal motility (Smith and others 1997). Other aspects of the space environment can lead to alterations in the chemosensory perception of foods; these include diet, illness, and biochemical shifts. Of special interest to sensory analysts is the effect of microgravity on the chemical senses. This area has been clearly under-researched in space missions, probably due to its lack of perceived terrestrial benefit. The scant literature that exists about chemosensory research under conditions of microgravity is sometimes contradictory and leaves a window for speculation.

Subjective reports from both Soviet and American astronauts report some attenuation of taste acuity (Rambaut and others 1977) and perception of an unpleasant taste in the mouth (Baranski and others 1983). A Russian study on

the change in taste perception of astronauts in flight against the background of fatigue (Popov 1981) recommended adding different spices and condiments to food products to improve appetite under such conditions. On a similar note, a Russian cosmonaut on Vostok VI reported a reduced appetite for sweets and a desire for pungent food flavors (Oberg 1981).

The physiological changes associated with microgravity and the chemical senses are not stated explicitly in the literature, but if one tries to relate observed physiological changes to the chemical senses, some conclusions can be drawn. From a physiological point of view, the most characteristic feature of space flight is the experience of micro-

gravity, which causes a shift of body fluids from the lower part of the body to the upper part. This fact has been well documented by a decreased leg volume (Leach and others 1996) and a facial puffiness (Figure 1) or edema of space crewmembers (Nicogossian and Parker 1982). These changes are substantial, leading to a reduction of leg volume by 1 L per leg within 6 to 10 h of reaching orbit (Leach and others 1996). Following this is a decrease in plasma volume and thirst.

Also relevant to the chemosensory organs is congestion of the nasal passages (Glendinning, personal communication), which results in decreased airflow, due to the engorgement of the non-olfactory mucosa, and a reduction

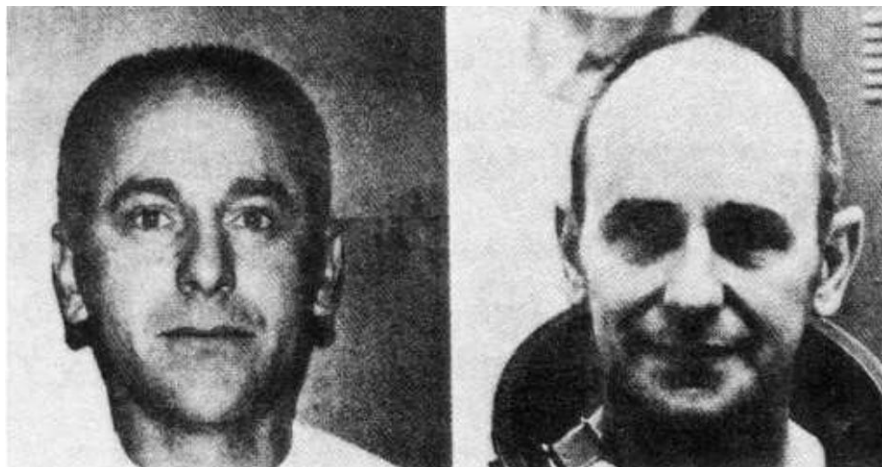


Figure 1—Facial edema, puffiness during flight as a result of microgravity: before flight (right), during flight (left) (Thornton and others 1977)

of the olfactory component in the flavor of foods, similar to having a cold or an allergy attack. Nasal congestion and associated symptoms occur in cold or allergic rhinitis. Several studies have reported an increase in smell thresholds in cold or allergic rhinitis and discussed the underlying causes (Eccles and others 1989; Akerlund and others 1995; Hummel and others 1998). Nasal congestion was a key symptom of simulated weightlessness studies (head-down tilt condition) (Hargens 1983; Aratow and others 1991; Hu and others 1999). In space travel, not only could the direct smell of the foods be partially lost, but part or all of the retronasal stimulation would be lost as well. This latter effect may be very important for the perception of some sensory qualities and the enjoyment of certain foods like juices because the perception of sweetness is increased by the retronasally perceived fruity flavor.

Astronauts frequently complain of the foods on the Shuttle being bland, and of a dislike for coffee while on orbit (Marshburn 1997). Not surprisingly, coffee is one of the foods that highly relies on the perception of its flavor components, having more than 500 chemical odorants, of which more than 20 potent odorants have been identified to date (Czerny and Grosch 2000). Eliminating the chemical odorants' contribution to the taste of coffee leaves only a bitter dark colored solution.

The objectives of this review were (1) to assess the literature on chemosensory perception in microgravity and weightlessness simulation studies, and consequently to judge if taste and smell alterations exist; (2) to examine any mechanisms that could be responsible for chemosensory alterations in space travel which have not been examined in previous space studies, and, (3) to assess the implications of chemosensory alterations on the space food system and accordingly to suggest compensatory changes to the foods.

Space chemosensory experiments

Four major space experiments have been performed in which taste, or smell have been assessed using astronauts as subjects. Russian and Polish scientists (Baranski and others 1983) conducted a study that followed a rather uncommon approach of using an electrogustometer with electrodes to measure taste thresholds. The usefulness of electrogustometry in microgravity was discussed by Kubiczkowa and Skibnewski (1979) who argued that studies of

thresholds of the "4 basic tastes" are not well suited for space because liquids and solutions behave differently in microgravity. The study of Baranski and others (1983) included 2 astronauts on each of the Soyuz 30 and Soyuz 31 spacecrafts. A direct current of increasing intensity was applied to the tongue and the subjective perception of a slight pinching or a slightly acidic taste was indicative of the threshold of the taste organ. The measurements were replicated in different places on the tongue.

