Factors affecting flavor perception in space: Does the spacecraft environment influence food intake by astronauts?

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ABSTRACT

The intention to send a crewed mission to the planet Mars involves a huge amount of planning to ensure a safe and successful mission. Providing adequate amounts of food for the crew is a major task but 20 years of feeding astronauts on the International Space Station (ISS) has resulted in a good knowledge base. A crucial observation from the ISS, is that astronauts typically consume only 80% of their daily calorie requirements when in space. This is despite daily exercise regimes that keep energy usage at very similar levels to those found on Earth. This calorie deficit seems to have little effect on astronauts who spend up to 12 months on the ISS, but given that a mission to Mars would take 30 to 36 months to complete, there is concern that a calorie deficit over this period may lead to adverse effects in crew members. The key question is why astronauts under-eat when they have a supply of food designed to fully deliver their nutritional needs. Although there are many potential reasons for under-eating, this review focuses on evidence from astronauts that foods taste different in space, compared to on Earth. The underlying hypothesis is that conditions in space may change the perceived flavor of the food, and this flavor change may, in turn, lead to under-consumption by astronauts. The key areas investigated in this review for their potential impact on food intake are the effects of food shelf-life, physiological changes, noise, air and water quality on the perception of food flavor, as well as the link between food flavor and food intake. The review also has relevance to understand drivers of food consumption on Earth.

1. INTRODUCTION

1.1 Space missions and food supplies

Like any other form of human exploration, space missions rely on a blend of scientific disciplines. While engineering is probably the most visible discipline in spacecraft, the provision of food for crewed space missions is also essential to deliver long-term success. The first human into space was Yuri Gagarin in 1961. Food was part of the mission, even though the flight lasted a total of just 108 minutes and the food was limited to squeeze-tubes containing pureed meat and chocolate sauce (Ahmed, 1988). Subsequent Russian and US spaceflights were followed by the establishment of space stations like Skylab, Salyut and Mir where missions lasted for days up to months, and food supplies were developed to provide nutrition in different formats, such as sealed pouches, small cans and thermostable foods (Smith, Zwart, Kloeris & Heer, 2009). Fast forward to the establishment of the International Space Station (ISS) in 1998 and food supply changed significantly, with a range of meals and a supply chain from Earth to the ISS, designed to feed around six astronauts at a time (Cooper, Douglas & Perchonok, 2011). Over the years, the provision of food has been further developed to deliver nutritious, tasty food in different formats and more than 200 different menu items are now available on the ISS (Cooper et al., 2011).

The next step for the US National Aeronautics and Space Administration (NASA) is to plan for a crewed mission to Mars and back, which will take around 2.5 to 3.0 years (see for example Perry, 2017). While re-supplying the ISS at a distance of about 400 km from Earth is feasible, the 225 million km distance to Mars represents a very different proposition. In readiness for a Mars mission, the criteria for food supplies have been studied by NASA (Cooper et al., 2011) as well as reviewed in other publications (Bayram, Aşar, Gökirmaklı & Özdemir, 2020; Jiang, Zhang, Bhandari & Cao, 2019). From these publications, several key challenges have been

identified. Supplying enough pre-packaged food for the 3-year Mars mission entails a huge cost to launch the food into orbit. Estimates are that with 1.8 kg of food per person per day, about 12 metric tons are needed for a 3-year trip with six crew (Cooper et al., 2011). With a launch cost in the region of \$15,000 per kg (Tkatchova, 2011), the overall cost would be around \$180 million for the food alone. There is also concern that the unknown radiation levels during the flight (Durante, 2014) may cause chemical reactions in the food that will adversely affect its nutritional and/or sensory properties and make the food nutrient deficient and/or inedible (Catauro & Perchonok, 2012). As an alternative, it has been proposed that astronauts could grow some of their food during the journey to Mars to supplement a smaller payload of pre-packaged food (Bayram et al., 2020; Monje et al., 2019; Zabel, Bamsey, Schubert & Tajmar, 2016). Currently, neither of these approaches are acceptable (Anderson et al., 2017). Another concern with food supply is that, from long-term studies on the ISS, astronauts do not achieve their required daily calorie intake (Heer et al., 2000; Smith, Zwart & Heer, 2015b). Although this does not seem to cause significant effects over a 6-12 month period (Smith, Zwart & Heer, 2015a), the effect over a 2.5 to 3.0 year period is, as yet, unknown. This review focuses on the potential causes of calorie deficit by collating and assessing the relevant published data from Earth- and space-based experiments. The aim is to identify potential causes, as well as areas where there are gaps in fundamental knowledge, so as to identify topics for future research, to support studies into the origins of calorie deficit during spaceflight.

1.2 Evidence for decreased food intake by astronauts during spaceflight

Weight loss in astronauts during spaceflight (Bergouignan et al., 2016; Heer, Baecker, Zwart & Smith, 2007; Smith & Zwart, 2008; Smith, Zwart, Block, Rice & Davis-Street, 2005) is due to

water loss, and loss of muscle and fat mass (Smith & Zwart, 2008). The loss of water and muscle mass is thought to be caused by microgravity but the loss of around 2 kg of fat on longer term missions indicates that the calorie supply is inadequate (Stein et al., 1999). Energy requirements for individual astronauts are calculated using the resting metabolic rate (RMR), as well as an activity factor that relates to the degree of movement (sedentary to energetic behavior) and the degree of daily exercise undertaken (for more detail, see Laurens et al., 2019). The diet supplied to astronauts is designed to deliver around 2,800 kcal/day (Smith et al., 2015a). Figure 1 shows the consistent calorie deficit in a group of 11 astronauts (on different missions) over a period of 28 weeks. Figure 2 shows a wider study where data from several different space programs were pooled. All missions showed a calorie deficit, apart from Skylab, where astronauts' food consumption was monitored daily and they were requested to eat more food to reach 100% of their daily calorie target (Michel, Rummel, Sawin, Buderer & Lem, 1977). The consequences of under-nutrition have been reviewed elsewhere (Smith et al., 2015a) and a more detailed study (Heer et al., 2000) has revealed that astronauts could suffer from sub-optimal levels of some micronutrients due to inadequate food intake. This under-consumption of food during spaceflight has been termed "space anorexia" (Varma, Sato, Zhang & Meguid, 2000) as there is apparently some trigger that overrides the usual mechanisms guiding food intake. Currently, the reasons for the calorie deficit are not known (see Schroeder, 2013), although various hypotheses have been proposed and some have been tested either in space conditions or on Earth using suitable protocols to mimic space conditions. Section 2 summarizes the hypotheses and the current state of knowledge.

Figs 1 and 2 hereabouts

116

117 **2. POTENTIAL FACTORS THAT COULD EXPLAIN THE CALORIE DEFICIT**

118 **2.1 Lack of nutrients in diet**

119 The rigorous design and testing of space food (Cooper et al., 2011; Cooper, Perchonok &
120 Douglas, 2017; Perchonok, Cooper & Catauro, 2012) ensures that the rations provided to
121 astronauts are nutritionally complete, so this potential source of calorie deficit can be
122 dismissed straight away.

123

124 **2.2 Physiological changes due to microgravity**

125 The transit of food through the human gut relies on peristalsis with some help from gravity
126 (Wood, 2004), so, in space, a lack of gravity may change the transit time of food through the
127 gut and therefore affect food uptake during the digestion process. Results from a space-based
128 study (Sawin, Taylor & Smith, 1995) showed no effect on gastric emptying nor any significant
129 difference in astronauts' gut transit time, although it should be noted that the participant
130 numbers were low and there was wide individual variation (Putcha, 1993). A supporting study
131 on food intake in rats during spaceflight (Wade et al., 2002) revealed no differences in gut
132 motility, food intake, or overall weight between Earth and space conditions, suggesting that
133 microgravity did not affect food intake (or uptake) in these animals. The Skylab experiment in
134 which astronauts were asked to eat more food to achieve 100% calorie intake was also
135 successful, again suggesting that changes to gut motility in space were not a significant factor
136 in food uptake (Michel et al., 1977). Head-down tilt bedrest is often used as an Earth-based
137 analog of spaceflight and will reduce the effects of gravity on the whole intestinal tract by
138 placing it in a horizontal, rather than a vertical plane. An experiment with patients in a bedrest
139 experiment (Roda et al., 2013) showed some changes in gut transit time but no follow-up

research has been conducted in space. Research is continuing to understand other factors, like the changes in the microbiome during spaceflight (Douglas et al., 2017) but this topic falls outside the scope of the current review.

2.3 Food consumption

Earth-based health problems like anorexia or obesity (Boesveldt & Graaf, 2017) are the result of under- and over-consumption of food, respectively; other instances of calorie deficit can also be found in the training of elite athletes (Lun, Erdman & Reimer, 2009; Mountjoy et al., 2018) or in elderly people whose sensory acuity is decreased (Spence, 2017b; Wylie & Nebauer, 2011). To determine whether food under-consumption was a factor in astronauts' calorie deficit, their food intake has been monitored for many decades (Lane, Gretebeck & Smith, 1998; NASA, 2016; Rice, Dlouhy, Zwart & Smith, 2011; Smith, Rice, Dillon, Davis-Street & Block, 2004; Smith et al., 2005). These data show that food under-consumption occurs in most astronauts and corresponds to a deficit of around 20% of the mean recommended daily calorie intake (Smith et al., 2005; Smith et al., 2015b). This compelling evidence from space studies leads to Section 3 of this review, which seeks to evaluate the factors and mechanisms that control food consumption.

2.4 Drivers of food consumption

Food consumption provides nutrients that keep the human body functioning. To maintain the body, it is necessary to replace the energy used metabolically and provide materials to renew and repair tissues and organs. To ensure that food consumption provides the appropriate mix of nutrients, the human body uses a control system, as shown in Figure 3 (Hopkins, Blundell, Halford, King & Finlayson, 2016).

Figure 3 hereabouts

Psychological, physiological and neurological factors are involved in the control pathways and, in humans, nutritional status is communicated throughout the day via feelings of hunger or satiety as food is consumed and utilized. However, Figure 3 shows that hunger is just one part of a complex mechanism for controlling food consumption (de Castro & Plunkett, 2002; Hopkins et al., 2016). Food consumption can be divided into two distinct phases, namely food intake and food (nutrient) uptake. In this review, food intake is defined as the process that occurs when food is first tasted (in the mouth), evaluated through its sensory properties to identify nutritious or dangerous foods, then swallowed or expectorated (Forde, 2018). Food uptake is defined as the process of digestion and absorption of nutrients into the body that takes place after swallowing. Both food intake and uptake should act together to ensure that the body receives the right type of nutrients, and at the appropriate levels, a process called homeostasis (Asarian, Gloy & Geary, 2012). In theory, the food intake process assesses food using multiple senses, such as smell, taste, vision and texture perception before ingestion (Boesveldt & Graaf, 2017). For the purpose of this review, taste is defined as the perception produced when a compound reacts with taste receptors located in the taste buds in the mouth, smell is the perception produced during sniffing (the orthonasal route) and flavor is the sensation that occurs during eating due to a combination of taste, retronasal aroma and possibly also trigeminal stimuli.

By means of these mechanisms, the risk of eating poisonous food, or foods which may contain pathogens, is decreased (Mattes, 2005). Bitterness is often associated with poisons; slimy foods are also treated with caution, as are foods with specific malodors or unfamiliar colors (Mattes, 2005). In practice, however, humans learn that foods like spicy chili or bitter-tasting beer and coffee are acceptable despite their initially challenging flavor. There is also evidence

that the flavor intake mechanism can be positively influenced, for example, by some aromas that encourage people to eat the food (Boesveldt & Graaf, 2017).

Food uptake involves processes such as the emulsification of fats with bile salts and the size reduction of biopolymers like starch or proteins into their subunits of sugars and amino acids, with these smaller molecules being taken up through the gut wall (Boland, 2016). Nutrient uptake may occur through passive or active transport, with evidence that active uptake of some nutrients is controlled by taste receptors (Dyer, Salmon, Zibrik & Shirazi-Beechey, 2005). Further research has found that taste receptors are widely distributed throughout the body (Kochem, 2017), suggesting that one of their roles is to act as sensors to monitor levels of key nutrients as part of the food control process. Therefore, the role and naming of these “taste” receptors has undergone a significant change and the terms chemosensors or chemoreceptor are now preferred (Krasteva-Christ, Lin & Tizzano, 2020). The current thinking is that taste and smell chemoreceptors control food intake through the hedonic response but also play a major role in the regulation of nutrient uptake (Behrens & Meyerhof, 2019). For the food intake function, the receptors act as sentinels to accept food that is nutritious while rejecting food that may cause harm. For the food uptake function, it is proposed that the chemosensory receptors found in the gut (Dyer et al., 2005) are linked to the homeostasis system and assist in the active uptake of nutrients to meet specific nutritional needs (Sclafani, 2006). There is evidence that the sensitivity of some chemosensors changes in relationship with the nutrient content of the diet (Gilbertson, Liu, York & Bray, 1998; Haryono, Sprajcer & Keast, 2014; Stewart, Newman & Keast, 2011) providing more information that supports their role as part of the food control process. Since the “taste receptors” seem to have a dual role, Table 1 lists the taste qualities sensed by the receptors and their putative role in screening the incoming food for nutrient composition.

