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Does sweetness exposure drive 'sweet tooth'?

David J. Mela[1]*† and Davide Risso[2]

[1]*Valkenswaard, The Netherlands*
[2]*Tate & Lyle PLC, London, UK*

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Abstract

It is widely believed that exposure to sweetened foods and beverages stimulates the liking and desire for sweetness. Here we provide an updated review of the empirical evidence from human research examining whether exposure to sweet foods or beverages influences subsequent general liking for sweetness ('sweet tooth'), based on the conclusions of existing systematic reviews and more recent research identified from a structured search of literature. Prior reviews have concluded that the evidence for a relationship between sweet taste exposure and measures of sweet taste liking is equivocal, and more recent primary research generally does not support the view that exposure drives increased liking for sweetness, in adults or children. In intervention trials using a range of designs, acute exposure to sweetness usually has the opposite effect (reducing subsequent liking and desire for sweet taste), while sustained exposures have no significant effects or inconsistent effects. Recent longitudinal observational studies in infants and children also report no significant associations between exposures to sweet foods and beverages with measures of sweet taste preferences. Overall, while it is widely assumed that exposure to sweetness stimulates a greater liking and desire for sweetness, this is not borne out by the balance of empirical evidence. While new research may provide a more robust evidence base, there are also a number of methodological, biological and behavioural considerations that may underpin the apparent absence of a positive relationship between sweetness exposure and liking.

Keywords: Sugars: Sweeteners: Intake: Liking: Preference

There are consistent national and international public health recommendations to limit intakes of free or added sugars[1,2]. However, there is less clarity and consistency in how this should be achieved. Part of this reflects debate around the physiological and health effects of low-energy sweeteners (LES), but there are also concerns about sweetness, and whether exposure to sweetness in the diet facilitates or hinders achievement of public health targets. Concern has been expressed about a 'sweetening of the global diet'[3], although the evidence for this may differ depending on the nature of the analyses and consideration of foods *v.* beverages. In the USA, sweetness of the diet appears to have declined over the period 2001–2018, driven by reductions in sweeteners in beverages and tabletop sweeteners, with little change in foods[4]. A further analysis concluded that, globally, sweetness and added sugar contents decreased in beverages but increased in packaged foods over the period 2008–2019[5].

While there is a general consensus that high intakes of free sugars (and sugar-sweetened beverages in particular) increase the risks of weight gain and metabolic disease[6], evidence on the effects of sweetness itself appears to contrast with this. Numerous reviews reflecting a large volume of research indicate that exposure to higher or lower levels of sweetness in the diet is not significantly associated with energy intake or body weight, and greater individual liking for sweetness generally is not clearly associated with obesity, sugar intakes or diet quality[7–15]. Nevertheless, it is possible that continued exposure to sweet foods and beverages, or LES in particular, may drive a heightened generalised preference for sweetness (and therefore also sugars) in the diet, a so-called 'sweet tooth', which would be counterproductive to public health initiatives. Against this, it is also possible that achievement of targets for sugar reduction is facilitated by continued access to sweet foods and beverages low in free sugars.

Variation in exposure to salt in the diet has been shown to influence preferred saltiness levels[16]. A corresponding belief that exposure to sweetness in the diet maintains or drives a liking or desire for sweetness is widely expressed in the professional literature[5,17–19] and also given as a basis for contemporary guidance on sweetened products from major public health

Abbreviations: LES, Low-energy sweeteners; SSB, Sugar-sweetened beverages.

* **Corresponding author:** David J. Mela, email djmela@djmela.eu

† Retired.

authorities[20–24]. These views are often framed as a statement of established fact or accepted conjecture, without reference to an underpinning body of empirical research or reviews.

The intent of this overview is to review and provide a consolidated update on the empirical evidence testing the relationship between sweetness exposure and subsequent liking in human adults and children, consider the mechanisms and research challenges that may influence observations of that relationship and make suggestions for future work on the topic.