The results revealed a highly significant alteration in the taste threshold, reaching, in one instance, a change of 220% (preflight as compared to in-flight, Figure 2). However, the direction of change was different for the 2 astronauts in both experiments. A valid question is whether the electrodes were really measuring the taste threshold or were in fact measuring the trigeminal response of the tongue. This possibility is suggested by the fact that the small pinching can be compared to irritation or a low level of sensation on the pain continuum. However, since the electrode responses reported in this study lie within the taste threshold range obtained with healthy individuals, 40 μ A (Frank and Smith 1991), trigeminal interference is unlikely. Further, the reliability and the efficiency of this instrument in a noisy and highly wired environment such as the spacecraft can be questioned. An earlier study by Baranski and others (1979) with Polish cosmonauts, on board of a Soyuz mission, showed conflicting results.

In Skylab-4 experiments, taste and odor thresholds were measured using slips of paper impregnated with different flavors. In this study, 3 crewmembers tasted orange and onion flavors in addition to the 4 basic tastes. Five concentrations were used with each flavor. The crewmembers were told in the beginning of the test about the different flavors and were asked to report the flavor when first detected and when definitely confirmed. Odor identification thresholds were measured similarly for lemon, orange, onion, pepper, chicken, wintergreen, chocolate, cherry, spearmint, and cinnamon, in addition to a blank. The subjects' task was to identify the various aromas. The tests were conducted 10 d preflight, mid-flight, and 12 d postflight. The aroma tests gave no evidence of change in the ability to identify odors but the results of the taste tests were more varied, showing a shift in taste thresholds for certain sensations though results were highly individualized (Heidelbaugh and others 1975).

The findings of Skylab-4 prompted Canadian researchers to do a similar experiment during the 41-G Space Shuttle mission with 2 astronauts (Watt and others 1985). Whenever the word "Space Shuttle" occurs in this review it will be relating to being in any type of spacecraft or being in microgravity in general. The objectives were to compare preflight recognition thresholds for sucrose, urea, sodium chloride, and citric acid with the microgravity threshold, and to assess the recovery period

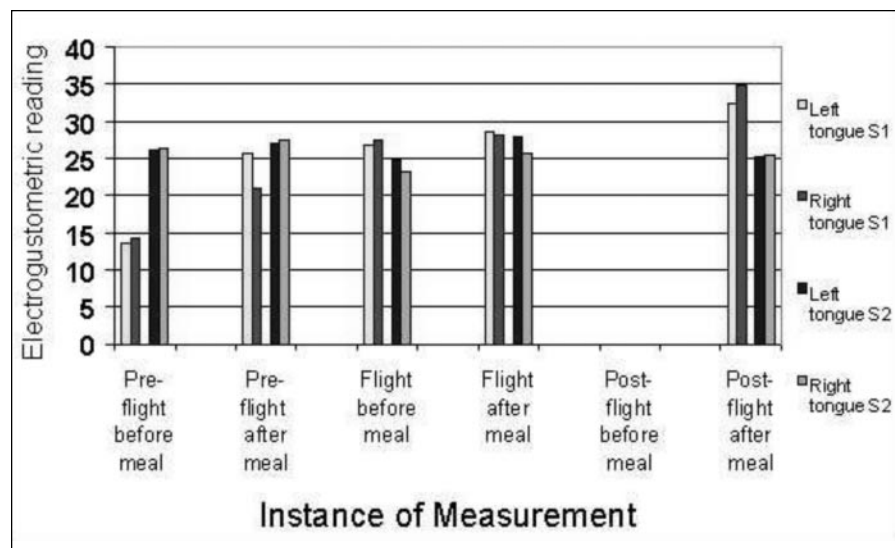


Figure 2—Electrogustometric measurements in Soyuz 30, adapted from Baranski and others (1983)

of taste and olfaction postflight. Olfaction was assessed as all or none by identifying the smell of the following substances: lemon, mint, vanilla, and distilled water. In the taste experiment the samples were supplied at the concentration of preflight thresholds, along with a higher and another lower concentration for each category in addition to 2 blanks. The recognition thresholds were determined preflight, in-flight, landing day and fifth day postflight. This experiment showed no effect of microgravity on either the smell or taste thresholds of the astronauts.

One weakness of this study was the small number of participants (2 astronauts) which is always a limitation in space research. Moreover, the method used to determine the recognition threshold was not fully described. It was not indicated whether a staircase method or the method of limits was used. Moreover, the step size, or the degree of change in concentration between successive trials is also not indicated. If the step size used was large, such as a 100% change, then the precision of the threshold is in doubt, assuming also that the same step size has been used to determine the higher and lower concentrations that were provided with the threshold solution to the astronauts, especially because the number of samples was very small. The authors also mentioned that the 2 astronauts in the 41-G trip, which lasted 8 d, did not experience any space sickness, which was not the case with the Skylab-4 astronauts who stayed for 84 d. The authors added that space sickness could have been a factor in altering taste thresholds. In a parallel example, Kekhayov (1974) found that healthy pilots exhibit changes in their taste sensitivity that can be the result of dynamic factors of flight. The space chemosensory studies and their results are summarized in Table 1.

Of great importance in all of these studies is how good or how reliable are the methods used in measuring taste alterations in space missions. Typical methods focus on the basic tastes but food taste alterations relate to a complex medium with various tastes, flavors, and mechanisms (taste, smell, retronasal, and orthonasal stimulation) contributing to the overall taste experience.