212 *Table 1 hereabouts*

213 Because the main cause of calorie deficit in space is inadequate food intake and because
214 flavor is a key property controlling food intake/uptake, the focus of this review is on the flavor
215 of food and specifically how conditions in space may change flavor perception compared to
216 Earth conditions.

217

218 **2.5 Factors affecting flavor perception**

219 Figure 4 shows the potential factors that could affect flavor perception during spaceflight.
220 The following sections assess the available information from Earth-based and space literature
221 to establish the scope of this review. Those that are in-scope, will undergo more detailed
222 review in Sections 4-8.

223 *Figure 4 hereabouts*

224 *2.5.1 Sensory properties of space food*

225 The Properties box in Figure 4 is a reminder that flavor perception involves the integration of
226 many senses and a “good-flavored” food will have these properties in the right balance. To
227 ensure that the flavor of space foods is acceptable to astronauts, manufacture is controlled,
228 and the crew taste the foods pre-flight to ensure acceptability (Cooper et al., 2011; Douglas,
229 Cooper, Bermudez-Aguiree & Sirmons, 2016; Jiang et al., 2019). A range of foods (dehydrated,
230 thermostabilized, fresh, snack bars etc.) with different flavors and textures are provided, a
231 16-day menu cycle is followed (Cooper et al., 2011), and crew members can also select some
232 favorite foods for celebrations such as birthdays. Therefore, foods prepared for ISS astronauts
233 are flavorsome, which suggests a lack of flavor in space food *per se* is not an issue that needs
234 to be further considered in this review. However, astronaut debriefs (Douglas et al., 2016)
235 indicate that the perceived flavor of these foods under space conditions is different. Evidence

from different missions and from individual astronauts was assessed and the report from Douglas et al. (2016) stated “Consistently during ISS crew debriefs, the crews have stated that their food preferences change from pre-flight to flight (documents not published due to confidentiality). Similar to Apollo and Shuttle, the crews have also noted that their tastes for certain foods change in microgravity and they may crave different foods on orbit compared to on Earth.” Douglas et al. (2016) then reviewed how the food supply could be optimised to improve food consumption.

2.5.2 Multisensory flavor perception

Multisensory refers to the fact that the food properties interact and influence sensory impressions, for example, sweetness can enhance fruit flavor and increase the perception of fruity odors (Green, Nachtigal, Hammond & Lim, 2012). Therefore, if there is a change in one component of flavor, it may affect the overall flavor or, if other flavor properties enter the food from the atmosphere inside the spacecraft or enter via the water used for drinking and rehydration of foods, then the overall flavor may change. If there are chemical changes during shelf life of food or if flavor-active compounds from the spacecraft environment enter the food (see paragraphs below), it is possible that the flavor profile of a food may change and affect its perception. The presence of background odors can also affect the perceived odor of a food and change its acceptability (Bult, de Wijk & Hummel, 2007) as well as the appetite of the consumer (Spence, 2015b). Multisensory effects are therefore in scope but will be discussed within the context of other studies.

2.5.3 Food rehydration

Rehydration of freeze-dried foods uses the recycled water from the spacecraft (Carter, Tabb & Perry, 2008). The recycling process makes the water safe to drink but could also concentrate some volatile and non-volatile compounds after multiple passes through the system (Limero

& Wallace, 2017). If these compounds are odor- or taste-active, then they may introduce a different note to the taste/flavor and change the overall flavor experience.

2.5.4 Environment inside spacecraft

The environment on the ISS is controlled so that air pressure and oxygen content are the same as on Earth, so these factors can be ignored in this review. However, CO₂ levels are 10x higher at 0.4% compared to 0.04% on Earth (Burlingame, 2016; NASA, 2015) and could activate the sour taste receptors (like carbonated beverages do) or some of the trigeminal receptors (Chandrashekar et al., 2009). Recycling of the air removes many odors but a background odor remains in the spacecraft (National Research Council, 2008), which may interfere (consciously or subconsciously) with flavor perception through the multisensory effect described in Section 2.5.2.

Noise can affect taste and flavor perception and originates mainly from the life support systems on the ISS. During the day, levels are 70 dB with peaks of 92 dB (Mallis & DeRoshia, 2005). Studies in aircraft and on the ground (Spence, 2014) have shown that noise can affect flavor perception, so this topic is included for further study.

The eating environment plays a role in flavor perception, which is why restaurants use table cloths, mood music or lighting to shape the dining experience (Spence, 2017a; Spence & Piqueras-Fiszman, 2014). In contrast, on the ISS, the eating environment is stark with none of the normal features of a dinner table, such as napkins, cutlery and so on. However, the constraints on space and weight in spacecraft preclude any great change on the ISS, or on a Mars mission, and this aspect is not subject to review.

2.5.5 Psychological effects

Hunger and satiety are the signals humans receive when nutrient levels reach the stage where replenishment is needed or achieved (de Castro & Plunkett, 2002). If space conditions cause

284 perturbations in the food control system (Figure 3) then the conditions for the “hunger
285 emotion” to be triggered may change. Hunger is also affected by the Sensory Specific Satiety
286 (SSS) effect. SSS is the situation that occurs when we eat one type of food (e.g. a savory food)
287 to satiety but then we “find room” for a sweet dessert (Rolls, Rolls, Rowe & Sweeney, 1981).
288 It has been proposed that this is a part of the food control system that ensures adequate
289 amounts of the macronutrients (fat, carbohydrate and protein) are ingested to meet
290 nutritional needs. It might seem that measuring hunger or satiety levels might be a way to
291 predict food intake but this has met with varying levels of success (Yeomans, 1998; Yeomans,
292 Weinberg & James, 2005) and this topic is excluded from this review due to a lack of
293 consensus. Emotional factors (e.g. stress and mood) and their relationship to food intake have
294 been studied on Earth and the underlying principles have been reviewed (Canetti, Bachar &
295 Berry, 2002; Piqueras-Fiszman & Jaeger, 2014). To create an emotional response, images on
296 film clips are often used and food intake is measured by the consumption of snacks or
297 confectionery (see for example Evers, Adriaanse, de Ridder & de Witt Huberts, 2013). How
298 these laboratory studies apply to real life, where mixed emotions may be involved and food
299 is presented as a meal rather than an individual snack is not clear. Given that astronauts are
300 chosen based on clear psychological characteristics (Landon, Slack & Barrett, 2018; Musson,
301 Sandal & Helmreich, 2004), the emotions measured in the general population may not
302 necessarily be the same as those exhibited by astronauts, so a comparison of Earth-based
303 studies with the space environment may not be valid. Because of these issues, the topic of
304 emotion is not considered in this review. In contrast, military food scientists have studied the
305 effect of monotonous diets and there is some evidence of an effect on food intake (see for
306 example Barrett & Cardello, 2012). The varied space diet and menu cycle mentioned in

Section 2.5.1, as well as the provision of fresh foods (and favorite foods for celebrations), are all designed to reduce monotony, therefore this factor is included in our review.

2.5.6 Taste and smell receptors

As part of the food control system, it is known that the sensitivity of the oral taste receptors changes to modulate food intake (Costanzo et al., 2019). Space-based experiments to measure changes in the sensitivity of these receptors compared to sensitivity on Earth have produced variable results (see review by Olabi, Lawless, Hunter, Levitsky & Halpern, 2002). The reported taste or odor thresholds vary by factors of 10 to 100 (see for example Devos, Patte, Rouault, Laffort & Van Gemert, 1990). Some of the variation is due to differences in genetic make-up, but the way that odor or taste stimuli are delivered in threshold experiments also contributes to the variation (Schmidt & Cain, 2010). Therefore, measuring receptor sensitivity in space with limited numbers of participants and with the difficulty of delivering exact concentrations of tastants or odorants in microgravity must increase the experimental variation significantly. Due to the lack of reliable data, the topic is mentioned, but not reviewed in detail. In contrast, trigeminal receptors, have not received much attention in the perception of food in space. They are responsible for recognizing irritating stimuli (Roper, 2014) such as capsaicin (the compound associated with the burn of chili), acids or the cooling effect of compounds, such as carvone, found in mint (Eccles, 1994). Although some space foods contain compounds that activate the trigeminal receptors, it is possible that contaminants from the recycled water or air may cause further activation and cause a change in the overall flavor perception profile, so this factor is included in our review.

2.5.7 Physiological changes

A well-known effect of microgravity in space is the redistribution of fluid in the body (Olabi et al., 2002). One of the effects this causes is extra fluid in the nasal passages (Yakovleva &

Baranova, 1982), which may decrease the amount of aroma that gets to the odor receptors located high in the nose. Nasal congestion also occurs in certain disease states on Earth and there is evidence that small changes in nasal flow can affect flavor perception (Raudenbush & Meyer, 2001; Trotier et al., 2007) and that surgery to restore flow is often successful in restoring the full sense of smell (Pade & Hummel, 2008). Since odor is a key part of overall flavor perception (Spence, 2015a) a review of current knowledge on nasal odorant transport is included in this review.

Changes in gut microbiota have been noted in astronauts (Douglas et al., 2017; Voorhies et al., 2019) and recent results from Earth- and space-based studies suggest that the oral, nasal or intestinal microbiota (Canon, Neiers & Guichard, 2018; Cattaneo, Gargari, et al., 2019; Cattaneo, Riso, Laureati, Gargari & Pagliarini, 2019; Koskinen et al., 2018; Turrone et al., 2020) may play a role in flavor perception or in the food control system. These studies are at an early stage but may be an area to re-assess when more data become available.

2.5.8 Shelf life of foods

Space foods currently require a 3-year shelf life (Cooper et al., 2017) but, for a potential Mars mission, a 5-year shelf-life is forecast (Douglas, 2019). Despite the high quality packaging used for space food, it is impossible to avoid chemical reactions that can affect product quality (Bell, 2007). A few studies have measured the changes in micronutrients in space foods over their shelf life (Cooper et al., 2011; Cooper et al., 2017) but little is known about food acceptability over shelf life (Catauro & Perchonok, 2012) and no formal reports on astronaut's perception of food in space were found in the published literature. Section 4 reviews the information available on food preparation methods and its shelf life.

2.6 Summary:- Potential factors to explain calorie deficit

We propose:

- That the calorie deficit in astronauts is due to insufficient food intake
- Since chemosensors play a key role in the control of food intake, changes to the odor and/or taste of a food may affect its intake
- Changes to taste and flavor of food could be due to chemical and physical changes in the food itself or due to changes caused by the spacecraft environment
- The areas chosen for a more detailed review include the link between flavor and food intake (Section 3), shelf life (Section 4), nasal congestion (Section 5), water quality (Section 6), air quality (Section 7) and noise (Section 8)

3. EVIDENCE THAT FOOD FLAVOR AFFECTS FOOD INTAKE

A literature search on the relationship between food flavor and food intake was carried out to discover if some basic principles could be identified. A 1986 experiment (Bobroff & Kissileff, 1986) deliberately changed the acceptability of a standard food by adding different levels of a non-congruent flavor (cumin). This experimental approach meant that although palatability did change, the nutrient composition of the meal did not change and this removed a potential confounding factor through the experimental design. Initially, the assessors scored the test drink for its palatability and then were fed the drink under controlled conditions, which included a standardized breakfast and a standard timing between breakfast and the sample. Figure 5 shows a clear increase in food intake with increased palatability for the majority of the assessors.

Figure 5 hereabouts

Surprisingly, the citations of this paper over the last 33 years do not include many follow-up experiments but one example is from Helleman and Tuorila (1991) who used rye bread

sandwiches as their food sample, with the addition of salt and acidity (regarded as negative tastes in this context) to change the overall flavor. The panel (n=27) initially evaluated the sensory properties of the samples using a “taste and spit” protocol and, in a separate session, were given the sandwiches to eat so that consumption (amount eaten) could be measured. Figure 6 shows the plot of amount eaten (x-axis, slices of bread) and the pleasantness ratings (y-axis). A strong relationship ($r= 0.82$) between pleasantness and the amount eaten was observed (Fig. 6).

