7.
Sweet taste in the human diet

Sweetness is an integral part of the human diet. Our appetite for sweet taste is innate, expressed even before birth, and spans across all ages and cultures around the world. However, our food environment has changed considerably over the last decades and high-calorie, palatable foods, which are usually high in fat and sugar content, are now widely available and easily accessible. In times when health organisations worldwide recommend that free sugars intake should be reduced to less than 10%, or even 5% of total daily energy intake, managing dietary sweetness is critical from a nutritional and a public health perspective.

This chapter aims to present scientific information about the role of sweet taste in the human diet and to discuss the role of low/no calorie sweeteners (LNCS) in managing our innate appetite for sweetness.

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Why do we like sweet taste?

Taste plays a key role in food choice and food intake *(de Graaf and Boesveldt, 2017)*. In conjunction with other senses, taste drives our decisions about whether a potential food will be accepted or rejected, while ensuring the intake of sufficient nutrients. In humans, as well as in many animal species, taste has the additional value of contributing to the overall pleasure and enjoyment of a food or drink *(Drewnowski 1997; Steiner et al, 2001)*. The generally recognised five "basic tastes" include: sweet, sour, bitter, salt and umami (Figure 1), while emerging evidence suggests that there may be a sixth basic taste: fat *(Running et al, 2015; Jaime-Lara et al, 2023)*.

Figure 1: Basic tastes

Sweet taste always was and remains an integral part of the human diet. The affective response to sweetness is also evident in the fact that the word "sweet" is used widely to describe not only this basic taste quality but also something that is pleasurable, e.g., "la dolce vita" [sweet life] *(Reed and McDaniel, 2006)*.

The sensory pleasure derived from tasting sweet substances has an innate basis. Experts believe that the inborn acceptance of sweet stimuli and rejection of bitter ones have developed through natural evolution and constitute an adaptive advantage, preparing the new-born to spontaneously accept sources of energy and to reject potentially toxic bitter substances *(Mennella and Bobowski, 2015)*. As a result, infants' appetite for sweetness facilitates the acceptance of breast milk which tastes sweet due to its content of lactose, the sugar found in maternal milk. Therefore, it has been suggested that it is basic biology that dictates a liking for sweetness *(Drewnowski et al, 2012)*.

"Liking" and "wanting" are two distinct components of food reward *(Morales and Berridge, 2020)*. "Liking" underpins the subjective pleasure elicited by tasting a particular food, while "wanting" refers to the desire to actually ingest a food *(Berridge, 1996; Blundell et al, 2010)*. On the other hand, "preference" involves a comparison between two or more stimuli, where one is preferred over others, and a hierarchy of attractiveness can be established *(Zellner, 2007)*. Different levels of "liking" or "wanting" can determine preferences between various stimuli.

How does our body "recognise" sweetness?

Sweetness is one of the basic tastes that humans recognise. A sweet tasting stimulus is detected by sweet taste receptors located in the oral cavity. Various sweet tasting molecules can bind to and stimulate the sweet taste receptor including sugars, polyols, and a broad variety of LNCS *(Renwick and Molinary, 2010).*

Sweetness perception involves two G-protein coupled transmembrane receptor proteins, T1R2 and T1R3, which dimerise to form the sweet-taste receptor. The G-protein associated with the sweet-taste receptor is alpha-gustducin. Binding of a sweet compound to the receptor activates the release of alpha-gustducin, which triggers intracellular signalling events such as the opening of ion channels or the generation of other biochemical signals, leading to a release of intracellular calcium (Ca2+). Stimulation of the T1R2 + T1R3 taste receptor activates peripheral gustatory nerves transmitting sensory information to the brain and, in turn, brain gustatory pathways *(Renwick and Molinary, 2010).*

Identical receptors have also been found in other parts of the digestive tract, from the stomach and pancreas to the colon and enteroendocrine cells *(Mehat and Corpe, 2018).* Such receptors respond to the presence of sugars by inducing a number of metabolic responses usually associated with satiety and glucose metabolism (e.g. secretion of gut hormones and insulin, reduction of ghrelin, slowing of gastric emptying). Contrary to the metabolic responses evoked by sugars, evidence from human studies suggests that LNCS do not significantly affect gut hormones, gastric motility, appetite or glucose metabolism in humans *(Renwick and Molinary, 2010; Steinert et al, 2011; Bryant and McLaughlin, 2016; Mehat and Corpe, 2018; Zhang et al, 2023).*