Microgravity Simulation Studies

Microgravity simulation studies are terrestrial studies which usually involve bed rest, or immersion in water, with a

Table 1—Space Chemosensory Experiments

Space Mission	Method	Sense(s) Assessed	Results	Reference
Soyuz 30-31	Electrogustometry (anodic)	Taste	Significant Effect	Baranski and others 1983
Skylab-4	Impregnated paper	Taste/Smell	Effect /No Effect	Heidelbaugh and others 1975
G-41 Shuttle	Taste solutions (detection + recognition thresholds)	Taste/Smell	No Effect/No Effect	Watt and others 1985
Soyuz	Electrogustometry (anodic)	Taste	Conflicting results	Baranski and others 1979

Table 2—Microgravity Simulation Chemosensory Experiments

Experimental Conditions: Bed Rest	Method	Sense(s) Assessed	Results	Reference
6 subjects laying on a -6° inclined bed	Taste + odor sensitivity (threshold)	Taste/Smell	No effect on Taste/Smell or Trigeminal system	Rice and others 1996
Head tilt down condition vs. bed rest at normal angle	Taste sensitivity test (threshold)	Taste	No significant change of taste sensitivity between the 2 conditions	Kanda and others 1993
53 subjects with bed rest (-8°) vs normal bed rest	Electrogustometry (anodic)	Taste	Significant increase in gustatory	Yakovleva 1982 thresholds
Head inclined bed rest to produce hypokinesia	Functional mobility method	Taste	Decrease in functional activity of taste receptors of the tongue	Kurlyandski and others 1974
Head inclined bed rest (+6°, -2° and -6°)	Taste sensitivity + functional mobility	Taste	Decreased taste sensitivity & increased mobilization of taste receptors	Budylna and others 1976
Several levels of body tilt (0°, 90°, 135°, 180°)	Odor identification tests + nasal resistance	Smell	Decreased odor identification No effect on nasal resistance	Mester and others 1988
A hypodynamia condition	Taste stimulation threshold + functional mobility	Taste	Decrease in taste sensitivity + decrease in mobilization of taste receptors	Volozhin and others 1974

slight head-downward tilt to cause a shift of fluids from the lower to the upper body. The conditions created in microgravity simulation studies aim at mimicking the effect of microgravity on the body. Microgravity simulation studies and their results are summarized in Table 2. Rice and others (1996) observed in a microgravity simulation (n = 6) that headward fluid shifts did not change subjects' sensitivity to taste (sodium chloride, sucrose, citric acid, qui-

nine, monosodium glutamate, and capsaicin), odor (isoamylbutyrate and menthone) or the trigeminal system. It is unlikely that any change in the trigeminal system would have been found since this system only responds to "extreme" or painful stimulants such as chemical irritation.

Kurlyandski and others (1974) studied changes in the taste of foods in 15 healthy men in a study that simulated weightlessness by using head inclined

bed rest to produce hypokinesia. The method of functional mobility was used in this study and the results showed a reduction of the functional activity of taste receptors of the tongue (and disturbance of the gastro-lingual reflex). The method of functional mobility with taste relies on the number of active taste buds at a certain time (Sniakin 1971). Not all of the taste buds will react to suprathreshold stimuli; some will be active and others will be idle. Sniakin (1971) defined functional mobility as "a process which determines the physiological ability of the organism/body to weaken or strengthen the functioning of systems by decreasing or increasing the number of active functional units". This is closely related to the condition of the digestive system, which in turn relates to the state of hunger of the individual (Zaiko 1956).

In a study involving both cosmonauts and healthy male controls (62 men aged 25 to 45), Yakovleva (1982) observed altered taste perception in a weightlessness simulating condition using an electrogustometer. Fifty-three men were used as controls and 9 cosmonauts were examined during 5 d under bed rest with a bed head slope of -8 degrees. Statistically significant increases in gustatory thresholds were found.

Budylna and others (1976) studied the effect of 3 bed rest angles: orthostatic (+6 degrees), antiorthostatic (-2 degrees) and highly antiorthostatic (-6 degrees) for a 30-d period. The first 2 conditions produced reduced taste sensitivity to nutritional stimuli and an elevated mobilization of taste receptors of the tongue. However, the third condition yielded opposite changes in the thresholds of taste sensitivity, and phasic changes in the mobilization of taste receptors. During a recovery period, taste sensitivity returned to the normal levels.

A recent Japanese study that also employed both the head down tilt condition and flat or 0 degree bed rest condition at 1G indicated no significant changes of taste sensitivity between the 2 conditions. Furthermore, food acceptability was found to be the same under both Earth gravity and simulated microgravity conditions (Kanda and others 1993). Volozhin and others (1974) assessed the taste sensitivity of 15 subjects subjected to a 30-d rigorous bed rest regime. The taste sensitivity was determined using the taste stimulation threshold and the functional mobility method. A decrease in taste sensitivity and a distortion of perception of tasty

substances was obtained. In addition, the level of mobilization of taste receptors of the tongue decreased considerably.

Many of the studies mentioned above, and especially the Eastern European ones, used the electrogustometer as the taste threshold-measuring instrument. Using anodal currents is a general practice, especially in clinical settings where the purpose is to measure taste loss. Taste loss or taste alteration can be either localized in 1 of the 4 taste fields (anterior tongue, posterior tongue, soft palate and oral pharynx) or common to all taste fields. Likewise, taste loss or alteration can be specific to certain substances or generalized to all substances. Electro-gustometry is convenient for measuring taste alterations in specific areas of the taste system since it uses a simple testing procedure, and overcomes the disadvantages that accompany the use of solutions in microgravity. If we consider the physiological effect of the facial puffiness and the blockage of the nasal areas, electrogustometry is well suited since it assesses taste irrespective of any input from the smell organ. The current used in the studies of Baranski produced an acidic taste, as reported by the author. In people with normal taste function, anodal and cathodal currents produce clear sour-metallic and indistinct bitter-sweet sensations, respectively (Frank and Smith 1991). In practice, electrogustometry nearly exclusively utilizes anodal electrical stimuli (Frank and Smith 1991), which implies that the current used in the Baranski studies was an anodal one.

Moreover, since the anodal current was the one used, only alterations in the taste thresholds of ionic stimuli (sour, salty substances, etc) could be implicated because anodal currents stimulate only salt or electrolyte sensitive receptor elements (Pfaffmann and Pritchard 1980) and cannot detect taste alterations from nonionic stimuli (for example, those producing sweet or bitter sensations), unlike cathodal currents.