Figure 6 hereabouts

In military situations, the effect of food acceptance and food intake has been studied in the laboratory and in the field. An early publication (Siegel & Pilgrim, 1958) described the rejection of military rations by soldiers in the field and attributed the rejection to monotony. To test this hypothesis, and to quantify the effect on food intake, 79 students were subjected to a strict meal regime for 22 days. At each meal, food intake and the liking of each meal was recorded for each student. The study showed that, after 18 days, the average decrease in food intake across all ten food items was 30% and that liking scores had also decreased. This represents a significant under-supply of calories and shows that variety in food types and food flavors is needed to maintain a healthy diet under these strictly controlled conditions.

Large-scale military trials (n=100-200) to study the palatability and consumption of field rations involved a very wide range of foods (Barrett & Cardello, 2012; de Graaf et al., 2005; Friedl & Hoyt, 1997; Hirsch, Kramer & Meiselman, 2005). de Graaf et al. (2005) gave standard military rations of different types to several hundred military personnel using a complex protocol involving some choice of food, combined with measurement of acceptability and food intake. The results revealed that the relationship between acceptability and food intake

was significant, although there appeared to be some other individual social factors (like the need to “eat the plate clean”) that influenced food choice and intake.

The acceptability and food intake of ready-to-eat (RTE) military rations was compared with freshly-prepared foods over a 42-day period (Hirsch et al., 2005). The two diets were isocaloric and contained the same macronutrient composition; both had a 12-day cycle of different dishes (similar to the menu rotation on the ISS). Calorie intake for the RTE group was lower at the start of the trial and continued to decrease with time whereas the group with freshly-prepared meals did not show a significant difference in calorie intake during the trial. This decrease in calorie intake was accompanied by a significant decrease in body weight, which was around 5% loss after 34 days for the RTE group and only 2% for the control group over the same period.

Trials with the general population to study the link between food sensory properties and food intake have also been carried out (Forde, 2018; Sorensen, Moller, Flint, Martens & Raben, 2003; Yeomans, 1998; Yeomans et al., 2005; Yin, Hewson, Linforth, Taylor & Fisk, 2017; Zandstra, De Graaf, Mela & Van Staveren, 2000). There is a general trend of food acceptability driving intake although, as in the military studies, other factors seem to be involved. The other research area that provides information on food intake and its sensory properties is in elderly people (Hays & Roberts, 2006; Rolls, 1999) where it is well-established that flavor sensitivity decreases with age and food intake can also decrease significantly unless food flavor is enhanced (Pouyet, Cuvelier, Benattar & Giboreau, 2015; Schiffman & Warwick, 1993).

3.1 Summary:- Flavor and food intake

- The conclusion from the review of the published information is that food acceptability is a key driver of food intake.

- Acceptability includes many different factors including flavor, the way food is presented, the eating location (ambience) or the sociability of the eating experience.
- Comparing the situation in spaceflight with the published information described above, the conclusion is that the reduced food intake in space is not an unusual experience and is highly likely to be associated with factors like food flavor, menu monotony, food presentation and the spacecraft environment.

4. PREPARATION AND SHELF LIFE OF SPACE FOOD

The development of space foods is subject to several constraints that must be addressed to deliver a successful product and a clear process has been established through the Human Integration Design Process (NASA, 2014). Food on the ISS is packaged in aluminum laminate bags or in cans and a typical “dining table” for the crew is shown in Figure 7. The diet consists of a mix of mainly dehydrated food with some semi-moist items like tortillas and pouches or small cans containing fully-hydrated meals (Figure 8). Some fresh fruit is provided via the regular, resupply visits to the ISS. To save weight and to prevent food particles from floating around the ISS cabin, the food packaging also acts as the dish from which the food or drink is consumed. In Figure 7, drinks such as coffee can be seen in laminate pouches with a drinking straw attached. Dehydrated foods are rehydrated with recycled water from the rehydration station (Figure 9). Cans and pouches containing hydrated meals are heated by contact with hot elements resulting in a 10-20 min re-heat time.

Figures 7, 8 and 9 hereabouts.

Besides the obvious goal of providing complete nutrition to astronauts, other factors such as shelf-life, the food format (dehydrated, thermally-stabilized etc.), the weight and the acceptability to astronauts must also be taken into account (Cooper et al., 2011). Choice of

450 packaging for the foods is also subject to a different set of criteria, such as weight, oxygen
451 and moisture permeability, and tear and abrasion resistance (Jiang et al., 2019).

452 With over 20-years' experience in providing food for space missions, many of the challenges
453 have been overcome (NASA, 2014; Perchonok & Bourland, 2002) but the longer-term Mars
454 missions present new challenges, such as the need to carry food for the whole mission (with
455 no resupply) as well as maintaining food so it is edible for 3-5 years. As outlined in Section
456 2.5.8, the nutritional and sensory properties of space foods have been studied to monitor
457 changes over time and to determine shelf life (Calligaris, Manzoco & Lagazio, 2012; Song et
458 al., 2012). One pertinent question arising was whether shelf life of foods was affected by
459 space conditions and whether Earth-based, shelf-life studies could be used to provide
460 relevant data. A comparison of nutrient degradation in samples carried on spaceflights and
461 stored on Earth for the same duration showed no significant differences (Dong, Chen & Lin,
462 2018; Zwart, Kloeris, Perchonok, Braby & Smith, 2009), suggesting that Earth-based studies
463 are relevant and valid.

464 Since the processing of space food controls microbial spoilage, shelf life is determined either
465 by the rate of chemical reactions like oxidation and the Maillard reaction, and/or by physical
466 changes such as moisture migration, starch retrogradation or phase separation (Singh &
467 Cadwallader, 2002). These chemical and physical changes alter the sensory properties of
468 space foods as well as impacting key nutrients. Although macronutrients are not significantly
469 affected during shelf-life studies, vitamin losses are significant and these sensory and
470 nutritional changes are the factors limiting shelf life of space foods (Catauro & Perchonok,
471 2012). A systematic study of 18 space foods used accelerated shelf life testing to measure
472 how long each food remained acceptable and to identify the factors that defined shelf life
473 (Catauro & Perchonok, 2012). Color, flavor and texture changes were responsible for

determining the point at which the majority of foods were no longer acceptable; the Maillard reaction and oxidation were proposed as likely mechanisms (Catauro & Perchonok, 2012). Controlling these two reactions to reduce their impact and increase shelf life is extremely difficult. The Maillard reaction can occur between the amino groups of amino acids, peptides and proteins and a carbonyl group from sugars or flavor compounds, and controlling the reaction in these naturally-occurring food compounds is not easy (Lund & Ray, 2017). In a similar way, oxidation, especially of lipids, is difficult to control in space foods, as the free radical mechanism that produces rancid-tasting compounds needs very low levels of oxygen and can be catalyzed by trace amounts of lipoxygenase, heme, iron or copper ions (Jacobsen, 1999). Lipid oxidation is also favored by the high porosity of dehydrated food products coupled with the fact that the moisture content of these foods is below the so-called 'monolayer' that accelerates the reaction (Bell, 2007). Therefore, oxygen-impermeable packaging plus other systems to prevent oxidation, like the addition of antioxidants or vacuum packing, are commonly used to ensure adequate protection during storage. It has been suggested that alternative food processing methods, such as 3D printing, irradiation, high pressure processing or microwave sterilization might decrease the rate of these chemical changes and therefore increase shelf-life (Jiang et al., 2019).

Vitamin stability has been studied in some detail. A 3-year shelf-life study of granola bars designed for space-use showed that vitamins A, B1, B9, C, and E were retained at 70% to 95% levels for 3 years at 21°C (Barrett et al., 2018). The sensory properties of the bars decreased at higher storage temperatures (38°C) after 1 and 3 years storage (Barrett et al., 2018). A study into the stability of micronutrients in 109 different space foods demonstrated that vitamins B1 and C were the most labile vitamins (Cooper et al., 2017). By doubling the usual vitamin contents, the nutritional value of most products was largely maintained (Barrett et

al., 2018). The use of microgels to protect vitamins during space flight has also been proposed (Schroeder, 2018).

An alternative approach to food supply is to develop a biogenerative system to supply fresh food and recycle resources during long-term missions when resupply is not possible (Perchonok et al., 2012). For this reason, studies involving Space Agencies from the USA, Europe, Russia, Japan and Canada are assessing the feasibility of closed artificial ecosystems, that could be used in-flight as well as at stations on the Moon and Mars (Massa, Fritsche & Wheeler, 2019). Systems typically use recovery of waste (Morozov, Trifonov, Ushakova, Anishchenko & Tikhomirov, 2018) to provide nutrients for hydroponic-like cultures to produce fruit and vegetables (Molders et al., 2012) that could potentially cover 60% of the astronauts' food needs. While the advantage of fresh, tasty, colorful and textured food on astronauts' engagement with food is clear, the consequences of some malfunction in the system is obviously a very serious concern (see Douglas, Zwart & Smith, 2020, for a recent review).

4.1 Summary:- Preparation and shelf life of space food

- Slow chemical changes that cause changes to vitamins, color, flavor and texture of space foods are the mechanisms that determine shelf life.
- Controlling these reactions is difficult due to the reagents being essential food components, the nature of some space foods (e.g. dehydrated foods) and the very low levels of reactants like oxygen that can activate lipid oxidation.
- To try and overcome some of these challenges, new food processing methods have been proposed as has the production of food during spaceflight.

- Currently, the provision of food with the necessary shelf life, nutritional and flavor properties for long-term missions requires further work to find a solution that guarantees success.

5. NASAL PHYSIOLOGY AND ODOR PERCEPTION

5.1 Odor physiology

Consumers often talk about the “taste” of a food, rather than its “flavor”, but from a physiological viewpoint, taste specifically relates to the sensations (salt, sweet, sour, bitter, umami) perceived through the receptors on the tongue. In fact, when eating food, odor is a key part of the perceived flavor of the food, contributing around 75-95% of the overall perceived flavor (Spence, 2015a). The Jelly Bean test where participants are challenged to identify the flavor of different jelly beans while wearing a nose clip is a good illustration of this concept (Yuhas, 2012). Odorants are released from food to give the characteristic smell and, before eating, the odorants pass through the nostrils (the orthonasal route) to the odor receptors at the olfactory cleft at the top of the nasal cavity. During eating, odorants pass backwards through the throat and then out through the nostrils (the retronasal route) (Bojanowski & Hummel, 2012; Brillat-Savarin, 1826; Buettner & Beauchamp, 2010). Therefore, wearing a nose clip greatly reduces access of odorants to the odor receptors in the nose. The physiological state of the small passages in the nostrils can significantly affect the flow of air (and therefore odor perception), so, for instance, a head cold often results in people complaining that they cannot “taste” (or smell) anything (Brillat-Savarin, 1826). The microgravity in space causes a similar effect due to redistribution of fluids in the body (Norberg, 2013). Since the olfactory cleft is about 1.5 mm wide, any nasal congestion may close this vital entrance to the olfactory receptors and affect the olfactory signal (Lang, 1989).

545 From clinical studies, it is known that nasal anatomy affects odor perception (Hummel et al.,
546 2017). When conditions like septal deviation are surgically corrected in patients with a low
547 olfactory sensitivity, surgery produces a change in nasal respiratory airflow (Courtiss &
548 Goldwyn, 1983), which also seems to be beneficial to the patients' olfactory abilities (Damm
549 et al., 2002). However, this type of nasal surgery may also worsen olfactory function
550 (Kimmelman, 1994; Pade & Hummel, 2008). The reason for this may again depend on changes
551 in airflow. Because only a small percentage of nasally-inhaled air reaches the region where
552 the olfactory receptors are situated (Beauchamp, Scheibe, Hummel & Buettner, 2014), tiny
553 changes in the airflow can have dramatic effects on the number of molecules reaching the
554 receptors (Zhao, Scherer, Hajiloo & Dalton, 2004). These examples indicate that nasal
555 anatomy is crucial for the perception of odors. Coupled to this is the fact that humans show
556 significant variation in their nasal anatomy and therefore the effects on odor perception may
557 differ markedly between astronauts.