Sweetness preference: From early life to adulthood

The acceptance of sweetness and the rejection of bitterness are innate traits *(Mennella and Bobowski, 2015)*. This is evident, for example, from the characteristic "gusto-facial reflexes", the stereotyped reactions elicited in human new-borns a few hours after birth by placing a small amount of sapid solutions into their mouths. Sugar elicits a characteristic acceptance response, which is in sharp contrast to the rejection caused by bitter- and sour-tasting substances *(Steiner, 1977)* (Figure 2). When a sweet solution is placed in the infant's oral cavity, face relaxation, tongue protrusion and lip searching, and sometimes a smile are observed *(Steiner et al, 2001)*.

Early research on the developmental trajectory of sweet taste preferences suggests that such preferences are even expressed before birth *(Mennella and Beauchamp, 1998)*. A recent study using 4D ultrasound scans showed that foetuses aged 32 to 36 weeks react to flavours of foods ingested by their pregnant mother in a similar way as postnatally *(Ustun et al, 2022)*. In this study, foetuses expressed different types and frequencies of facial movements in relation to the type of flavour that they were exposed to, namely, more laughter-face expressions when exposed to a carrot (sweet) flavour and more cry-face expressions when experiencing a kale (bitter) flavour.

Infant facial expressions

Image courtesy of John Wiley and Sons

Figure 2: Infant facial expressions in response to sweet, sour, bitter and salt taste stimuli (After Steiner, 1977)

Humans are born with a liking for sweetness, which decreases from childhood to adolescence and into adulthood.

Our natural appetite for sweetness remains until old age, however, there is clear evidence that it decreases from childhood to adulthood *(Desor et al, 1975; Desor and Beauchamp, 1987; de Graaf and Zandstra, 1999; Mennella et al, 2011)*. Children prefer higher sucrose concentrations than adults with the changeover occurring during adolescence *(de Graaf and Zandstra, 1999; Petty et al, 2020)*.

A study in 485 individuals showed that children had higher sucrose taste detection thresholds compared with adolescents, who in turn required higher concentrations than adults, meaning they required higher concentrations of sucrose to detect a taste different from water *(Petty et al, 2020)*. However, no significant relationship between sweet taste detection thresholds and preferences across age groups was found, indicating that sweet preference is not readily explained by differences in the ability to detect sweetness. It has been suggested that the heightened preference for sweetness during childhood and adolescence may in part reflect the higher caloric and nutritional needs during periods of maximal physical growth, as shown in studies linking the most preferred level of sweetness with children's height and levels of a biomarker for bone resorption and growth *(Coldwell et al, 2009; Mennella et al, 2014)*.

Finally, research suggests that, in general, taste perception declines during the healthy ageing process, although the extent of decline – including for sweetness – varies between studies *(Methven et al, 2012)*.

Determinants of sweetness preference beyond age

While all humans express the same response to sweetness immediately after birth, preference for sweet taste changes over time and becomes highly idiosyncratic in adults *(Reed and McDaniel, 2006)*. An appetite for sweetness is present in most adults but large inter-individual differences exist in the preferred level of sweetness intensity. It is not yet clear why individuals exhibit so different hedonic responses to sweet tastes *(Armitage et al, 2021)*.

Some research suggests that humans fall into three phenotypic sweetness response patterns: those whose liking increases with sweetness intensity (sweet likers), those who show increasing dislike as sweetness increases (sweet dislikers), and a third group who show preference for moderate levels of sweetness *(Iatridi et al, 2019)*.

Recent reviews have examined the potential role of several determinants of sweetness preference and liking in humans *(Venditti et al, 2020; Armitage et al, 2021)*. The impact of age, genetics, dietary and lifestyle factors, reproductive hormonal factors, body weight status and weight loss, personality and cultural factors, previous exposure and disease status was reviewed.