Methods

While this is a narrative review, a systematic effort was made to identify recent research publications which measured or intervened in exposures to sweetened foods and beverages, and reported an explicit measure of sweetness liking subsequent to exposure. These measures include sensory hedonic testing (e.g. preferred sweetener level), choice of sweet *v.* non-sweet foods or reported liking or desire for sweet foods. The topic of sweetness exposure and preferences had last been systematically reviewed by Appleton et al. for publications up to 15 August 2017[25]. Systematic searches adapting their syntax were carried out on the Embase® and MEDLINE® databases, using the ProQuest Dialog search platform, for the period August 2017 through 13 February 2024. As a further check on the completeness of the formal search, supplemental searches were carried out using Google Scholar to highlight any papers in this period that cited the available systematic reviews and potentially relevant papers cited by publications newly identified from the formal search. The scope included full publications of controlled trials and longitudinal observational cohort studies in all ages and regions, but excluded patient populations, maternal exposures and languages other than English. Cross-sectional studies were excluded because they are particularly prone to confounding, especially reverse causality (e.g. if liking for sweetness increases exposure), and cross-sectional diet-taste relationships have largely been captured in other contemporary reviews[12]. Titles and abstracts were reviewed and relevant full publications were extracted by one of the authors. In addition, related ongoing and recently completed trials and systematic reviews were identified by a search of the ClinicalTrials.gov trial registry and PROSPERO register of systematic reviews.

Results

Prior systematic reviews

Three systematic reviews have assessed human studies on the relationship between sweetness exposure and subsequent preferences, and all have come to similar conclusions.

The earliest systematic review focused on the influence of taste exposures *in utero* and up to age 6 months, based on controlled and uncontrolled intervention studies and cohort studies published through November 2014[26]. The evidence base included a variety of study designs comprising a diverse range of pre- and post-natal food exposures, only a small number of which explicitly assessed sweet taste. The authors concluded that '. . . whether exposure to sweet and salty tastes early in life may increase acceptance for such tastes in later infancy are equivocal'.

Appleton et al. published the most direct and comprehensive systematic review of the topic, which included fourteen controlled trials and seven population cohort studies published up to August 2017[25]. The authors concluded that controlled studies indicate a higher sweet taste exposure may reduce sweetness preference in the short term, but with limited effects in the longer term. The evidence from longitudinal cohort studies and the conclusion overall for the relationship between sweet taste exposure and preferences were judged to be 'equivocal'.

Most recently, Venditti et al. published a scoping review based on a systematic search of evidence on the determinants of sweetness preference in humans[15]. From six identified sources that studied the possible effects of prior exposure, only one of these[27] was published after the systematic review of Appleton et al.[25]. On the basis of this smaller sample of the literature, Venditti et al.[15] concluded that the research findings 'are inconsistent' and highlighted a number of challenges to the interpretation of this body of research.

Recent intervention trials with sweet and non-sweet product exposures

Table 1 gives a summary of the newly identified trials reporting on the effects of exposures to sweet *v.* non-sweet stimuli since August 2017. Seven publications reported eight studies where exposure was followed by an assessment of generalised sweet taste liking (pleasantness, desire), comprising tasting and rating of sweet (and in some cases also non-sweet) products[28–34]. In three other studies, the measure was the relative intake (choice) of sweet foods in mixed buffet snacks or meals[32,35,36]. None of the interventions involving sweet taste exposure resulted in increases in measures of sweet taste liking and, in line with a large volume of previous research, acute exposures to sweetness generally decreased desire for and liking of the same and other sweet stimuli.

Four additional publications reported on the effects of exposures to sweet *v.* non-sweet products, followed by assessments only related to sweetness liking or choice within that same product format, either beverages[37–39] or an infant feeding supplement in oatmeal[40]. These generated a mixed pattern of results, mainly no significant effect of sweetness exposure or possible (inconsistent) differences between results for exposure to LES relative to sugar.

Recent observational/longitudinal cohort studies

Only three recent longitudinal cohort studies were identified that reported associations of sweet taste exposure with liking, and these are summarised in Table 2. Two longitudinal studies reporting on sweetness exposures in infancy found no associations with subsequent measures of sweet taste liking either later in infancy[41] or in pre-adolescent childhood[42]. A further study found no longitudinal relationships between intakes of sugar and liking for milkshakes that varied in sugar and fat contents[43].