558 The overt signs of fluid redistribution in astronauts, like puffiness of the face and obvious
559 nasal blockage, usually disappear after a few days but the knowledge that even tiny changes
560 to the nasal passages can affect odor perception, especially in the region where the odor
561 receptors are situated (Trotier et al., 2007), could compromise odor perception for much
562 longer. Some evidence to support this can be found in bedrest studies where volunteers are
563 placed in a head-down tilt position for several days, which simulates some of the effect of
564 microgravity (Hu et al., 1999; Olabi et al., 2002). However, a study of 14 cosmonauts whose
565 nasal resistance was measured before and after spaceflight using a rhinopneumometer
566 (Yakovleva & Baranova, 1982) showed no significant differences. Although it appears obvious
567 that there should be a correlation between odor concentration/airflow and the intensity of
568 odor perception, several studies have shown this may not always be true and explanations

range from “Perceptual Constancy” (Engen, 1982; Teghtsoonian, Teghtsoonian, Berglund & Berglund, 1978) to mechanisms based on neuroscience principles (Mainland, Lundstrom, Reisert & Lowe, 2014; Shusterman, Sirotin, Smear, Ahmadian & Rinberg, 2018). Whatever the mechanism, the take-home message is that changes in odor perception caused by nasal congestion may be more complicated than originally proposed.

There is some evidence from Earth studies that body position can affect nasal airflow and therefore odor perception (Lundström, Boyle & Jones-Gotman, 2006). The lack of gravity in space removes the concept of up and down for the astronauts with the result that they float in different configurations in the spacecraft. Therefore, the finding from Earth-based studies that body position decreased the ability of participants to identify odors (Mester, Doty, Shapiro & Frye, 1988) and changed their odor threshold values (Lundström et al., 2006) is difficult to apply in this situation as it is impossible to determine whether astronauts are standing up or sitting down. However, some of the potential biological mechanisms that might cause this effect, like intracranial pressure (de Kleine, Wit, Avan & van Dijk, 2001), a change in sniffing behavior (Mester et al., 1988), or a shift in inspiratory/expiratory airflow (Lundström et al., 2006) may still be relevant in the space environment.

5.2 Measurement of odor sensitivity

Some tests on odor sensitivity and odor identification have been carried out during spaceflight using longitudinal-type experiments (testing before, during and after spaceflight) (Olabi et al., 2002). The results are not clear and the small sample numbers involved (typically $n=2$ to 3), plus the lack of information on the testing methods used, makes it difficult to come to any firm conclusions. Experiments using bedrest conditions to simulate microgravity conditions allowed larger numbers of people to participate (up to 53 in one study) and five

out of seven trials showed a decrease in either taste or odor sensitivity (Olabi et al., 2002). Most of the data available on odor sensitivity in spaceflight were obtained in the 1990s and the increased knowledge on sensory methods and the availability of easy-to-use odor samples may allow this topic to be revisited.

Odor sensitivity can be measured using sensory discrimination tests, with odors presented to people via odorous pens known as “Sniffin’ Sticks” (Hummel, Sekinger, Wolf, Pauli & Kobal, 1997; Oleszkiewicz, Schriever, Croy, Hähner & Hummel, 2019) or so-called “scratch & sniff” cards, like the University of Pennsylvania Smell Identification Test (Doty, Shaman, Kimmelman & Dann, 1984). The low weight of these materials might allow tests to be carried out during spaceflight. The methods typically have test-retest reliabilities of 0.7 to 0.9 (Hummel et al., 1997), so can deliver reliable results.

Odor testing can be sub-divided into one of the following domains: testing of odor identification, odor discrimination, odor thresholds, or odor memory. The threshold task has been suggested to reflect more the function of the olfactory periphery, while supra-threshold tests (e.g. discrimination and identification) are more related to cognitive function (Hedner, Larsson, Arnold, Zucco & Hummel, 2010; Lotsch, Reichmann & Hummel, 2008; Whitcroft, Cuevas, Haehner & Hummel, 2017). Although tests for retronasal testing have been established (Croy et al., 2014; Small, 2012), the experimental protocols are more difficult to apply to the space situation due to the specialist equipment needed. Any olfactory tests that are conducted in space are limited to the crew on board at that time, so the number of participants is small, which limits any serious statistical analysis of the data.

5.3 Summary:- Nasal physiology and odor sensitivity

- There is detailed knowledge on the relationship between odor sensitivity and the nasal passage anatomy and physiology.
- It is clear that small changes in nasal airflow can have significant effects on odor perception. What is not so clear is whether nasal blockage in astronauts affects odor sensitivity only in the first few days of acclimatization or whether it has long-lasting effects.
- Experiments to determine changes in astronauts' odor sensitivity during spaceflight have delivered conflicting results, but simulated microgravity experiments using tilted bed rest have suggested that changes do occur.
- Measuring odor thresholds provides basic information on one part of the odor process but there are other ways of odor testing that probe into issues like odor recognition and discrimination, which might be measures that are closer to the flavor perceived when eating real foods.
- Given the restrictions on weight and the limited number of participants available on any one mission, longitudinal experiments with easy-to-use odor samples like Sniffin' Sticks seems to be the best way forward for future experimentation.

6. WATER QUALITY ON THE ISS

6.1 Recycled water – processing and quality monitoring on the ISS

To minimize the transport of water from Earth to the ISS, wastewater is recycled. On the US side of the ISS, water from urine, washing water and water vapor from the air are recycled by a series of procedures (Carter et al., 2008) with 93% of water being recycled (Bai, 2008). On the Russian side of the ISS, only water from the atmosphere is recycled (Atkinson, 2013). While the recycling of water decreases the resupply needs of the ISS, recycling can also

640 concentrate certain chemical compounds in the drinking water that may be detrimental to
641 human health and may impart an undesirable taste or flavor to the drinking water. Given that
642 water is recycled from the atmosphere as well as from liquid wastes, it is no surprise that
643 recycled water contains a wide range of volatile and non-volatile compounds (Carter et al.,
644 2008). Since the quality of recycled water is essential for astronaut safety and well-being,
645 samples are regularly sent from the ISS to Earth for comprehensive chemical analyses to
646 monitor the levels of organic and inorganic contaminants, with the results published (Straub
647 II, Plumlee & Schultz, 2012; Straub II, Plumlee, Schultz & McCoy, 2011; Straub II, Plumlee,
648 Schultz & McCoy, 2012, 2013; Straub II et al., 2017). Separately, a panel of toxicologists have
649 identified which compounds in recycled water are potential toxicants and calculations have
650 been carried out to ensure that there is no risk to astronauts at the regular levels in ISS water
651 (National Research Council, 2000). Given that repair of systems in space cannot always be
652 immediate, the toxicologists further calculated the absolute maximum concentrations of toxic
653 compounds that astronauts could tolerate in normal and emergency situations, which are
654 listed in the Spacecraft Water Exposure Guidelines (SWEG) (Ryder, McCoy, Hayes & Koerner,
655 2017). The SWEG document specifies limits that could be tolerated over a 1-day, 10-day, 100-
656 day or 1000-day timeframe, to cover all eventualities.

657 Reports concerning the hedonic taste quality of water on the ISS are scarce and anecdotal
658 (see for example Bai, 2008; BBC, 2011). In one instance, NASA presented samples of water
659 (that had been recycled on Earth) to journalists for a taste experiment, but the reported
660 descriptions were rather vague such as "Aside from a slight tang of iodine, it tasted like, well,
661 water. I've had tap water that tasted much more like things I don't want to think about" (Bai,
662 2008). In an on-line interview, one astronaut (Paolo Nespoli) was asked about the drinking
663 water quality on the ISS and replied that "it tastes better than that on Earth, despite being

recycled” (BBC, 2011). Informal information obtained during discussions with astronauts by M. Heer (personal communication, April 2020) revealed that while some drink the recycled water directly, others only drink it with fruit cordial added. Whether this is personal preference or to mask the taste of the water is not known. Robust data on recycled water quality (such as data from a trained sensory panel using blind samples and suitable controls) was not found in our literature searches so it is not possible to draw clear-cut conclusions from the limited, anecdotal information that is available.

6.2 Flavor-active compounds and food intake; Earth-based studies

As explained in Section 2.5.3, one potential hypothesis for under-eating is that flavor-active compounds from recycled water could interfere with taste/flavor perception of foods and beverages in space and reduce their appeal and therefore their intake. A survey of the relevant scientific literature suggests the presence of two general mechanisms. One is that low levels of background tastes/odors in the recycled water could create “noise” somewhere in the flavor-signaling pathway and change the perceived flavor of foods, as has been described in published studies (Oleszkiewicz, Rambacher, Whitcroft & Hummel, 2018; Proserpio, de Graaf, Laureati, Pagliarini & Boesveldt, 2017). Another phenomenon is that a background aversive taste may not be consciously detected, but can nevertheless lead to a decrease in food intake in some situations (Wang, Liszt & Depoortere, 2020).

Evidence for low levels of background taste or odors interfering with the perception of an odor or taste is limited and most published data used model systems that do not easily translate to real foods. For example, the work on how a background odor could affect the sensitivity to a second odor (Oleszkiewicz et al., 2018) was limited to a pair of odorants, presented to human panelists via the orthonasal route (i.e. sniffing through the nostrils). In

688 the real world, however, multiple background odors may be present and odor perception
689 during eating occurs via the ortho- and retro-nasal routes (Linforth, Martin, Carey, Davidson
690 & Taylor, 2002). During eating and drinking, the actions of chewing and swallowing carry
691 odors to the throat and, when air is exhaled, the odorants are carried via the nasopharynx to
692 the olfactory epithelium and then leave the body through the nostrils. Studying odor
693 interactions with multiple odorants, and with perception occurring through ortho- and retro-
694 nasal introduction of odorants, makes experimentation complex and it is difficult to make any
695 real progress in understanding the effect of background odors on flavor perception. However,
696 there is evidence that low levels of some flavor compounds do influence flavor perception
697 and some studies have examined the concept of “additivity”, usually between a tastant and
698 an odorant (Marks, Veldhuizen, Shepard & Shavit, 2012). Additivity is defined as the situation
699 when two flavor compounds are not detected at levels below their taste or odor thresholds
700 when presented alone (Young, Horth, Crane, Ogden & Arnott, 1996), but are detected when
701 presented together (Dalton, Doolittle, Nagata & Breslin, 2000; Delwiche & Heffelfinger, 2005;
702 Labbe, Rytz, Morgenegg, Ali & Martin, 2007; Miyazawa, Gallagher, Preti & Wise, 2008;
703 Murphy & Cain, 1980; Oleszkiewicz et al., 2018; Pfeiffer, Hollowood, Hort & Taylor, 2005). The
704 number and scope of publications supporting the additivity principle does suggest that sub-
705 threshold levels of background odors or tastes could affect flavor perception in space.

706 In contrast to the effects of background tastes/flavors on food intake, aversive tastes,
707 especially bitterness, have been studied in more detail. A recent review (Wang et al., 2020)
708 highlighted that bitter receptors are located in oral and intestinal tissues and are in close
709 contact with parts of the food intake control system (Wang et al., 2020). Some studies indicate
710 that bitter compounds can affect specific parts of the food-intake control mechanism (e.g.
711 changes in hormone levels or gut motility (Avau et al., 2015; Bitarafan et al., 2020)), whereas

other studies have focused on the overall effect of bitter compounds on food intake compared to a control diet (Andreozzi et al., 2015; Mennella et al., 2016; Walker et al., 2019).

6.3 Presence of off-flavors in recycled water; space-based data

Although astronauts have delivered no specific information about off-tastes in recycled water on the ISS, the SWEG documentation (Ryder et al., 2017) designates some compounds as RWC, which stands for Reduced Water Consumption. RWC denotes that certain compounds are taste-active at high levels and may decrease the amount of water an astronaut will drink, presumably because of the associated unpalatable taste/flavor. Table 2 lists the RWC compounds, along with information on their sensory properties, all of which are related with odors that are aversive.

Table 2 hereabouts

Little information was found in the literature on RWC definitions or testing, so we used the taste activity concept (Hofmann, Ottinger & Frank, 2004) to assess whether these compounds could be detected at the levels found in the recycled water consumed by astronauts. The taste activity concept is to divide the actual concentration of a compound in water by its taste threshold to produce a “Dose over Threshold” (DoT) value. Values below 1 indicate that the concentration is sub-threshold and therefore not detectable, whereas values greater than 1 indicate that the compound can be detected. This is a rather crude way of assessing the contribution of a compound to the taste/flavor of a sample and the previous discussion about how sub-threshold levels can activate other tastes/flavors should be borne in mind as well as the variation in taste/olfactory thresholds between individuals (Devos et al., 1990). The fact that the published threshold values are measured in pure water or clean air and will differ in

foods, depending on their composition, is another weakness of this approach. However, with limited methods to assess these RWC compounds, DoT values were calculated. Data is available on the chemical composition of recycled water from many missions and from different points in the water-recycling system (Straub II, Plumlee & Schultz, 2012; Straub II et al., 2011; Straub II, Plumlee, Schultz, et al., 2012; Straub II et al., 2013; Straub II et al., 2017). From the analytical datasets, the highest and lowest values were taken and DoT values were calculated for the RWC compounds along with 2-mercaptobenzothiazole, a compound known to have a strong odor and bitter taste that is likely present in the ISS as it is a common constituent of gaskets and seals used in pipework (Nielsen, 2014). Odor threshold values were taken from a study on the effect of contaminants on drinking water quality and were defined as the concentration of the contaminant in water that gave a detectable odor signal in the headspace above the water, i.e. the orthonasal detection threshold (Amoore & Hautala, 1983). Table 3 shows that none of the RWC compounds, apart from trimethylamine (TMA), had a DoT value greater than 1, which indicates that only this compound could individually contribute an off flavor (fishy) in recycled water.