In addition, electrogustometry cannot provide much information about the perception of actual foods in microgravity. Are foods perceived as less flavorful? This technique can only separate the taste sense from the smell and conclude about the taste sense. More research is needed using both electrogustometry and other techniques with a larger sample of astronauts in a "real microgravity situation" in order to understand more completely taste chang-

es that occur in space.

Mester and others (1988) examined the effect of body tilt on odor identification performance. In addition, the authors measured several physiological parameters: nasal airflow resistance, blood pressure and heart rate. The intent was to relate any physiological alterations to the expected changes in the olfactory function, as a result of the body tilt. They chose odor identification tests for practicality and because these tests correlate highly with measures of olfactory sensitivity. The study revealed a decrease in odor identification performance as a function of increased body tilt, but no significant effect of the body tilt on total nasal resistance, an apparent contradiction. By way of explanation, the authors argued that the method they used for measuring nasal resistance, anterior rhinomanometry, was not sufficiently sensitive to airflow alterations in the higher recess of the nose. The authors also suggested that tilt-induced temporary changes to the cephalic circulation might alter the olfactory function.

Yakovleva and Baranova (1982) examined the intranasal resistance of 14 cosmonauts 30 to 45 d before space flight and 3 to 5 d after the completion of space flight. Intranasal resistance was measured using a rhinopneumometer in several positions of the body; in sitting position, lying 15 min in the horizontal position and then returning again to the sitting position. Intranasal resistance tended to increase in the horizontal position. The authors concluded that a modification of rhinopneumometry could be used to predict vasomotor reactions of the nasal mucosa in the period of acute effect of weightlessness.

It is not clear how much the situation used in microgravity simulation experiments would mimic all the physiological changes that occur in microgravity. It would surely lead to a similar fluid shift, but it is doubtful that the other microgravity related side effects that may affect the chemical senses would occur under the kinds of simulations that have been done to date.

Possible Mechanisms of Chemosensory Alterations

Microgravity and space travel are characterized by unique parameters and/or environment, which can also contribute to alterations in taste and smell. The microgravity-specific phenomena have not been, in most of the cases thoroughly researched, at least in

the context of microgravity or space research, and thus they are presented in this review as hypotheses for chemosensory alterations in space travel which warrant further investigation. Some of the possible mechanisms are reviewed below

Space Sickness

Space motion sickness, sometimes called space adaptation syndrome, occurs in many astronauts. Its major symptoms include nausea, malaise, pallor, sweating, and vomiting (NRC 1987). Space sickness is a manifestation of the body's attempts to adapt its sensory and motor skills to the new, weightless environment. It is quite possible that space sickness may cause a change in taste or smell perception of astronauts similar to the change in taste or odor perception that occurs as a result of terrestrial motion sickness or seasickness. Space sickness when present usually lasts a few days to a week.

Conditioned taste aversion (CTA) is known to occur in laboratory animals (Fox and others 1984) as a result of motion sickness, which is similar in its symptoms to space sickness. One can readily imagine the occurrence of a mild conditioned taste aversion in astronauts and the possible effect of this CTA on the perception of the taste of foods by the astronauts. Although conditioned taste aversion typically occurs as a response to the repeated consumption of unfamiliar foods or beverages paired with a malaise inducing stimulus (Andrykowski and Otis 1990), it can develop in humans subjected to strong malaise which is repeatedly paired with familiar foods (Hu and others 1996). CTA is usually encountered with cancer patients, who experience malaise and nausea similar to space sickness as a result of chemotherapy. The correspondence among CTA due to chemotherapy and due to terrestrial motion sickness suggests that it would be interesting to look for a relationship between astronauts' reported taste alterations and the incidence of space sickness and to see whether taste alterations are more concentrated and significant during the space sickness period and whether there is any change in post vs. preflight food likes and dislikes. The answers to these questions would reveal the possibility of the occurrence of CTA as a response to microgravity induced space sickness.

Tennissen and others (1987) studied motion effects on the chemical senses with 2 subjects in the Ashton Gabriel

spatial orientation laboratory in a rotating room. The solutions used were sodium chloride, sucrose, citric acid and quinine sulfate for taste and 10 food odorants. The purpose of this study was to investigate shifts in suprathreshold intensity and preference judgments. The subjects rated both the intensity and pleasantness of these solutions or odorants before and after the time spent in the rotating room. This motion affected 1 subject, whose taste intensity ratings increased significantly on post rotation tests, supporting the idea that motion may be a cause of reported taste changes in space flight. Although the changes in the pleasantness ratings were not statistically significant, shifts to a less pleasant rating on the post-rotation tests were consistent with a conditioned taste aversion phenomenon. One concern with the relevance of this test is that the rotating room gives a continuous angular acceleration but in microgravity there is no gravitational acceleration at all.

Shuttle Atmosphere

The physical environment of microgravity in several previous space missions was characterized by a lowered atmospheric pressure (Apollo, Gemini, Skylab; Nicogossian and Parker 1982), typically at a higher oxygen concentration than the Earth atmosphere (Skylab; Drysdale, personal communication). The Shuttle environment in space missions may affect the stimulation of the chemical senses and consequently the astronauts' thresholds. Several instructive studies have been reported in the high-altitude literature and are reviewed below.

Singh and others (1997a) examined the effect of high altitude (3500 m) on the taste thresholds of glucose, sodium chloride, quinine and citric acid, finding an increase in the taste thresholds of glucose and sodium chloride with a concomitant decrease in the thresholds of quinine and citric acid. In addition to the measurement of thresholds, the 'hedonicity' of the solutions was recorded. There was an increase in the acceptability of glucose solutions at the high altitude condition. The authors related the changes in the thresholds and 'hedonicity' of the solutions to hypoxic stress, which in turn increases the palatability of glucose solutions (high carbohydrate). They argued that a high carbohydrate diet stimulates ventilation and increases alveolar and arterial blood oxygen pressure at low ambient oxygen pressure.