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Table 1. Intervention trials published since August 2017 testing the effects of exposure to sweetened *v.* unsweetened test products on subsequent measures of sweet taste liking

Reference	Subjects	Exposure duration	Design and interventions	Measure(s) of sweet liking	Effect of sweet taste exposure on sweet-liking measure(s)
Trials assessing general sweet liking or liking for a range of sweet products					
Thanaraja et al, 2023[28]	Adults, *n* 49	8 weeks	Parallel: High-fat/high-sugar *v.* isoenergetic low-fat/low-sugar yogurt 2 times/d (Note: Actual difference in sweetness not reported)	Liking and wanting (taste test) for sucrose in apple juice	No significant difference in effect on liking or wanting
Appleton et al 2022[29]	Adults, *n* 54	3 weeks	Crossover: Breakfast cereal sweetened with LES *v.* isoenergetic unsweetened	Liking (taste test), intake	No significant difference in effect on pleasantness, desire to eat and sweetness of 3 sweet and 3 non-sweet foods, or intake of these in buffet breakfast and lunch test meals.
Appleton, 2021[35]	Adults, *n* 20	1 d	Crossover: LES-sweetened beverages, sugar-sweetened beverages *v.* water, 4 × 330 ml servings over a day	Consumption of sweet *v.* non-sweet foods	Relative to water, the proportion of energy from sweet foods over the day was not different after LES and was reduced after sugar-sweetened beverages.
Chaaban & Anderson, 2021[30]	Adults, *n* 85	Single meal	Parallel groups: Meals with sweet *v.* salty *v.* sweet and salty taste profiles	Liking and desire (taste test) for sweet and salty foods	The sweet meal reduced the desire and liking for sweet foods, with no effect on rating of foods with other taste profiles.
Carroll et al, 2020[31]	Adults, *n* 29	3 weeks	Crossover: Breakfast porridge sweetened with sugar *v.* isoenergetic unsweetened	Desire to eat something sweet	Reduced desire for sweet taste immediately after sweet but not unsweetened breakfasts.
Rogers et al 2020[32]	Study 1 Adults, *n* 40	Single meal	Crossover: LES-sweetened drink *v.* water	Liking (taste test)	Reduced ratings of desire to consume and pleasantness of 4 sweet foods and beverages.
	Study 2 Adults, *n* 64	Single meal	Crossover: LES-sweetened drink *v.* water	Liking (taste test)	Reduced desire to consume and pleasantness of 5 sweet foods and beverages, but not 2 savoury foods or water immediately after exposure. No differences after 2 h.
	Study 3 Adults, *n* 51	Single meal	Crossover: Still water, carbonated water, LES-sweetened cola, sugar-sweetened cola	Intake of sweet snacks	LES- and sugar-sweetened colas reduced sweet snack intakes relative to water, but with no relative differences in savoury snack intake (no significant drink exposure by food choice (intake) interactions).
Okronipa, Arimond, Arnold, et al., 2019[33]	Infants, *n* 624	18 months	Parallel groups: Sweetened daily nutrient supplement from birth to 18 months *v.* controls given no supplement or a non-sweet supplement	Preferred concentration (taste test) at age 4–6 years	No significant difference in effect on the preferred level of sucrose in water.
Okronipa, Arimond, Young, et al., 2019[34]	Infants, *n* 985	18 months	Parallel groups: Sweetened daily nutrient supplement from birth to 18 months *v.* controls given no supplement or a non-sweet supplement	Reported liking for sweet foods and beverages at age 4–6 years	No significant difference in effect on self-reported liking or 5 favourite of 30 foods and beverages, 15 of which were sweet. No significant effect on sweet food preferences as reported by caregivers.
Fantino et al 2018[36]	Adult LES non-users, *n* 166	2 d acute, 5 weeks sustained	Crossover for acute responses, parallel groups for sustained exposure (660 ml/d); LES-sweetened soft drink *v.* carbonated water	Number of sweet foods chosen in a buffet meal	Acute exposure: Reduced number of sweet foods chosen. Sustained exposure: No effect on the number of sweet foods chosen.
Trials assessing liking for sweetness only in the exposed format					
Kendig et al., 2023[37]	Adult SSB users, *n* 80	12 weeks	Parallel groups: Replace SSB with LES-sweetened beverages or with water, or continue SSB	Preferred concentration (taste test)	Significant group × concentration interaction for the liking ratings: Reduced liking for 12 % sucrose in water after water or SSB relative to LES; reduced liking for 24 % sucrose solutions after water relative to LES.
Ebbeling et al., 2020[38]	Adult SSB users, *n* 203	12 months	Parallel groups: Replace SSB with LES-sweetened or with unsweetened beverages, or continue SSB	Preferred concentration (taste test)	Significant overall treatment effect. No significant difference LES *v.* unsweetened drink groups in preferred sweetness level (both decreased significantly from baseline; SSB group did not); direct comparisons to SSB group not reported