Table 3 hereabouts

Since DoT is a crude measure of taste-/odor-/flavor-activity, an alternative method was used to assess whether TMA could realistically cause an off-taste in recycled water. The US Environmental Protection Agency (EPA) has published detailed assessments of many odor-active compounds and determined a factor they call the “Limit of Awareness” (LOA), which is related to orthonasal perception (Environmental Protection Agency, 2008). The LOA values are more useful in estimating the sensory impact of compounds in a human population, as LOA is defined as the air concentration of a compound at which half the population will experience a distinct odor intensity with about 10% of the population experiencing a strong

odor intensity. Because LOA and odor threshold values are quoted in different ways, conversion is necessary (a 1 ppb LOA value corresponds to 1 nL of odor in 1 L air, whereas a 1 ppb odor threshold value, as quoted in Table 3, corresponds to 1 µg of odor compound in 1 L of water). The LOA value of TMA is 0.51 ppb (Environmental Protection Agency, 2008) while the highest level of TMA in recycled space water was 125 ppb (Straub II et al., 2013). The relationship between the LOA and odor threshold values (Table 3) is the partition coefficient, which for TMA is 1.04×10^{-4} (Environmental Protection Agency, 2020), so a concentration of 125 ppb would produce a maximum concentration of $125 \times 1.04 \times 10^{-4}$ ppb or 0.013 ppb in the air. This is well below the LOA of 0.51 ppb, so most astronauts will not detect TMA at this concentration.

6.4 Summary:- Water quality and potential effects on food intake

- Analyses by NASA have proved that recycled water from the ISS has a consistent chemical composition.
- No systematic sensory analyses on the taste/odor/flavor of recycled water could be found and the few anecdotal reports do not mention off flavor.
- Given the Earth-based literature, there is some evidence that aversive sensations such as bitter taste can affect food intake, but the research on how low-level tastes and odors can affect food flavor is at an early stage and it is not possible to evaluate this concept adequately.
- Using the DoT concept, the RWC compounds listed in the SWEG document were present at sub-threshold levels in all the recycled water samples analyzed, apart from trimethylamine, which has an extremely low odor threshold. However, applying the

782 LOA concept showed that trimethylamine was very unlikely to affect food flavor unless
783 it interacts with other compounds in the recycled water or in the food itself.

- 784 • The current state of knowledge suggests that recycled water on the ISS is unlikely to
785 cause significant changes to food flavor (and therefore to food intake) and is not rated
786 as a significant source of under-eating during spaceflight. However, it is evident that
787 the effect of background odors and tastes is not well-documented and further
788 research is needed to clarify the situation, not only in space, but also on Earth, where
789 control of over-eating is the main focus.

790

791

7. AIR QUALITY ON THE ISS

7.1 Spacecraft air quality

Terrestrial indoor air quality has been the subject of intense research over the past half a century (Weschler, 2009). Given that people increasingly spend more time indoors than out, both vocationally and domestically, contaminants in the indoor air environment can have negative implications for human health. Extending this issue beyond the Earth's atmosphere, astronauts are in an enclosed environment for the entire duration of their mission; maintaining 'spacecraft indoor air quality' is therefore imperative in order to limit exposure to potentially hazardous compounds and to maintain wellbeing.

Due to various logistical and practical limitations, spacecraft air is recycled to maintain its quality. On the ISS, the Environmental Control and Life Support System (ECLSS) maintains suitable ambient air conditions, a process referred to as atmospheric revitalisation, supply and control (National Research Council, 2008). In relation to air quality, the ECLSS has four key tasks, namely to i) provide oxygen, ii) control the levels of carbon dioxide and volatile organic compounds, iii) filter particulate matter and microorganisms, and iv) monitor and control cabin air partial pressure (National Aeronautics and Space Administration, 2008). The focus of this Section is on aspects related to ii), i.e. the presence (and removal) of carbon dioxide (CO₂) and volatile organic compounds (VOCs) from the cabin air. Specifically, the hypothesis that ambient gas-phase concentrations of CO₂ and VOCs to which the crew are continually exposed might affect flavor perception through interaction and influence on taste and olfaction is explored. No consideration is given to other (terrestrial) health implications of indoor air quality.

7.2 Ambient carbon dioxide on board the ISS

Carbon dioxide is a by-product of human metabolism, making up ~5% of exhaled breath gas (Comroe, 1974). Assuming a crew of six astronauts breathing at 15 breaths per min with a tidal volume of 500 mL, this equates to ~6 kg CO₂ output per 24 h; this estimate does not take into account physical activities relating to work or exercise, which increases the breathing rate, so actual cumulative output levels are likely to be higher. Since high levels of CO₂ can cause headaches (Law et al., 2014) and mental slowness (Burlingame, 2016), removal of CO₂ from the cabin atmosphere is crucial for crew health. The ECLSS removes some CO₂, but achieving Earth levels would require significant resource, so the ISS levels are typically between 0.4% (Stenger et al., 2017), which is around an order of magnitude higher than the levels on Earth (0.04%). Although continuous exposure of astronauts to these elevated levels poses no apparent negative health effects, they might affect olfactory and/or taste receptors, and thereby play a role in changing the flavor perception of food in space conditions, as is explored in the following Sections. An overview of the literature from Earth-based experiments shows that CO₂ could interact with flavour perception in its gaseous form as well as in solution (Scott, 2011) and these two types of interaction are discussed in more detail in the following Sections.

7.3 Gaseous carbon dioxide and its effect on humans

Some organisms are able to detect gaseous CO₂ via their olfactory system; for example, bees monitor and control the CO₂ levels in their hives (Ohashi, Okada, Kimura & Ikeno, 2009), and other species use CO₂ to locate food (Jones, 2013). However, humans only detect sensations elicited by gaseous CO₂ at high levels (around 30%), depending on stimulus duration (Shusterman & Avila, 2003). Experiments on nasal irritation caused by administration of CO₂ gas to a human sensory panel (Wise, Wysocki & Radil, 2003) determined the threshold for the

panel, suggesting that 35% CO₂ was the minimum level at which clear nasal irritation was reported, while 70% CO₂ caused pain. Lower levels (around 5%) are known to cause discomfort to humans and NASA has introduced a training program to make astronauts aware of the responses to high CO₂ (e.g. headache, dizziness) and its effect on individual astronauts (Law et al., 2017). Because CO₂ levels during spaceflight are around 0.4%, a series of studies were reported in 1998 on the effects of “Moderately elevated ambient carbon dioxide levels on human physiology and performance” (Frey, Sulzman, Oser & Ruyters, 1998). Levels of 0.7 and 1% CO₂ were used to study the effects on bone loss, sleep, mental and cardiac performance. Elevated CO₂ levels had significant effects on mental performance, calcium loss and cerebral blood flow (Frey et al., 1998). At the levels typically found in the ISS (0.2 to 0.4%), gaseous CO₂ does not appear to be directly involved in flavor perception, but its transformation into carbonic acid in aqueous media is the key mechanism, as shown in Figure 10A and discussed in the next Section.

Figure 10 hereabouts

7.4 Role of carbonic anhydrases in flavor perception

Carbonic anhydrases (CA) reversibly catalyze the conversion of gaseous CO₂ into bicarbonate ions and free protons (Figure 10B). The general role of CAs in the human body is to maintain acid-base balance and aid transportation of CO₂ (Supuran, 2018). CAs are expressed in many tissues and fluids, and are important for many physiological processes (Lindskog, 1997). For taste perception, two isoforms are relevant; CA VI is found in bodily fluids, while CA IV is located in membranes in close proximity to sour taste cells (Bryant, 2000). In saliva, CA VI is present at high levels (up to 47.0 ± 39.2 mg/L) and is one of the major salivary proteins, comprising 3% of total proteins (Bryant, 2000). Although the physiological function of CA VI

in saliva is not established, the suggestion is that it maintains oral homeostasis by enhancing its buffering capacity (Bryant, 2000).

Numerous studies provide evidence that CA VI is important in taste perception. Sensitivity to the bitterness caused by 6-n-propylthiouracil (PROP) is known to be associated with polymorphism in the bitter taste receptor gene TAS2R38 (Bufe et al., 2005). Animal studies conducted with a knockout mouse model confirmed that CA VI is involved in bitter taste perception (Patrikainen, Pan, Kuleshkaya, Voikar & Parkkila, 2014). A study has also shown that variation within the CA VI gene may be responsible for differences in salt perception in the absence of differences in fungiform papilla number (Feeney & Hayes, 2014).

In contrast, the membrane-bound CA IV is expressed in sour-sensing cells. Using engineered mice lacking the gene coding for CA IV, Chandrashekar et al. (2009) found that the neural response to CO₂ was totally inhibited and concluded that CA IV was the primary molecular sensor for CO₂. The free protons created by CA IV probably stimulate the sour-sensing cells, similarly to free protons created by acidic food or beverages (Figure 10C).

In humans, drugs used clinically to inhibit CAs also alter taste. Administration of a low-dose of acetazolamide eliminated the sparkling taste of beverages and promoted decreased consumption of carbonated drinks and therefore weight loss (Munoz, Lamm, Poppers & Lamm, 2018). Acetazolamide is also used by mountain climbers to combat altitude sickness but it affects flavor perception, notably of the beer or champagne consumed to celebrate reaching the summit with the result that it tastes “like dishwater”; this phenomenon has been appropriately termed ‘*the champagne blues*’ (Graber & Kelleher, 1988).

7.5 Effect of carbon dioxide on overall flavor perception

886 Flavor perception and flavor quality of a food requires the activation of specific chemosensory
887 receptors to create the neural signature of that food in the consumer's brain, so the food can
888 be recognized and its quality evaluated: for example, in the case of a banana, is it under- or
889 over-ripe? If the conditions in which food is eaten cause stimulation of other receptors, then
890 the neural signal can change, leading to a downgrade in the perceived flavor quality.
891 Therefore, if CO₂ activated receptors directly (rather than via carbonic anhydrase) it could
892 indirectly affect the perceived flavor of foods eaten during space flight. In humans, CO₂ has
893 been reported to activate the trigeminal receptor TRPA1, which is also activated by chemicals
894 such as allyl isothiocyanate (found in mustard oil and wasabi), allicin (garlic) and
895 cinnamaldehyde (cinnamon oil) (Jordt et al., 2004). The TRPA1 channel also detects CO₂ at
896 high concentrations (Wang et al., 2020) when CO₂ diffuses into cells across cell membranes
897 and generates intracellular acidification causing TRPA1 activation. Similarly, TRPA1 has been
898 shown to be sensitive to organic (weak) acids (Wang et al., 2020).

899 It should be noted that the published examples of CO₂ affecting taste/flavor perception all
900 come from research on carbonated beverages. Effects such as a decrease in sweetness
901 perception (Coward, 1998; Di Salle et al., 2013; Hewson, Hollowood, Chandra & Hort, 2009),
902 enhancement of sourness, (Le Calve, Goichon & Cayeux, 2010) and a bitter aftertaste
903 (Hewson et al., 2009) have been reported. Some publications report that consuming a
904 carbonated beverage compared to a non-carbonated beverage before a meal can decrease
905 food intake therefore suggesting that CO₂ is the factor responsible (Suzuki, Mura, Taniguchi,
906 Moritani & Nagai, 2017) and the role of CO₂ in regulating gut hormones such as the glucagon-
907 like peptide (GLP-1) in the duodenum has also been reported (Akiba & Kaunitz, 2014).
908 Although these are interesting findings, the level of atmospheric CO₂ in space flight is around
909 0.4% whereas the CO₂ levels delivered to the nose when carbonated beverages are consumed

are probably much higher. No information on nasal or bodily CO₂ levels after drinking carbonated beverages was found in the literature, but 1 mL of these beverages typically contains 1.5 to 3.5 mL CO₂ in the form of free gas, dissolved gas and carbonic acid (Abu-Reidah, 2020). Therefore, drinking 20 mL of a beverage could potentially release a maximum of 30 to 70 mL of CO₂, although it is difficult to estimate what CO₂ concentration this would produce in the nasal gas phase of consumers. The information currently available does not provide evidence that the higher levels of CO₂ found in spaceflight could affect food taste/flavor or food intake significantly.