There is evidence that genetic differences among people may partly account for individual variations in sweetness perception and preference *(Reed and McDaniel, 2006; Keskitalo et al, 2007; Fushan et al, 2010; Reed and Knaapila, 2010; Bachmanov et al, 2011; Joseph et al, 2016)*. However, how these genetic differences might translate into food intake and food preference at each age is still unclear.

The associations between sweetness preferences and reproductive hormonal factors are overall inconsistent, as assessed in the scoping review by Venditti and colleagues *(Venditti et al, 2020)*. Similarly, there is limited and heterogeneous evidence regarding the links between various personality traits with sweetness preference, with no clear or consistent associations. Also, no clear pattern for sweetness preference based on dietary macronutrient composition or meal composition has been reported. However, there is some consistency in the literature regarding a general increase in sweetness preference in the fasted versus satiated state, as well as some suggestion, albeit from a very limited number of studies, that increased physical activity may be associated with a reduction in sweetness preference *(Venditti et al, 2020)*

Other potential determinants of sweetness preference and/or liking, including body weight status and previous exposure to sweet taste, are discussed in the following paragraphs.

Is there a link between sweetness and obesity?

The attraction of humans to sweet tasting foods has given rise to the notion that a strong appetite for sweet taste may be a key driver of obesity. It has been suggested that an individual's appetite for sweet-tasting foods and drinks could facilitate overconsumption and, in a society where palatable and convenient food products are widely available, potentially override the physiological energy-regulation mechanisms *(Bellisle, 2015)*.

There is no doubt that overconsumption of energy-dense products, some of which are sweet-tasting, may lead to an imbalance between energy intake and expenditure, and consequently, to weight gain. However, current evidence shows no clear support for the wide assumption that a strong attraction to sweetness is associated with overeating and obesity *(Venditti et al, 2020; Armitage et al, 2021)*. In fact, a recent review pointed to many studies reporting the opposite, i.e. that individuals with obesity express a lower overall liking for sweetness, and that sweet dislikers, rather than sweet likers, may have slightly higher body fat *(Armitage et al, 2021)*. Also, current evidence does not clearly support the assertion that people with obesity have altered sweet taste sensitivity and perception, compared to normal-weight people *(Ribeiro and Oliveira-Maia, 2021)*. In all, available data do not support the notion that sweet liking is linked to higher body weight and obesity in adults, and if anything, provides evidence to the contrary *(Armitage et al, 2021)*. However, potential effects of weight loss, including after bariatric surgery, on sweetness preferences and perception need to be examined in future studies *(Ribeiro and Oliveira-Maia, 2021)*.

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Studies in children and adolescents also show no differences in sweetness preference, or sweet food intake, based on weight status *(Venditti et al, 2020)*. For example, in a study of 366 children, aged 7-9 years, no association was found between adiposity and liking for sweet-tasting sugary foods *(Hill et al, 2009)*. Similarly, a study in 574 children and adolescents, aged 10-17 years, indicated no different sensory preferences or taste sensitivity among the different body weight categories *(Alexy et al, 2011)*. In adolescents, results from the Finnish Health in Teens cohort study in 4237 girls and boys suggested that a higher consumption of sweet-tasting treats was unrelated to being overweight or to weight change over a 2-year follow-up period *(Lommi et al, 2021)*. Finally, a study in both children and adults found that, regardless of age, sweet preference and liking for both caloric sweeteners and LNCS did not differ between individuals with or without obesity (Figure 3) *(Bobowski et al, 2017)*. Altogether, these findings suggest that stronger liking or preference for sweetness is not related to body weight status in children, adolescents, or adults.