Maga and Lorenz (1972) conducted a similar study at 5000 ft (1525 m) in a special chamber equipped with pressure, temperature and humidity controls. Using this chamber, the authors were able to simulate altitudes of 0, 5000 ft, and 10000 ft (1525 and 3050 m) above sea level. They assessed the thresholds of sucrose, sodium chloride, citric acid and caffeine. When the 4 tastes were considered as a unit, there was a statistically significant increase in the threshold for the 5000 ft elevation vs. sea level. However, no significant difference resulted from going from 5000 to 10000 ft. From a chemosensory perspective, it is questionable whether it is a good idea to consider the 4 tastes as a single unit. The authors suggested that taste sensitivity declines with increasing altitude. If hypoxic stress is the main determinant for these threshold changes, then these studies cannot accurately predict what happens in a microgravity environment.

Although the 2 high altitude simulations matched barometric pressure of the spacecraft, they were both done under low atmospheric O₂ content, which is opposite to the space missions norm of a high O₂ content. Zaiko and others (1963) combined both changes, a simulated high altitude environment (5500 m) and a gas mixture with increased O₂ content. Sodium chloride, sucrose and citric acid were the stimuli and the method of functional mobility was used to assess changes in taste sensitivity. The study revealed no changes in taste sensitivity between high altitude with high O₂ concentration and regular atmospheric pressure with atmospheric air.

Singh and others (1997b) conducted a study in which rats were put under continuous exposure to hypobaric hypoxia equivalent to 7620 m altitude in a decompression chamber. This condition resulted in decreased water and food intake and a preference for sweet solutions over water, citric acid, sodium chloride and quinine sulfate. The authors added that changes in taste preferences observed in this study could be due to changes in the taste sensitivity at the receptor level. However, other studies have linked the reduced food intake in hypoxia to changes in appetite (Tschop and others 1998; Westerterp and others 1999) rather than taste changes.

Ettinger and Staddon (1982) examined the effect of several conditions, including hypobaric hypoxia, normobaric hypoxia, hypobaric pressure and high

O₂ condition, and a normal atmospheric condition, on the feeding behavior of rats. Both hypoxia conditions decreased the rate of feeding, but the oxygen-sufficient conditions did not. The third condition in this study mimics what happens in space travel and did not result in any change in the rats' feeding rate. High altitude studies and their results are summarized in Table 3.

These 5 studies favor the conclusion that when oxygen pressure is sufficient, lower barometric pressure is not likely to affect gustatory thresholds and the stimulation of taste. However, they do not rule out in any way the possible effect of the reduced pressure on the smell component of foods and possible alterations of olfactory thresholds. We speculate that the smell function of astronauts is likely to be affected by the presence of volatile trace contaminants present in the Shuttle atmosphere, which can render the astronauts' smell fatigued or adapted to some odors (Neilson 1985).

Stress effects on the chemical senses

Astronauts usually experience stress on space missions due to both physiological/physical and to mental stress. Several studies have researched the effect of stress on chemosensory perception. It is noteworthy to mention here that "stress" in this section refers to physical and/or mental stress resulting from overstimulation only and not understimulation. The effect resulting from understimulation of the monotonous space environment will be discussed in the psychological factors section of this review. Nakagawa and others (1996) studied the effect of mental or physical stress on taste perception. Mental stress was induced by performing a demanding letter search and physical stress was induced by performing an exercise using an ergometer. The taste intensity of solutions of sucrose, quinine sulfate and citric acid were measured using time intensity techniques. The mental task resulted in a reduction of the duration of after-taste for all tastes. The authors assumed that this phenomenon is likely to be due to some type of central inhibition of taste perception. The physical task resulted in a reduction of the time intensity curve of sourness. The authors linked this outcome to an increase in the buffering capacity of saliva due to hard exercise. Hence mental stress appears to have a stronger effect on taste perception than pure physical stress.

Dess and Edelhait (1998) showed that

stress altered taste ratings of sweet and bitter solutions. Subjects were divided into stressed and control groups and stress was induced by subjecting the subjects to a noxious noise while performing a specific task. In addition, the temperament of the subjects was assessed by several questionnaires. The subjects were asked to rate the sweetness and bitterness of saccharin solutions in addition to the tone loudness of several tones. The study revealed an increase in sensitivity to saccharin's bitterness in the stressed group. Moreover, stress resulted in higher bitterness ratings and lower sweetness ratings in the individuals classified as "low" on a pleasure trait.

Budylna (1990) assessed the characteristics of taste and visual perception in emotionally stressed students performing a goal-directed activity. The effect of emotions on the 2 studied senses was shown to be dependent on the sign of these emotions and their sthenic or asthenic character (sthenic refers to excitability and asthenic the opposite).

Personality differences could also mediate alterations in taste perception in certain individuals. Harries (1973) related sensory acuity to the personality of individuals, specifically their level of extroversion and its relationship to the discrimination of differences in meat texture and juiciness. Extrovert personalities were found to make less discriminating assessments of textural differences than introverts. Stress studies and their results are summarized in Table 4.

There seems to be a link between stress, personality and chemosensory measurement. However, it is not clear how much these factors could play a role in space travel. Is it a more influential component of chemosensory alterations when coupled with physiological stress such as space sickness? Similar questions cannot be answered without actual space experiments or Earth experiments combining both simulated space sickness and a stressful task requirement. Proper psychological and behavioral criteria for the selection of future astronauts (Palinkas and others 2000) as well as an adequate countermeasures program are essential for the success of long-term manned space missions (White and Averner 2001).