7.6 Volatile organic compounds in the spacecraft ambient environment

Volatile organic compounds (VOCs) are defined as carbon-containing molecules that have a low boiling point and are typically present in the gas-phase under conditions of standard temperature and pressure (Environmental Protection Agency, 2017). On-board the ISS, VOCs are primarily derived from two sources, namely off-gassing from the interior fittings (equipment, panels, cabling and pipework) and metabolic emissions from the astronauts themselves. In relation to the former, the degree of emissions is taken into account in the choice of materials used for equipment and fittings, many of which undergo treatment to reduce off-gassing and decrease the VOC load in the ISS atmosphere. In terms of the human occupants, volatile metabolites are released into the environment via exhaled breath, with emissions from the skin also contributing to the volatile profile (Beauchamp, Davis & Pleil, 2020). The human body emits a great variety of VOCs, as summarized in a comprehensive review of the literature, which reported 1840 individual compounds from breath and other bodily fluids (de Lacy Costello et al., 2014).

Removal of VOCs on board the ISS is carried out by the ECLSS, which contains an active trace contaminant control subassembly (TCCS) unit that comprises an activated carbon filter bed and a thermal catalytic oxidation reactor; an equivalent but functionally variant Russian micro-purification unit – referred to as BMP – for removal of trace constituent is located in the Russian segment of the ISS (Perry & Kayatin, 2016). Removal efficiencies are generally high but compound dependent, and are broadly in the range 70-100% (Perry & Kayatin, 2016). It is pertinent to note here that, as with (legislative) occupational exposure limits (OELs) on Earth, guidelines for concentration limits exist for spacecraft in the form of the Spacecraft Maximum Allowable Concentrations (SMACs) (National Research Council, 2008). Real-time analyses of VOCs on board the ISS are in place to monitor concentrations of key constituents. The air quality monitor (AQM) is an analytical system based on gas chromatography-differential mobility spectrometry (GC-DMS) that was installed on the ISS experimentally in 2009 and has been operational since, replacing the previous volatile organic analyzer (VOA) that was in use from 2001 to 2009 (Limero, Reese, Wallace, Cheng & Trowbridge, 2012). Further, the composition of ambient air on the ISS is routinely sampled and returned to Earth for laboratory analyses, typically via gas chromatography-mass spectrometry (GC-MS) (Limero & Wallace, 2017). Such analyses show the overall composition of gas-phase compounds (Figure 11), with methane being the largest contributor (making up 63%) and the group of non-methane hydrocarbons (NMHCs) second (22%) (Macatangay & Bruce, 2010). Within the NMHCs, alcohols contribute 76%, aldehydes, ketones and halocarbons each account for 6%, and the remaining trace compounds comprise aromatics and esters, making up 4% and 2%, respectively.

Figure 11 hereabouts

956 To assess the potential for these VOCs to affect the crew's flavor perception, we consider
957 their odor thresholds in relation to their ambient ISS air concentrations. In order to assess
958 which VOCs might be odor-active (Czerny et al., 2008), the identity and concentrations of
959 individual VOCs in Figure 11 can be compared against published odor threshold data using
960 the DoT concept outlined in the previous Section (i.e. concentration of odor in air divided by
961 odor threshold concentration). Concentration ranges reported are: 0.006-0.176 ppm for
962 aldehydes (from heptanal to acetaldehyde), 0.058-2.15 ppm for alcohols (n-butanol to
963 ethanol), 0.012-0.134 ppb for ketones (cyclohexanone to acetone), and 0.008-0.025 ppm for
964 aromatics (benzene to *o*-xylene) (Macatangay & Bruce, 2010). These ranges derive from
965 successive archival sampling over an 11-year period (1998-2009), with Earth-based GC-MS
966 analyses, as mentioned above. Most of these compounds are at levels below the mean odor
967 thresholds of humans (Nagata, 2003), thus the crew are unlikely to perceive them, with the
968 notable exception of the aldehydes, as well as n-butanol. Calculating the DoT values based on
969 the reported concentrations (Macatangay & Bruce, 2010) and their associated odor
970 thresholds (as reported in Nagata, 2003), the DoTs range from 2 for acrolein to 117 for
971 acetaldehyde (spanning propanal, butanal, pentanal, hexanal and heptanal); by comparison,
972 the derived DoT value for n-butanol is 1.5, i.e. with a concentration only slightly above the
973 odor threshold. In this context, two important aspects should be noted, first that odor
974 threshold values reported in the literature vary widely (see for example Leonardos, Kendall &
975 Barnard, 1969, with higher values than Nagata, 1990) whereby taking alternative literature
976 values delivers DoT values below 1; and second, odor thresholds are not equivalent to
977 perception thresholds, i.e. the threshold at which an odor can be perceived (identified), which
978 can be several factors higher. Nevertheless, based on these calculated DoT values derived

979 from the data available, it can be concluded that a background odor is present on-board the
980 ISS and potentially detectable by astronauts.

981 No systematic study on the odor on the ISS could be found in the scientific literature, but
982 anecdotal evidence indicates that the astronauts are aware of, and perceive, some sort of
983 odor; an account by veteran astronaut Scott Kelly described the odor of ISS as being a
984 “combination of antiseptic, garbage, and body odor” (Stockton, 2017). Both astronauts and
985 cosmonauts have used subjective terms like “gunpowder, hot metal, welding” to describe the
986 odor (New York Hall of Science, 2016). These anecdotal accounts do not always make it clear
987 when the odor was assessed; some seem to refer to the “odor of space”, the sensation
988 experienced after a spacewalk, others seem to refer to the general ISS odor. Perception is
989 subjective, and the exact makeup of the odor background is likely to be transient, yet taken
990 together the evidence suggests that an odor is present on board the ISS. Whether this
991 background odor has the potential to affect overall flavor perception is unclear.

992 In this context, however, the phenomenon of olfactory habituation must be taken into
993 account, whereby the perceived intensity of a specific odor diminishes with exposure
994 duration (Pellegrino, Sinding, de Wijk & Hummel, 2017). Given that astronauts spend most of
995 their time within the ISS (with only occasional exterior excursions in the form of spacewalks),
996 it is reasonable to assume that any constant background odor -elicited by ever-present VOCs
997 in ambient ISS air - is not persistently perceived by the astronauts, thus should not directly
998 affect flavor perception. Nevertheless, even if odor-active compounds that are present – such
999 as the aldehydes reported above – do not cause a conscious response (i.e. a distinctive odor),
1000 they may still interact with olfactory receptor cells to elicit a subconscious response.

1001 Additionally, it is possible that the presence of sub-threshold concentrations of odors may act
1002 on chemoreceptors in an additive or cooperative way to create some sort of ‘accumulative’

odor signal (Dalton et al., 2000). As discussed in the Water Quality Section (Section 5.2), more fundamental research on the effect of habituation and multiple odors/tastes on flavour perception is needed before conclusive explanations can be made.

7.7 Influence of ambient volatiles on flavor perception

The effects of human exposure to VOCs has been studied extensively in the context of health and safety, e.g. in workplaces (Hummel, Guel & Delank, 2004). However, the focus of this review is not long-term adverse health effects from exposure to irritants or carcinogens, rather, the question is whether continual exposure to trace levels of (odor-active) VOCs might influence and impair flavor perception – potentially subconsciously – that might lead to a diminished enjoyment of food, and ultimately be a contributing factor for decreased caloric intake of astronauts over the course of a space mission. Studies on indoor air quality, or food-related aroma perception, might offer some clues – albeit limited – on this hypothesis. It is worthy of note that i) such research necessarily focuses on odor-active compounds, for human sensory assessments, ii) evaluations invariably reflect subjective perception, rather than objective analytical assessments, and iii) participants are often required to evaluate hedonically, i.e. liking/disliking, or acceptable/unacceptable.

Many studies have focused on air quality and the related subjective perception, either odor intensities, hedonics, or discomfort. In one study, perceived air quality was investigated in relation to temperature and humidity. While temperature and humidity did not significantly affect perceived *odor intensity* of air samples, they elicited a strong and significant change in perceived *air quality*, with the air being (subjectively) perceived as less acceptable with increasing temperature and humidity (Fang, Clausen & Fanger, 1998). Odor nuisance has been widely investigated, typically with dose-response gradients of odor annoyance correlating

with exposure level (Atari, Luginaah, Gorey, Xu & Fung, 2013). Although such studies do not directly relate to flavor perception, odor annoyance can elicit negative effects on wellbeing; anecdotally, a 'bad' smell can be off-putting when eating, so it is reasonable to assume that a background odor, if at sufficient concentration and of significant offense, and notwithstanding habituation effects, could influence appetite and food intake.

In tests specifically on human olfactory sensitivity, effects of congruent and incongruent background odors on threshold scores were explored. Using the target odorants phenyl ethanol and linalool, it was observed that congruent background odors (and to a less extent, non-congruent odors) impaired target odor threshold scores to a significant extent (Oleszkiewicz et al., 2018). Exposure time is also an influencing factor on perceived irritation. Cross-modal interactions have also been investigated, for instance when odor affects taste perception, or the taste impression elicited by an odor. The latter phenomenon was studied with regard to sweet or sour taste perception of sucrose and citric acid solution in relation to 20 odors, whereby it was found that some odors enhanced sweetness or sourness, whereas others suppressed these taste impressions (Stevenson, Prescott & Boakes, 1999). The study provided evidence that odor can influence taste impressions, so the possibility of this phenomenon occurring on the ISS in relation to the background odor cannot be ruled out.

7.8 Summary:- Effects of air quality on flavor perception in space

- CO₂ levels in the ISS are 5 to 15x higher than on Earth but below the odor threshold of gaseous CO₂.
- CO₂ is most likely to affect flavor via the action of CA and through the sour taste receptor and the TRPA1 trigeminal receptor.

- 1050 • Flavor perception is affected in the presence of CO₂ but the link between CO₂ levels
1051 and food intake is weak and would need focused experiments to investigate whether
1052 the elevated levels had any impact on the food control mechanisms.
- 1053 • Published data shows that odors can influence (enhance/suppress) flavor perception,
1054 or affect the perceived intensity of odorant mixtures, but there is no direct evidence
1055 that trace concentrations of VOCs in ambient air can affect olfactory acuity, flavor
1056 perception, or appetite, especially if the VOCs in question are predominantly not odor-
1057 active.
- 1058 • The VOCs in the ambient environment of the ISS are below the odor perception
1059 thresholds of humans (Nagata, 2003), with the exception being a series of aldehydes,
1060 with derived DoT values ranging from 2-117.
- 1061 • While sub-threshold effects cannot be ruled out – especially in relation to exposure
1062 duration – the body of evidence suggests that VOCs present in ISS air are unlikely to
1063 affect olfactory perception or be an influencing factor in astronauts' eating behavior.
- 1064 • Humidity on the ISS is controlled to deliver similar levels to those experienced on Earth
1065 and therefore, is not considered to a relevant factor in odor perception.
- 1066 • A final aspect when discussing this subject is that, although air is circulated throughout
1067 the ISS, the assumption that the concentration of VOCs is the same in all locations is
1068 probably not valid. A combination of microgravity (which rules out convection
1069 currents – hot air no longer rises!) – and confined spaces in the ISS means that air
1070 circulation is non-uniform (Matty, 2010), thus there might exist areas of high and low
1071 odor intensity, and the exact odor quality is likely to vary transiently and in different
1072 parts of the ISS.

1073 • Further direct investigations of odor on-board the ISS and the associated VOCs would
1074 be needed to elucidate whether there is any influence of these factors on astronaut
1075 odor perception and food enjoyment.

1076

8. AUDITORY CONTRIBUTIONS TO FLAVOR PERCEPTION IN SPACE

8.1 Perceived flavor modulation through noise

Over the last half-century or so, there has been a steady increase of interest in the provision and perception of food and drink in space. In part, this is a natural consequence of manned missions lasting longer and hence the importance of ensuring adequate nutrition becoming an increasingly salient factor in mission planning (Smith, Rice, Dlouhy & Zwart, 2013). However, beyond the nutritional element, there has also been a growing realization of the important social/psychological role that mealtimes and eating together can play amongst those who may be away from their home environment for long periods of time, see for example, (Belasco, 2006; Boothby, Clark & Bargh, 2014; Bourland & Vogt, 2010; Roach, 2011; Spence & Piqueras-Fiszman, 2014).