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Table 1. (*Continued*)

Reference	Subjects	Exposure duration	Design and interventions	Measure(s) of sweet liking	Effect of sweet taste exposure on sweet-liking measure(s)
Johnson et al., 2021[40]	Children aged 7–24 months, *n* 55	2 weeks	Parallel groups: 10 portions of unsweetened *v.* sugar-sweetened versions of a nutrient supplement	Intake; caregiver ratings of supplement liking	Intake of sweetened and unsweetened versions increased similarly with repeated exposure. (No test of intake of the alternative version; caregiver ratings of changes in liking for the alternative versions not reported.)
Judah et al., 2020[39]	Adults SSB users, *n* 158	2 months	Parallel groups: Substitute SSB with water *v.* 'diet drinks'	Reported SSB intake and liking; liking and preference for the assigned alternative drink	No significant difference in the effect of water *v.* 'diet drinks' groups for any outcome.

LES = Low-energy sweetener; SSB = Sugar-sweetened beverage.

Ongoing (registered) trials and reviews

A substantial number of additional, potentially relevant intervention trials with as-yet-unpublished results on measures of sweet taste liking were identified through public registries or protocol publications. These trials have a range of different designs and objectives, allocating subjects to diet periods varying in sweetness or free sugar levels, or specifically testing the effects of the use of LES (e.g. *v.* water). The status of these trials was reported (per 13 February 2024) to be 'completed' (ClinicalTrials.gov identifiers NCT05010408, NCT04609657 and NCT04226911[44]), or with estimated completion dates in 2023 (ClinicalTrials.gov identifier NCT04633681[45]), 2024 (ClinicalTrials.gov identifiers NCT02591134[46,47], NCT04816955[48], NCT05672017, NCT04497974[49], NCT05684757 and NCT05932329) or 2025 (ClinicalTrials.gov identifiers NCT04567108 and NCT04079855). Most of the studies have exposure durations of several weeks or months and include only adult participants. In addition to these intervention trials, one relevant systematic review was identified in the PROSPERO register of systematic reviews. This lists a number of research questions on the associations of sugar and sweetener exposures with sweet taste preference during childhood[50]. The registered protocol includes both intervention trials and cohort studies, and its status is given as 'ongoing'.

Discussion

A moderately large and varied body of research has tested for a relationship between sweetness exposure and subsequent liking for sweetness in human adults and children. Taken together with the conclusions from earlier systematic reviews, more recent research is consistent with the view that evidence for this relationship leans towards disconfirmation or is at best equivocal. Professional positions and public health guidance should therefore be cautious in expressing a presumption that sweetness exposure drives a liking for sweetness or otherwise provide underpinning for that view.

None of the recent trials involving acute or sustained sweet exposures followed by assessments of generalised liking found that these exposures increased the liking or choice of sweet stimuli or foods (Table 1). Arguably, test batteries with a range of products best assess the effects of an intervention on generalised 'sweet tooth'. In line with a large volume of previous research, acute exposures to sweetness generally led to a transient decrease in desire for and liking of the same and other sweet stimuli. Trials where exposures were accompanied by tests for the preferred level of sweetness only within that same (exposed) product format generated less consistent results. While that design may be relevant for that single product type (mainly beverages), it does not allow conclusions to be drawn about a more generalised effect on liking for sweetness in the diet. A further limitation is that this design may be susceptible to a demand artefact, whereby the experience with or knowledge of the intervention itself may prompt subjects to shift their reported liking toward the direction of the product sweetness level they recently experienced as part of the intervention.