Radiation induced taste injury

Another unusual effect of microgravity and space travel is the level of radiation to which the astronauts are subjected. The radiation effect on astronauts' taste and/or odor receptors can

be estimated based on studies of sensory acuity changes in patients undergoing radiation therapy for cancers of the oral cavity or neck.

Tanigawa (1965) studied the dose of radiation needed to induce taste injury in the 4 basic tastes: solutions of sucrose, acetic acid, sodium chloride and quinine hydrochloride. The solutions were assessed using the drop method. Subjects selected ($n = 30$) were individuals of normal taste sensitivity who were being treated by radiation from neck or head cancer. The radiation source was Telecobalt (⁶⁰Co) and was applied on a daily basis at the rate of 150 r/d. Taste sensitivity in most patients was affected after exposure to 1000 r to 4000 r (8.3 to 33.2 Gy). Sweet and sour tastes were more affected than salty and bitter tastes, and bitter taste was the most resistant to alteration. No injury was observed below the level of 800 r (6.64 Gy) and the disappearance of taste occurred completely at doses > 3000 r (24.9 Gy), returning within 30 to 40 d in most of the patients.

Tanigawa's results (1965) were later confirmed by more recent studies of taste (Sato and Kamata 1984; Mossman 1986; Mossman 1983) and smell (Ophir and others 1988). In all of these studies, the radiation level needed to increase chemosensory thresholds or to induce taste loss was higher than 800 r (6.64 Gy), the level indicated in the Tanigawa study (1965).

Astronauts typically receive far lower radiation doses than the subjects of these studies. The average skin dose for Skylab 3 astronauts was 17.85 rem; Skylab 4 exposure was higher (Nicogossian and Parker 1982; Pence and Yang 2000). NASA guidelines limit exposure to: (at 5 cm depth in tissue) 25 rem/30-d exposure, 50 rem annually and a career limit between 100 and 400 rem depending upon gender and age (Simonsen and others 1990). The level of radiation needed to treat cancer patients and induce taste/smell injury and/or loss is significantly higher than those encountered in space flights to date. Although radiation exposure is unlikely to have affected taste and smell in previous Shuttle missions, radiation and its sensory effects remain of concern for future Mars missions which involve a much longer space travel time (Simonsen and others 1990; White and Averner 2001).

Psychological factors: Sensory deprivation, environmental and social isolation, food monotony and sensory specific satiety

Space flight is characterized by a

state of environmental and social isolation. The environment prevailing outside the spacecraft is monotonous and does not provide much variation in terms of stimulation. Many investigators in the 1960's and early 1970's expected the space environment to create a state of sensory deprivation. However, a clearer description was provided by Berry (1973), who described the situation as a state of "sensory invariance". Berry also argued that the extremely busy schedule of the astronauts and the high ambient noise level in the spacecraft are all sources of stimulation. Ryback and others (1971) who simulated microgravity with prolonged bed rest, concluded that the microgravity simulation condition is a subtle form of sensory deprivation. However, the authors did not relate the sensory deprivation of bed rest to the 5 senses but described it somatically, in terms of reduced neurological input from the muscular system. The conclusions of this study do not apply to modern-day space flight with its high level of physical activity. Schutte and Zubek (1967) measured the olfactory threshold of benzene and gustatory thresholds of the 4 major tastes after 1 wk of visual deprivation. Olfactory sensitivity to benzene increased at the end of the deprivation period but returned to normal prestudy levels 2 d after visual stimulation was restored. The measures of gustatory sensitivity were more varied. Sensitivity to sodium chloride and sucrose increased after visual deprivation but no significant effect was measured for HCl and quinine. The authors added that their results were in accordance to a model formulated by Schultz (1965). The model stated, "When stimulus variation is restricted, central regulation of threshold sensitivities will function to lower sensory thresholds. Thus, the organism becomes increasingly sensitized to stimulation in an attempt to restore the balance". In Schutte and Zubek's study, there was an increase in gustatory and olfactory sensitivities in response to visual deprivation. However, the anecdotal reports by astronauts show a trend in the opposite direction where foods taste blander in space. Furthermore, previous sensory deprivation studies have encountered symptoms like hallucinations (Morgan and Bakan 1965; Rossi and others 1964; Shulman and others 1967) or "phantom smells" (Shulman and others 1967). Similar symptoms have not been reported in space missions. Though the notion of

Table 3—High Altitude Chemosensory Experiments

Experimental Conditions	Method	Sense(s) Assessed	Results	Reference
3500 m altitude	Taste threshold (4 basic tastes)	Taste	Thresholds shifted: increased glucose & NaCl; decreased quinine & citric acid	Singh and others 1997a
Simulated 5000 and 10000 ft	Taste threshold (4 basic tastes)	Taste	Significant increase in threshold (all solutions as one) between control & 5000 ft level	Maga & Lorenz 1972
Simulated 5500 m + high O ₂	Functional mobility with sucrose, NaCl and citric acid	Taste	No difference between control and treatment	Zaiko and others 1963
Simulated hypobaric hypoxia (7620 m)	Rat experiment with H ₂ O + 4 basic tastes solutions	Taste	Changes in taste preferences	Singh and others 1997b
Hypobaric, normobaric hypoxia, hypobaric pressure + high O ₂	Rat experiment, feeding behavior	Taste	decrease in rate of feeding with 2 hypoxia conditions	Ettinger & Staddon 1982

Table 4—Stress Chemosensory Experiments

Experimental Conditions	Method	Sense(s) Assessed	Results	Reference
Mental stress (letter search) & physical stress (ergometer)	Time intensity of solutions of sucrose, quinine sulfate & citric acid	Taste	Mental task decreased after-taste (3 solutions) Physical task decreased TI curve of citric acid	Nakagawa and others 1996
Solving scrambled words + sudden noise (stress)	Examine relationships of taste/stress /temperament	Taste	Increased sensitivity to saccharin's bitterness in "Stress" group	Dess & Edelheit 1998
Emotional stress while performing a goal-directed task	Examine the perception of vision & taste	Taste	Some significant effects	Budylna 1990
Assess the texture & juiciness of meat samples	Examine relationship b/w sensory acuity and personality of subjects	Taste	Less discrimination of texture in extroverts	Harries 1973

sensory deprivation may not completely apply to space flight, environmental and social isolation conditions do, and these conditions may have an effect on chemosensory thresholds or even food preferences.