While early researchers investigated whether the flavor of space foods could be made a little less unpalatable simply by changing the descriptions/names of the food items themselves (Wolfson & Oshinsky, 1966), recent work has tended to focus more on trying to understand how the conditions experienced by astronauts may influence their multisensory tasting experiences in space (Bayram et al., 2020; Olabi et al., 2002). This part of the review is focused specifically on the role of auditory cues in multisensory flavor perception in space. As previously explained in this review, it is well-known that the human senses can interact to produce the overall flavor perception (the so-called cross-modal effect). Three broad categories of cross-modal auditory influence on taste/flavor perception will be discussed, namely: i) modifying the sounds of mastication; ii) quantifying the influence of background noise on taste/aroma perception; and iii) the potential use of “sonic seasoning” to enhance the experience of eating and drinking in space.

1100 Given that, at least so far as we are aware, no research has yet been conducted on the impact
1101 of sound on taste/flavor perception specifically in space, relevant inferences are drawn
1102 primarily from Earth-based research. At the same time, however, it is important to bear in
1103 mind that there are also some pertinent questions associated with the ethics of conducting
1104 research in space (see Tachibana, 2020). Suggestions are also drawn from the growing body
1105 of research that has addressed the role of atmospheric conditions on the perception of food
1106 in aircraft (see for example Holthuysen, Vrijhof, de Wijk & Kremer, 2016; Spence, 2017d). In
1107 particular, the loud background noise (Ozcan & Nemlioglu, 2006), lack of atmospheric
1108 humidity (Kuehn, Welsch, Zahnert & Hummel, 2008), and reduced air pressure (Bert, 1878;
1109 Burdack-Freitag, Bullinger, Mayer & Breuer, 2011; Maga & Lorenz, 1972) have been studied
1110 and are relevant to the situation in spacecraft, apart from the pressure aspect – the ISS is
1111 pressurized to 1 atmosphere, the same as on Earth. Therefore, studies of food flavor on
1112 aircraft provide an analogous situation from which to develop theories concerning how
1113 auditory cues might interfere with, or potentially enhance the perception of food and drink
1114 in space. That said, we will return later to highlight a number of potentially salient differences
1115 between these two situations (tasting in aircraft versus in space), as well as identifying a
1116 number of key outstanding questions for future researchers to address.

1117

1118 **8.2. Modifying the sounds of oral mastication**

1119 Post-mission interviews with astronauts on some of the longer recent spaceflights have
1120 revealed that one of the most common complaints is the lack of freshness in the food (see
1121 Masters, 2013; Preston, 2015). The notion of freshness is undoubtedly a complex one (see
1122 Roque, Lafraire, Spence & Auvray, 2018, for a review), with the term being used to refer to
1123 many different aspects of food/flavor experiences depending on the food/situation under

1124 consideration (e.g. freshly-grown, freshly-ground, freshly-made, a fresh taste, etc.). There is
1125 a sense in which noisy foods are associated with freshness (Bonnell, 1966; Roque et al., 2018;
1126 Spence, 2017c) and anecdotal evidence suggests this can occur during spaceflight as
1127 described by (Preston, 2015) *“The astronauts complain sometimes... While the food tastes*
1128 *pretty similar to Earth food, they say it lacks a certain crunch”*. As such, there may be
1129 innovative ways in which to augment the food-mastication sounds that are generated when
1130 astronauts eat and drink in space in order to augment the perceived/apparent freshness of
1131 their provisions. Note that a conceptually similar approach has recently been adopted in
1132 Japan in a series of studies using a headset to bring back the sounds of food texture for those
1133 elderly individuals who, for whatever reason, have been moved on to a pureed-meal diet
1134 (Endo, Ino & Fujisaki, 2016, 2017; Fujisaki, 2020).

1135 Relevant here, Zampini and Spence (2004) demonstrated that they could bias participants to
1136 rate potato chips as tasting up to 15% fresher and crisper simply by enhancing, rather than
1137 suppressing, the sound of the participant’s own crunch when first biting into the dry food
1138 with their front teeth (i.e. modifying air-conducted rather than bone-conducted sound). It is
1139 important to note that such cross-modal effects appear to be maximally effective when the
1140 augmented sounds are synchronous with the corresponding eating action (Luckett, Meullenet
1141 & Seo, 2016; Seo & Hummel, 2011). There is also some evidence to suggest that the
1142 experience of eating fresh produce, specifically apples, can be enhanced by augmenting the
1143 sounds of mastication too (Demattè et al., 2014), as can the perception of carbonation in
1144 beverages, at least to a certain limited extent (Roque et al., 2018; Zampini & Spence, 2005).

1145 Going beyond augmenting the sound of the food itself, there are also human-computer
1146 interaction approaches to synchronizing other kinds of sound with eating activities, what the

authors of one project refer to as ‘gustosonic experiences’ (Mathiesen, Byrne & Wang, 2019; Spence, 2020; Wang, Li, Jarvis, Khot & Mueller, 2019; Wang, Jarvis, Khot & Mueller, 2018).

8.3. Background noise and its influence on taste/flavor perception

A large body of Earth-based research has shown that background noise exerts a deleterious effect on taste perception (Spence, 2014; Woods et al., 2011; Yan & Dando, 2015). For instance, in one oft-cited study, Woods et al. (2011) reported that the perception of sweet and salt were rated lower in real foods when loud, background, white noise was presented over headphones at 75-85 dB (see Figure 12A&B). Woods et al. (2011) conducted two laboratory-based experiments designed to assess the impact of presenting loud versus quiet background noise (75–85 dB or 45–55 dB, respectively) over headphones on the perception of the sweetness, sourness, and liking of a variety of foodstuffs. Using a repeated measures experimental design, participants rated potato chips, cheese, biscuits/crackers, and flapjack on a number of Labelled Magnitude Scales (LMS). The 48 participants in Woods et al.’s (2011) first experiment rated salty foods (chips and cheese) as significantly less salty and sweet foods (biscuits and flapjack) as significantly less sweet under conditions of loud background noise (see Figure 12A). By contrast, there was no such effect on the participants’ liking (i.e. hedonic) ratings. These results therefore highlight the significant effect that loud noise can have on the sensory-discriminative aspects of taste perception. It should also be noted that in their second experiment, Woods et al. (2011) also observed a significant increase in the rated crunchiness of various flavoured rice cakes when sampled under the loud background noise conditions, as compared to quiet background noise or the silent baseline condition (see Figure 12B). This intriguing cross-modal effect on texture perception would be worth pursuing should the finding prove replicable.

Figure 12 hereabouts

The apparent ubiquity with which passengers order tomato juice and/or Bloody Mary cocktails during air travel (Jackson, 2014), while typically not doing so on Earth, led Spence, Michel, and Smith (2014) to suggest that umami might be one of the basic tastes that stands up particularly well to the atmospheric conditions; specifically the loud background noise in aircraft (estimated at 80-85 .dB for passengers depending where in the place they happen to be sitting) (Ozcan & Nemlioglu, 2006). Yan and Dando (2015) conducted a laboratory-based study of taste perception for each of the five basic tastes when presented in solution. The participants had to rate the intensity of a range of solutions containing one of the five basic tastes at one of a range of concentrations using a linear scale. The results demonstrated a significant increase in intensity ratings of umami, while at the same time documenting a significant drop in ratings of sweetness intensity when the 48 participants were exposed to 85 dB of airplane noise (see Figure 13). Rating of the intensity of the sour, bitter, and salty solutions were, however, unaffected by the presence of airplane noise (see also Griffiths, 2015).

Figure 13 hereabouts

Background noise has also been shown to impact olfactory judgments in some, but by no means all, studies (Seo, Gudziol, Hähner & Hummel, 2011; Seo, Hähner, Gudziol, Scheibe & Hummel, 2012; Velasco, Balboa, Marmolejo-Ramos & Spence, 2014). Although likely of less relevance to astronauts, it is still perhaps worth noting in passing that loud noise/music has been shown to impair people's ability to discriminate the alcohol content of drinks (Stafford, Agobiani & Fernandes, 2013; Stafford, Fernandes & Agobiani, 2012). Burdack-Freitag et al. (2011) reported higher taste and odor thresholds at low atmospheric pressure and noise compared to subsequently-applied normal pressure. Rahne, Köppke,

1195 Nehring, Plontke, and Fischer (2018) have also recently published research in the area of
1196 background noise. They assessed both taste (gustatory) and orthonasal olfactory detection
1197 thresholds as a function of varying the ambient noise (present vs. absent) and atmosphere
1198 (normal vs. hypobaric). In the case of taste, participants were presented with taste strips
1199 having one of four basic tastes at one of four concentration levels (with blanks too), and had
1200 to discriminate what taste, if any, was present. For hypobaric measurements, the pressure
1201 was set to 800 mbar (6380 ft), similar to the cabin pressure of commercial aircraft. The
1202 background noise level in the chamber in the 'No sound' condition was 59 dB, whereas white
1203 noise was presented over earphones as 70 dB in the noise condition. Sixteen young males
1204 were tested. Perhaps unsurprisingly, olfactory sensitivity for the model odorant (n-butanol)
1205 and gustatory sensitivity were both impaired in the hypobaric atmosphere. Intriguingly,
1206 however, white noise impaired participants' sensitivity for detecting sour and enhanced
1207 sweet taste ratings, while having no effect on the perception of bitter or salty tastants.
1208 Furthermore, Rahne et al. (2018) reported no effects on olfactory detection thresholds. It
1209 should be noted that the n-butanol used in these experiments is not a food odor and these
1210 non-food odors may be perceived differently (Albrecht et al., 2009).

1211 Exposure to sudden loud noises can also be associated with stress (Ferber & Cabanac, 1987;
1212 Kupfermann, 1964; McFadden, Barr & Young, 1971). This, then, might be another route by
1213 which, what we hear, affects what we taste (Spence, 2014). Indeed, stress has been argued
1214 to be one of the factors affecting taste perception amongst airplane passengers (de Syon,
1215 2008; Spence, 2017d). However, the average stress levels on longer-term spaceflights are
1216 unknown.

1217 Given the distracting/masking influence of background noise on taste and smell perception,
1218 it should come as little surprise to find that researchers have suggested that the use of noise-

cancelling headphones might, in fact, help to improve taste/flavor perception in noisy environments such as air travel or spaceflight (Spence et al., 2014). Typical noise levels during air travel are around 80-85 dB, whereas the ISS levels are around 70 dB with peaks of 92 dB (Mallis & DeRoshia, 2005). At the same time, however, it will be important to assess whether taste perception is affected by long-term exposure to background noise (on longer space voyages). While the perception of sweetness has often been demonstrated to be affected by the presence of white noise/airplane noise (Ferber & Cabanac, 1987; Woods et al., 2011; Yan & Dando, 2015) the impact of noise on the perception of the other tastes appears to be a little less consistent when comparing results from different studies. Resolving what is behind such differences will be an important question for future research to try and resolve. One other thing to note here is that results might differ as a function of whether simple basic taste solutions or non-food odors are used, compared to more complex realistic meals (Holthuysen et al., 2016).

8.4. Sensation transference and sonic-seasoning

Beyond dealing with the deleterious effects of background noise on taste and multisensory flavor perception, there might also be an opportunity to enhance the experience of food and drink through the targeted use of music (and soundscapes). This suggestion is built on a large body of research conducted on Earth over the last decade or so demonstrating that music and soundscapes can exert a significant influence over the tasting experience (see Spence, Reinoso-Carvalho, Velasco & Wang, 2019, for a recent review). There are, in fact, multiple routes by which what we hear/listen to can affect how we perceive taste, and how much we enjoy the experience. Perhaps the most fundamental route by which this happens is ‘sensation transference’, such that the more a person likes the music that they happen to be

1243 listening to, the better that person tends to rate food or drink they are tasting, and the more
1244 they enjoy the food experience (Reinoso-Carvalho, Dakduk, Wagemans & Spence, 2019). For
1245 instance, the participants in laboratory research tend to rate food and drink as tasting better
1246 when tasted while listening to matching or preferred music than when tasting in silence
1247 (Spence et al., 2013).