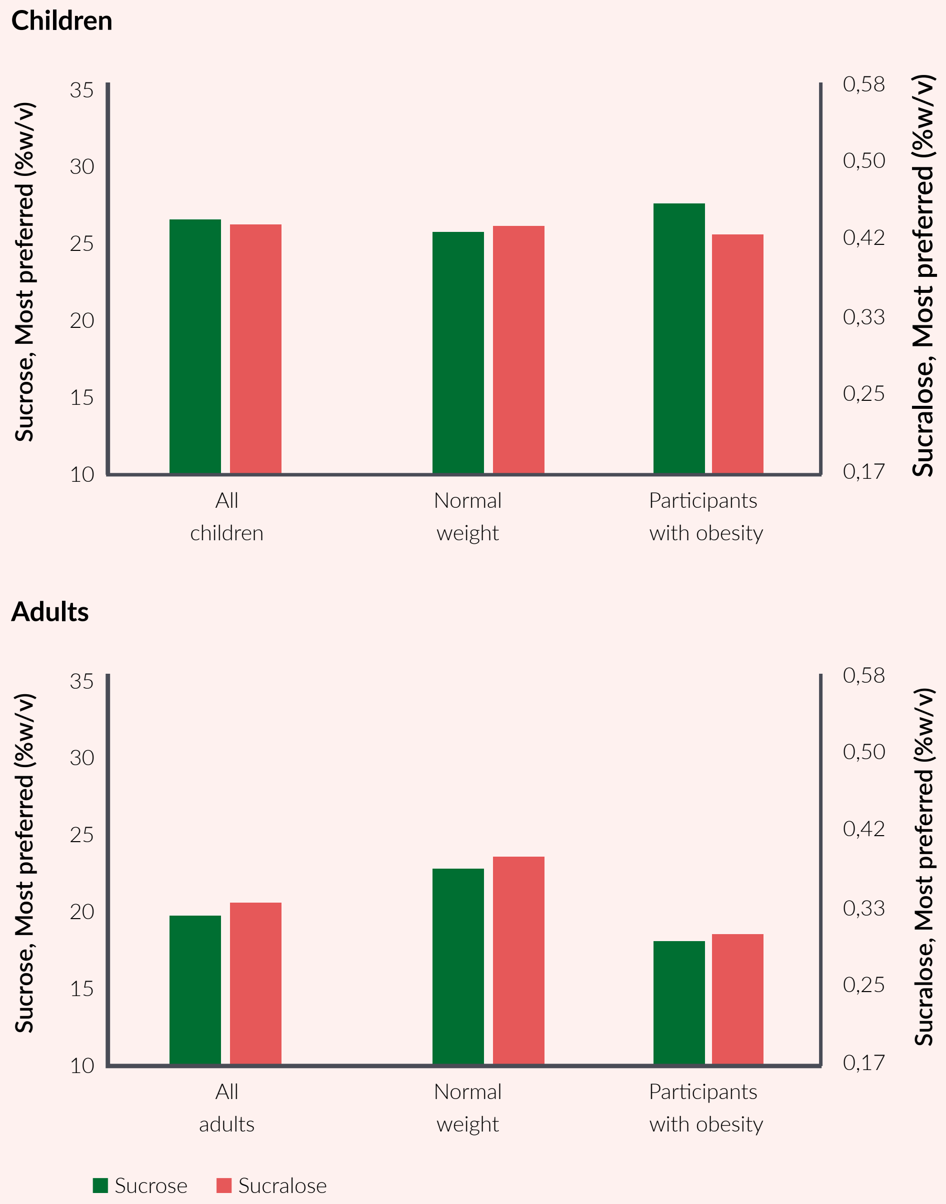

Figure 3: Most preferred levels of sucrose and sucralose among all children (a) and adults (b), or according to weight status: There were no significant relationships between BMI and most preferred level of sucrose or sucralose, regardless of age. Data are means ± standard error. (Bobowski et al, 2017)

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Exposure to sweet taste and sweetness preference

There is a common belief that repeated exposure to sweet taste through the diet may stimulate our appetite for sweetness, lead to overeating, and hence, weight gain, despite a lack of clear evidence to support this notion *(Bellisle, 2015; Public Health England, 2015; Rogers, 2018; Appleton et al, 2018; Wittenkind et al, 2018; Venditti et al, 2020; Armitage et al, 2021; Higgins et al, 2022).*

A systematic review that examined the outcomes from 21 studies in both children and adults concluded that current evidence from human controlled trials do not support the assertion that dietary exposure to sweetness affects the subsequent generalized acceptance, preference, or choice of sweet-tasting foods or beverages in the diet *(Appleton et al, 2018)*. In fact, a higher sweet taste exposure rather tends to lead to reduced preferences for sweetness in the shorter term, a phenomenon known as sensory-specific satiety (exposure to a particular sensory attribute, for example sweetness, can lead to reductions in the apparent pleasantness and choice of foods and beverages with that same attribute).