Several studies have confirmed the increasing importance of food in space and environmental isolation. In a study

on early space flights and long-term ground-based studies, Berry (1973) argued that food becomes a critical morale building or degrading factor in isolated micro societies. The author added that dining became a major social event of the day and a time for communication. Stuster and others (2000) analyzed journal entries of leaders and physi-

cians of French circumpolar expeditions. More than 100 themes emerged from the analysis and were distributed across 22 categories. Food was one of the most important categories and had predominantly positive diary entries. Milon and others (1996) have stressed the importance of food in isolated environments and explained that expedition members viewed food as a compensation for the hardships of living and working in these environments.

A recent study by Smith and others (2001) has shown that participants in a 60-d and 91-d ground-based closed-chamber maintained a caloric intake similar to prestudy and post study levels. However, the energy intake of 2 Mir astronauts, estimated by a food frequency questionnaire, was less than 50% of their predicted energy requirements (Smith and others 2001). Inadequate dietary intake has been reported on Apollo, Shuttle and Mir missions. The reasons for this low level of intake are not well determined but could include the following: time constraints, lack of appetite, inadequate menu selection, menu fatigue and the effect of confined environments. Milon and others (1996) assessed the nutritional status of crewmembers participating in the EXEMSI project, a ground-based simulation study on the effects of isolation and confinement. The mean energy intake during the 9 wk of isolation was not significantly different from the crewmembers' regular intake. In addition, no changes in eating habits were recorded over the isolation period. The authors attributed these results to the high palatability of the diet, the absence of feelings of hunger or monotony, large variety, and adequate selection of foods made with direct prior involvement of the crew. The few studies on intake in isolated environments suggest that maintaining proper intake and regular food habits is possible in ground-based isolated environment studies; however, this situation may differ in actual space missions. Whether the psychological impact of ground-based simulations was able to simulate the isolation of space missions, and whether other stresses related to space missions would enhance isolation feelings and related symptoms, are all issues that could be addressed by future research.

Studies by Redd and de Castro (1992) and de Castro and de Castro (1989) have demonstrated that food intake could be increased, sometimes by as much as 60%, when subjects ate with

others present than when they ate alone, so the fact that astronauts are always together in the same environment and have the opportunity of having their meals together should be fully exploited. Milon and others (1996) indicated in their study that 89% of the meals in the EXEMSI simulation were consumed by crewmembers at the same time. Moreover, special meals shared by the crew of Stuster's study (2000) were among the most reported positive entries in the journal diaries. Roberts (2000; 2001) conducted a review on age-related changes in energy regulation and suggested mechanisms for decreased energy intake in elderly persons. Prominent among these were social isolation and a decrease in sensory specific satiety.

Isolation has also been reported to bring about changes in olfactory response. Barabasz and Gregson (1979) noted that men returning from summer and winter Antarctic duty often reported changes in olfactory responses. The authors assessed the effect of Antarctic wintering-over on olfactory stimulation of 9 men. EEG evoked potential and electrodermal responses to real and suggested odorants were recorded. The study showed that the subjects responded less strongly to real odors and more strongly to suggested odorants after their isolation experience. The authors interpreted these results as implying a shift involving both sensory adaptation and sensory sensitization. A similar result was obtained in an animal study; Bauer and Bauer (1969) suggested that isolated female rats would exaggerate their responses to preferred and nonpreferred stimuli as compared to non-isolated rats. This theory was partly confirmed by the fact that isolated female rats drank less of a quinine solution than rats housed in groups. The authors noted that changes in behavior due to social isolation might result from a change in reactivity to stimulation. Though few reports are available, they strongly suggest that social and environmental isolation can bring about changes in food preferences or acceptability of foods, due to the low level of stimulation from the surrounding environment. This notion is compatible with previously mentioned anecdotal reports about astronauts' craving for spicier foods.

The classic studies on food monotony by Schutz and Pilgrim (1958) and Siegel and Pilgrim (1958) demonstrated that food monotony or repetitive diets result in lowered acceptance and intake

of foods. Plattig and Berg (1974) assessed the taste thresholds of 4 subjects who had been subjected to a monotonous diet and found changes in the taste threshold. They concluded that a monotonous diet might be equivalent to a deprivation of sensory information, which might induce changes of the specific taste thresholds. However, the astronauts' diets, especially in the last few years, have been quite varied and included around 150 different food items (Bourland, personal communication). Nevertheless the low stimulus level in space missions might require an exceptionally high level of variety to insure adequate food acceptance and consumption. Rolls and others (1982, 1981) developed the term "Stimulus Specific Satiety" or sensory specific satiety, to describe the observation that it was possible to make humans who were satiated on a single food to consume more food by offering them a different contrasting food. The unusual environment encountered in space missions and its associated symptoms might affect the astronauts' sensory specific satiety, in a similar manner to the change that occurs with the elderly population (decrease in sensory specific satiety).

The results of the studies focusing on physiological/environmental factors like microgravity simulation studies, Shuttle environment, space sickness or radiation studies do not present a compelling and coherent explanation of chemosensory perception changes in space. Perhaps the variables tested were not very influential. Psychological variables could thus be important influences on chemosensory perception and reported food problems. However, the comparison between physiological and psychological factors in the current Earth studies is a complex one and determining the relative importance of these factors in terms of their influence on chemosensory perception is not a straightforward task. Hence it becomes even more difficult to make the comparison for space research/studies since only limited data is available for physiological factors and only anecdotal data is available for psychological factors. Clearly, more space research is needed on both psychological and physiological factors and their effects on the chemical senses and related variables (acceptability, intake).