1248 A second route to enhancing the taste of food and drink musically, is through the use of what
1249 has come to be known as ‘sonic seasoning’ (Spence, 2017c). This relates to the recently-
1250 emerging body of empirical research demonstrating that specific taste, texture, and flavor
1251 attributes can be enhanced by playing the corresponding music. So, for example, it is possible
1252 to enhance the perceived sweetness or bitterness in a dish (by about 5-10%) by playing
1253 tinkling, high-pitched music versus low-pitched music instead (Crisinel et al., 2012). Specific
1254 music/soundscapes have now been developed to enhance sourness (Knöferle, Woods,
1255 Käßler & Spence, 2015; Kontukoski et al., 2015), saltiness (Guetta & Loui, 2017), creaminess
1256 (Reinoso Carvalho, Wang, Van Ee, Persoone & Spence, 2017), and spiciness too (Wang, Keller
1257 & Spence, 2017). The use of sonic seasoning would appear to offer an innovative, new, and
1258 promising route to enhance the taste of food in space, and in particular to make up for the
1259 environmental/atmospheric degradation. That said, there has been rather less research thus
1260 far trying to enhance the perception of umami. Though, of course, one might re-describe
1261 white noise/airline engine noise as a kind of sonic seasoning that helps to enhance the umami
1262 taste. Looking to the future, it might be interesting to investigate whether there is a kind of
1263 sonic seasoning that can help to enhance the perceived freshness of food. Certainly, playing
1264 the sounds of nature, as in the Sound of the Sea seafood dish, served at The Fat Duck
1265 restaurant in Bray, UK, has been shown to enhance the taste of seafood (Spence, Shankar &
1266 Blumenthal, 2011; Youssef, Keller & Spence, 2019).

1267

1268 **8.5. Evaluating multisensory taste experiences under realistic space conditions**

1269 In the future, it will be important to try and replicate the particular combination of
1270 environmental conditions found in space rather than studying merely a single cue at a time
1271 (such as the effects of sound, background volatile compounds, or the lack of convective air
1272 currents). This is because it is presumably possible that the various atmospheric conditions
1273 may well operate in an unpredictable manner. Increasing blood flowing to the head under
1274 extended conditions of microgravity also means that astronauts' nasal airways are likely to
1275 exhibit reduced airflow, certainly in the first days of transitioning to the space environment
1276 (Anon., 2012; Philpott, Goodenough, Passant, Robertson & Murty, 2004). What this means,
1277 in practice, is that food will lose much, if not all, of its flavor! Indeed, according to many
1278 researchers, 75-95% of what we think we taste we actually smell (see Spence, 2015a, for a
1279 review). And while one can certainly question the precision of the claim, there is little doubt
1280 that a loss of the olfactory contribution to tasting has serious consequences for individuals on
1281 Earth (Spence, 2015c). One possible solution here might be to investigate the possible effect
1282 of wearing a breathe-right strip to enhance nasal airflow (Raudenbush & Meyer, 2001).
1283 However, sonic interventions are likely to have a more pronounced influence on tasting in the
1284 absence of a strong olfactory component.

1285

1286 **8.6. Summary:- Effect of auditory signals on food acceptability**

- 1287
- 1288 • Flavor perception is undoubtedly one of our most multisensory experiences and is
1289 influenced by a wide range of product-intrinsic and contextual/atmospheric factors
(Spence, 2015c; Spence & Piqueras-Fiszman, 2014).

- 1290 • There has been a recent increase of awareness in the cross-modal influence of noise,
1291 music, and soundscapes on tasting.
- 1292 • While loud background noise has been shown to suppress various aspects of
1293 taste/flavor/aroma perception, the strategic use of particular music or soundscapes
1294 can, and increasingly is, being used to modify both the sensory discriminative and
1295 hedonic aspects of multisensory tasting experiences.
- 1296 • While the majority of research has so far been conducted on the ground, the
1297 implications for tasting in space would appear worthy of further investigation,
1298 especially given early interventions in air travel.
- 1299 • Indeed, while sonic seasoning might sound a little too futuristic it is worth noting that
1300 a more design-led approach to enhancing food and beverage experience in space has
1301 recently started to gain some traction amongst researchers (Obrist, Tu, Yao & Velasco,
1302 2019). What is more, it is worth stressing that there have already been several short-
1303 term marketing-led sonic seasoning interventions for passengers on British Airways
1304 (Skift, 2014; Victor, 2014), and subsequently on Finn Air flights (for example,
1305 <https://www.finnair.com/gb/gb/stevenliu/en>; see also
1306 <https://www.youtube.com/watch?v=gkPyC11dXT0>).
- 1307 • Hence, especially when combined with visual cues, not to mention a number of other
1308 gastrophysical interventions (Spence, 2017a, 2017d), there would seem to be good
1309 hope that the experience of food and drink in space can be enhanced, through the
1310 more intelligent use, and consideration, of sound.
- 1311 • Finally, here, there may also be an important role for sound in terms of ‘digital
1312 commensality’, dining while talking with, or being advised by a dining

assistant/companion (Niewiadomski, Ceccaldi, Huisman, Volpe & Mancini, 2019; Spence, Mancini & Huisman, 2019).

Table 4 hereabouts

9. CONCLUSION

In each of the sections above, results have been summarized in some detail and discussed to indicate what is known and where there are gaps in our knowledge. For the overall conclusion, Table 4 lists some of the many outstanding questions that need answering before we can understand whether flavor has a role in astronauts' under-consumption of food. Some questions relate to fundamental knowledge (e.g. whether mixtures of sub-threshold odor/taste compounds can activate the relevant odor/taste receptor), others are focused on more applied knowledge, such as exactly how space conditions affect nasal physiology or whether the elevated background levels of CO₂ in space can affect flavor perception. By identifying these areas for future research, it is hoped that research teams across the world will take up the challenge and help pave the way for exploration "to infinity and beyond".

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1340

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1343 wrote Section 8; AJT edited and combined the sections and built the Bibliography. All authors
1344 read, edited and approved the final draft.

1345

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2177 **TABLES**

2178

2179 **Table 1. Translating taste function into food screening functions.**

2180

Receptor	Screening for
Salt	Micronutrient content – minerals
Sour	Acid – marker for potential spoiled food
Bitter	Potential toxic compounds
Sweet	Carbohydrate – through sugars
Umami	Protein – through specific amino acids
Fat	Fat – through specific free fatty acids

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2182

2183 **Table 2. Compounds in the SWEG document that are marked as RWC (Reduced Water**
 2184 **Consumption) and their reported odor descriptors.**

2185

Compound	CAS #	Odor properties
Methyl ethyl ketone (Aka Butan-2-one)	78-93-3	Chemical-like and fruity/green
Dichloromethane (Aka Methylene chloride)	75-09-2	Sweet, ether-like
Chloroform	67-66-3	Sweet, ether-like
Ammonia	7664-41-7	Decaying fish
Acetone	67-64-1	Sweet odor to nail polish remover depending on concentration
Monoalkylamines e.g. Methylamine	74-89-5	Fishy
Dialkylamines e.g. Dimethylamine	124-40-3	Ammonia, fish-like
Trialkylamines e.g. Trimethylamine	75-50-3	Fishy
Phenol	108-95-2	Sweet and tarry

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2188 **Table 3. Estimation of sensory effect of RWC compounds in ISS potable water samples.**

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		Odor				
		Lowest	Highest	threshold	DoT	DoT
Compound		level ^a	level ^a	in water ^b	Level/OT	Level/OT
		µg/L (ppb)	µg/L (ppb)	µg/L (ppb)	Low	High
Methylethyl ketone		5	20	8400	0.0006	0.0024
(Butan-2-one)						
Dichloromethane		5	20	9100	0.0005	0.0022
(Methylene chloride)						
Chloroform		5	20	2400	0.0021	0.0083
Ammonia				1.5	0.0000	0.0000
Acetone		3	34	20000	0.0002	0.0017
Monoalkylamines						
e.g. Methylamine		125	125	2.4	0.0521	0.0521
Dialkylamines						
e.g. Dimethylamine		No data	No data	29	0.0000	0.0000
Trialkylamines						
e.g. Trimethylamine		125	125	0.20	625.0	625.0
2-Mercaptobenzothiazole		40	320	1760 ^c	0.0227	0.1818
Phenol		4	20	790	0.0005	0.0025

2190 a) Data taken from Appendix 3 in Straub *et al.* (Straub II, Plumlee & Schultz, 2012). The data in the

2191 reference are quoted in increments e.g. <5 or <20 µg/L but, to calculate DoT values, they have been

2192 quoted in the Table as discrete values.

- 2193 b) Odor threshold values (Amoore & Hautala, 1983) were determined in drinking water as the
2194 concentration in water that would elicit a detectable odor in the headspace.
- 2195 c) Odor threshold of 2-mercaptobenzothiazole (Nielsen, 2014)
- 2196

2197 **Table 4. Knowledge gaps and research questions on factors affecting flavor perception**
2198 **during spaceflight.**

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***Knowledge gaps and research questions on factors affecting flavor perception during
spaceflight***

What effects does space-level radiation have on shelf life of space foods?

Is nasal congestion during spaceflight a temporary or a permanent condition and does it
affect odor (flavor) perception?

What experimental design is needed to measure changes in astronauts' odor perception?

Do bitter compounds affect food intake; which bitter compounds/receptors are involved;
what is the magnitude of the effect?

If regular foods are spiked with trialkyl amines, what levels cause decreased intake?

Can sub-threshold mixtures of tastes or odors activate flavor receptors?

Does a background odor mixture affect the flavor perception of real foods during eating?

Does a 0.4% CO₂ atmosphere affect the flavor perception of food during eating?

If "crunch" is added to food, is food intake increased compared to the standard food?

Does the ISS background noise affect the flavor perception of real foods during eating?

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2204 **Figure 1. Energy intake during spaceflight (Smith et al., 2005). Data are expressed as**
2205 **percentage of energy requirements predicted using the calculation of the World Health**
2206 **Organization. Values are the mean intake ($\pm$ standard deviation) from a group of 11**
2207 **astronauts.**

2208

Figure 2. In-flight dietary intake of crew members in different space programs. Data are expressed as percentage of daily energy requirements predicted by the World Health Organization calculation. Mean values and standard deviations are shown (Smith et al., 2015b).

Figure 3. Schematic of the control mechanisms involved in food intake (Hopkins et al., 2016). AA: Amino acids, AgRP: Agouti-related protein, CART: Cocaine- and amphetamine-regulated transcript, CRF: Corticotropin-releasing factor, CCK: Cholecystokinin, FFA: Free fatty acids, GI: Gastrointestinal tract, GLP-1: Glucagon-like-peptide, GRP: Gastrin-releasing peptide, NPY: Neuropeptide Y, NST: Solitary Tract Nucleus, PYY: Peptide YY, T:LNAA: Tryptophan.

Figure 4. Factors that have the potential to affect the flavor perception of foods in space.

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2232 **Figure 5. Plot of test meal intake (grams; y-axis) and post-meal rating (9-point scale; x-axis)**
2233 **for the standard meal and the meal with the incongruent flavor added. Each line represents**
2234 **the results from individual panelists, identified by a random capital letter (Bobroff &**
2235 **Kissileff, 1986).**

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Figure 6. Plot of bread consumption (food intake) and post-consumption pleasantness scores ($r=0.82$) from the sensory panel (Helleman & Tuorila, 1991). The icons represent different samples with the regression line representing the relationship between pleasantness and bread consumption (measured as the number of slices eaten).

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Figure 7. Food table in the ISS showing the packages of meals and drinks laid out for the

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crew. Note, each item is anchored using Velcro or tethered to prevent it floating around the

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cabin. Image from NASA.

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2251 **Figure 8. Canned gourmet meals, the opened can shows sausage and lentils. Image courtesy**
2252 **of Alain Maillet, CNES, France.**

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2256 **Figure 9. The rehydration station on the ISS. Image from NASA.**

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2261 **Figure 10. Schematic representation of the carbonation perception. (A) CO_2 is odorless to**
2262 **humans but activates the taste and trigeminal systems. (B) The reaction catalyzed by**
2263 **carbonic anhydrase (CA). (C) CA operates in CO_2 sensing and provokes a taste response to**
2264 **acidity.**

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*OFP = Octafluoropropane (Freon 218)

Figure 11. Composition of volatiles in a sample of ISS recycled air, returned to Earth for detailed analysis (Macatangay & Bruce, 2010). Percentages are on a volume basis.

Figure 12. Effects of quiet and loud background noise on sugar, salt, flavoursomeness, crunchiness, and liking. (A) The effect of background noise levels on sugar, salt, and liking intensity ratings in Woods et al. (2011). Experiment 1, relative to the baseline condition; a negative value indicates a lower level than the baseline and a positive value a higher level. Error bars = 2 SEM. (B) The effect of quiet and loud background

2277 sounds on flavorsomeness, crunchiness, and liking intensity ratings
2278 reported in Experiment 2, relative to the baseline condition. Source:
2279 (Woods et al., 2011). Note the significant increase in the rated crunchiness
2280 of various rice cakes when sampled under the loud background noise
2281 conditions.
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Figure 13. Summary of the effects of airplane noise on ratings of basic tastes in solution as reported by Yan and Dando (2015). The results show that the perception of umami was enhanced, while the perception of sweetness, from sucrose, was suppressed (* $p < .05$; ** $p < .01$; *** $p < .001$; and **** $p < .0001$).