In a 3-month RCT, a low-sugar, low-sweetness exposure diet did not change sweet preference compared to a habitual diet, despite heightened ratings of sweetness intensity perception *(Wise et al, 2016)*. However, if sweet intensity perception does not result in a shift in the preferred sweetness of foods, it is unclear how food choice would be altered. Results from seven available studies assessing the impact of exposure to different levels of dietary sweetness do not support the assertion that exposure to a high versus low dietary sweetness affects calorie and sweet food consumption, or that it results in overeating *(Higgins et al, 2022)*. A longer-term RCT is currently under way with the aim to assess the effect of low, regular, and high dietary sweetness exposure over 6 months on sweetness preference and perception, food choice and intake, among other health outcomes *(Čad et al, 2023)*.

Sweetness without calories: the role of low/no calorie sweeteners

In times of an obesity epidemic, with increased sugar and fat intakes contributing to excess energy intake and ultimately to weight gain, different strategies for managing our innate appetite for sweetness, such as the use of LNCS in place of caloric sweeteners, have been proposed as useful tools in reducing sugars and thus overall energy intake.

In traditional food products, sweetness is brought primarily by sugars. Sugars are carbohydrates with a distinctive sweet taste and an energy content of 4 kcal per gram. In order to allow consumers to enjoy the palatable sweet taste of their favourite foods and beverages without the energy load of sugar, a number of LNCS have been developed in the last decades *(Bellisle, 2015)*. LNCS have a much higher sweetening power compared to sugars, so that they can be used in very small amounts (mg in place of grams of sugars) to create the desired level of sweetness of a food or drink, while contributing very little or no energy at all to the final product. By reducing the energy content of foods and beverages, LNCS may potentially be a helpful tool for satiating our desire for sweet taste with fewer or zero calories.

However, over the years, concerns have been expressed about potential adverse effects of LNCS on appetite for sweet taste *(Yunker et al, 2020)*. More specifically, it has been suggested that LNCS might enhance the natural appetite for sweet taste, and therefore increase intake of sweet foods and beverages, preventing consumers from managing their response to sweetness. Likewise, a review that examined the related evidence rejected this claim and concluded that consumption of LNCS does not increase food or energy intake compared with water and may have the advantage of to some extent satisfying desire for sweetness when consumed shortly before or with a meal *(Rogers, 2018)*.

Several controlled clinical studies have shown that the use of LNCS is associated with a lower intake of sweet tasting substances in children *(de Ruyter et al, 2013)* and adults *(Piernas et al, 2013; Fantino et al, 2018; Higgins et al, 2018; Maloney et al, 2019)*. For example, a large RCT in children found that the consumption of beverages with LNCS for 18 months did not exacerbate liking or desire of sweet tasting products, and in contrast, LNCS use was associated with a lower intake of sweet foods *(de Ruyter et al, 2013)*. The CHOICE study, a 6-month RCT in 104 adults with obesity, showed a broader suppression of appetite for sweetness in participants with a high daily intake of LNCS drinks than in the control group allowed only water *(Piernas et al, 2013)*. Similarly, the study by Fantino and colleagues showed that acute or longer-term consumption of low/no calorie sweetened beverages with meals does not affect appetite and hunger or overall calorie and food intake, when compared to water *(Fantino et al, 2018)* (see also Chapter 4). More recently, a study by Maloney and colleagues found that low/no calorie sweetened beverages may help some individuals to better control food cravings possibly by satisfying their desire for sweetness *(Maloney et al, 2019)*. Further recently published studies addressing these concerns found no support for an exacerbation of the appetite for sweetness with the use of LNCS *(Rogers et al, 2020; Appleton, 2021; Appleton et al, 2021)*.