Implications for Space Food Systems

The food system of space missions has evolved a long way, from pastes

squeezed from a “pontube” (Heidellaugh and others 1968) to a collection of foods similar to our Earth food products with some minor necessary alterations in formulation and processing (Anon 1969). Alterations included having freeze-dried foods, dehydrated, irradiated or thermostabilized foods. Bite-size cubed foods were added, these consisted mainly of cereal based foods cooked under high pressure, and covered with a gelatin coating in order to prevent crumbs from contaminating the cabin (Bourland 1993). Experiments performed in the C-135 jet aircraft, which can experience during the course of its trajectory a small period of microgravity, concluded that higher viscosity liquid foods would be better for space and that this could be achieved by the addition of thickening agents (Rambaut and others 1972). In addition, several designs for food packages and utensils have been tested in space missions and generally the conclusion was that space travel allows the consumption of most foods under regular “Earth” eating conditions (Flentge and others 1971) (Figure 3).

From what has been reviewed in the earlier sections, we can conclude that foods with a higher flavor intensity are desired, assuming that all types of tastes are perceived less in microgravity, which might not be necessarily the case. The first response in fulfilling this desire can be the use of flavor enhancers. On the other hand, astronauts tend to avoid choosing foods with strong odors that will linger in the spacecraft atmosphere (oranges and their peel odor being an example) (Bourland 1997). Not all flavor enhancers will be equally useful, because of the difference in their mode of action. For example, MSG and ribotides will boost taste intensity, but ethyl maltol imparts a retro-nasal olfactory sensation that is often confused with sweet taste (Bingham and others 1990). A good compromise might be foods that have a strong flavor, like a high sweetness in a pudding. Spices and flavor concentrates can also add intensity to the foods, as long as their volatile components are not unpleasantly persistent in the atmosphere.

Another consideration is the viscosity of foods. This relates to the behavior of liquids in microgravity and how the chewing process is affected so that the proper alterations will be made to eliminate any decreased chemosensory perception of the foods. An increase in viscosity has been shown to decrease sweetness intensity (Launay and Pas-

quet 1982; Theunissen and others 2000) and to delay the onset of mouth-burn for capsaicin solutions (Nasrawi and Pangborn 1988). Accordingly, texture alterations required for space foods to make them compatible with safety, dietary and other requirements must take into consideration the effect of any viscosity changes on the taste intensity and acceptability of the altered foods or ingredients.

Storage volume is always scarce in spacecraft, which means that foods will tend to be overcompressed. This overcompression might have an effect on the texture of products when ready to eat or on the chemical properties of these foods (Battey and others 1965). The use of packaging material that can stand a high level of pressure yet still provide protection to the texture of foods is a consideration.

Radiation in space could lead to a higher degree of oxidation in susceptible foods such as those high in fats and some of the oxidation susceptible vitamins. A countermeasure would be to increase the level of antioxidants, preferably natural ones, in susceptible foods so that the sensory and nutrition-

al qualities of these foods can be preserved. Moreover, novel technologies might allow the consumption of foods or beverages that have previously been excluded in space missions. An example is the development of a carbonated beverage system able to cope with the peculiarities of a microgravity environment (Horner and others 1996).

CONCLUSIONS

The complex problem of chemosensory perception in space provides one of the opportunities to assess the chemical senses in a unique “pathological” situation. Although the literature is somewhat contradictory, there seem to be changes in chemosensory perception in microgravity. The question remains, what is the best method in space to assess any chemosensory perception changes? A combination of physical (electrogustometry), psychophysical, and psychological experiments, with carefully designed ground-based controls, would be the best approach. Comparison of results obtained with different methods can provide evidence to validate the previous findings. Additional information from space about chemosensory function has potential to shed light on the workings of the chemical senses.

It is clear that many variables may affect the chemical senses during space missions: the physiological effects of microgravity, the physical and psychological stresses of the workload, sleep schedule, noise, confinement and the novel environment. In studying taste and odor alterations, we should attempt to address the effects of these variables. Ground-based research that attempts to simulate the effect of microgravity on the chemical senses should take into consideration the presence of these variables in space and any possible interactions between them. The research path here should follow in the steps of other biomedical space research. The first step is to characterize the nature and extent of taste and odor alterations in space and to discover the important causes and mechanisms. The second step is to investigate the effects of taste and odor alterations on the mood and performance of astronauts, and the last step is to design and test appropriate countermeasures.

Several issues should be addressed in future chemosensory space research. One would be to examine if there are any changes in smell intensity using suprathreshold measures. This will shed the light on the possible attenuation of smell in microgravity and its effect on



Figure 3—Astronaut’s meal consumption (NASA Facts 1996)

the flavor of foods. Conducting taste experiments with different techniques with a larger number of astronauts would be also useful. Microgravity simulation studies could explore changes to both taste and smell or could combine several of the space flight-related conditions like microgravity and isolation. Food frequency questionnaires, food acceptance measures during flight and post-hoc food preferences assessments could give an idea about the possible effect of space sickness or the workload on the preferences or intake of foods. Ground based chemosensory research could accommodate more stress studies, whether it would be stress resulting from overstimulation or understimulation. The later case could be done by testing subjects in confined monotonous environments. Other issues that can be investigated include the possible effect of microgravity and space flight on sensory specific satiety, the level of variety needed in the space diet or the level of isolation experienced by astronauts during missions.

Eating is one of the basic needs of humans and any disturbance in the enjoyment of eating foods due to taste alterations can have an effect on the health and morale of astronauts in long term space missions, in a similar manner to what occurred with individuals on Antarctic missions (Stuster, 1996). Thus this issue remains one of importance for future human explorations.

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