In conclusion, **current evidence does not support the notion that LNCS use can lead to a heightened appetite for sweetness, sugar, or sweet products, or that there is an association between exposure to sweetness and a change in taste preferences.** In many instances, LNCS contribute to satisfy a desire for sweetness *(Bellisle, 2015)*.

There is no evidence of an association between low/no calorie sweeteners' use and a heightened appetite for sugar or sweet products in children or adults.

Can exposure to sweet taste enhance the "sweet tooth"?

Dr France Bellisle: The term "sweet tooth" refers to a person's strong preference for sweet-tasting foods. It is not a scientific concept with any rigorous definition. However, it is legitimate to ask whether repeated exposure to sweetness, with or without calories, could enhance the liking of and appetite for sweet tasting products, which could in turn lead to increased consumption. An increased use of LNCS in many foods and beverages could create such a situation.

Current evidence does not support the notion that repeated exposure to sweet taste in general, or to sweetness without calories in particular, leads to a heightened appetite and/or consumption of sugar-sweetened foods and drinks *(Rogers, 2018; Appleton et al, 2018)*. What laboratory and field studies have shown, however, is that consumption of products with a particular sensory attribute (e.g. sweetness) leads to reductions in the momentary pleasantness and attractiveness of foods and beverages with that same attribute, a robust phenomenon known as "sensory-specific satiety" *(Rolls, 1986; Hetherington et al, 2000; Liem and de Graaf, 2004)*. Therefore, exposure to the sweet taste of foods and beverages with low amounts of sugars, sweetened with LNCS, may not only decrease the consumption of free sugars but could also satiate the desire for sweetness from other sources *(Appleton et al, 2018)*.

Conversely, the potential effects of reducing sweetness in the diet (from caloric and non-caloric sources) on appetite remain to be investigated in randomised controlled trials *(Wittenkind et al, 2018)*. One study *(Wise et al, 2016)* showed that a low-sugar diet maintained for three months did not change the preference for sweetness, even if the participants rated sweet foods as tasting sweeter after the end of the intervention period. However, once the low-sugar diet ended, people quickly increased their ad libitum sugar intake to baseline levels and their judgments of sweet taste intensity reverted to pre-diet levels. It seems that preference and appetite for sweetness do not change according to the higher or lower exposure to sweet tasting foods, at least in adults.

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Can use of low/no calorie sweeteners disrupt the control of energy intake?

Dr France Bellisle: The notion that LNCS might paradoxically enhance appetite and intake is not a new one *(Bellisle, 2015)*. It was formulated in the 1980's by John Blundell and his team *(Blundell and Hill, 1986)*, who made the important point that LNCS uncouple sweet taste and energy content. When a sweet-tasting and energy-containing product is ingested, the sensory stimulation is followed by post-ingestive effects that act to limit intake; such effects include satiation signals from the gastro-intestinal tract that inform the brain that energy and nutrients have been obtained. By contrast, according to Blundell's early hypothesis, LNCS stimulate appetite via their sweet taste, but exert no post-ingestive inhibitory influence since they provide no energy. Thus, the experience of sweetness in the absence of calories might possibly weaken the learned "sweetness = energy" association and consequently disrupt appetite control mechanisms.

Numerous studies using very different methodological approaches (observational, RCTs, and Magnetic Resonance Imaging) in various types of participants (men, women, lean, obese, never obese, formerly obese) have examined the impact of LNCS on appetite for sweet taste and ultimately on intake of sweet tasting products *(Anton et al, 2010; de Ruyter et al, 2013; Piernas et al, 2013; Fantino et al, 2018; Higgins et al, 2018)*. Furthermore, several systematic reviews and meta-analyses have evaluated the available data. Overall, the existing studies reach largely consistent conclusions: the short- or long-term use of LNCS shows no association with a heightened appetite in general, or specific appetite for sugar or sweet products. In fact, in many instances, the use of LNCS is associated with a decreased intake of sweet tasting substances *(Rogers et al, 2016; Rogers, 2018)*. Likewise, a report by Public Health England (2015) concluded that there is no evidence to suggest that maintaining the sweet taste through the use of LNCS increases the selection of higher calorie foods and drinks.

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