Results from acute studies of sweetness exposure are in line with the well-established principle of sensory-specific satiety, whereby exposure to a sensory attribute such as sweetness

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Table 2. Longitudinal cohort studies published since August 2017 testing the association of exposure to sweet foods with liking for sweetness

Reference	Population recruited	Observation period	Measures of exposure	Measures of sweet liking	Association of sweet taste exposure with sweet-liking measures
Müller et al., 2022[41]	Infants age 3 months	9 months	Reported frequency of intake of specific foods and beverages and their sweetness as rated by a trained sensory panel	Facial reactions and intake of 0·20 M lactose in water relative to plain water	No significant association between earlier exposures to sweetness and either measure of liking for sweetness at age 6 (*n* 182) or 12 (*n* 197) months
Yuan et al., 2021[42]	Infants age 8–12 months	7–11 years	Food records to determine intakes of added sugars, including natural sweeteners and sweetened beverages	Questionnaire on liking for sweetness	No significant associations between infant dietary exposures to sweet sensations or added sugars and reported liking for sweetness at age 8–12 years (N > 500 in all analyses)
Papantoni et al, 2021[43]	Adolescents age 14–16	3 years	Food Frequency Questionnaire to determine per cent energy intake from sugar	Liking for milkshakes that varied in sugar and fat contents (high-fat/high-sugar, low-fat/high-sugar, high-fat/low-sugar, low-fat/low-sugar)	No significant associations of sugar intakes with liking (*n* 105)

produces a transient reduction in the relative liking or intake of foods and beverages sharing that attribute[51]. With repeated exposure to sweetness, some decrease in liking due to monotony or boredom might also be hypothesised; however, no relative change in liking was reported in studies where the intervention required subjects to consume sweetened stimuli daily over several weeks (Table 1). Research on the expression and interpretation of food-related monotony has yielded inconsistent results and may be influenced by factors related to the subjects, methods of assessment and nature of test foods[52–56]. That literature suggests that acute sensory-specific satiety effects may be sustained or somewhat attenuated over time, but it is not clear whether the 'monotony' of repeated exposures mainly manifests as a decrease in actual liking for the target foods or a decrease in desire to consume them. The studies on sweetness identified here generally used commonly consumed food formats, and monotony effects may be more likely to be seen with an increased frequency of foods that are usually infrequently consumed[52]. Given that liking for sweetness is innate and unconditioned, and may be reinforced by frequent association with the concomitant intake of energy and macronutrients, the general liking for sweetness may be little affected by variation in exposure to any individual sweet food(s).

The evidence here has not directly tested whether the response to sustained additions or reductions in sweetness in the diet would have similar (opposing) effects. Interventions where sweetness exposure is reduced would seem most relevant to public health interests in reducing intakes of free sugars. In contrast, tests of increased sweetness exposure and longitudinal observational studies are focused more on identifying possible influences on the establishment or maintenance of sweet taste liking. Of the sustained intervention trials in Table 1, three clearly tested the effects of reduced sweetness exposure in adults, mainly where water replaced SSB[37–39]. In other cases, there was insufficient information to determine whether the interventions represented an increased or decreased exposure to sweetness for the participants[28,31,36], or the interventions were a balance of increased and decreased sweetness exposures for different individuals[29]. All the studies in children used designs where test foods provided a supplemental source of sweet (relative to non-sweet or no) exposures[33,34,40].

There were very few new longitudinal cohort studies (Table 2). Neither of the two fairly large studies found significant associations of sweet taste exposures in infancy with later measures of liking. A further study reported no longitudinal associations between sugar intakes and liking for sweet stimuli in an adolescent population. One additional study was excluded, although it had a longitudinal element. Vennerød et al. collected data on a cohort of children at mean ages of ~4 and ~5 years[27]. Path modelling was applied to explain children's preferences for sweetness levels in drinks and chocolate, based on latent factors including concurrent measures of their parents' attitudes to children's foods and eating, and the child's reported intake of foods including sweet foods and snacks. The authors report a small but statistically significant, positive association between sweet food exposure and sweetness preferences; however, it appears only the age 5 (thus cross-sectional) data were used in the analysis model, which also assumed *a priori* a direction of causal interpretation (from exposures to preferences).

The conclusions of earlier systematic reviews as well as more recent research therefore suggest that sweetness exposure makes only a limited contribution to observed variance in sweet taste liking or preferences. However, many of the intervention trials were small, and the various intervention and observational studies were diverse in design, intent and interpretation, with few explicitly designed to address this specific research question. Nevertheless, the general conclusions from the current research corpus contrast with widely held beliefs about sweetness exposure as a driver of sweet taste liking. It is therefore relevant to consider possible reasons why there is poor empirical support for this 'expected' relationship.

Limitations in methodologies

It is possible that the 'expected' relationship (sweet taste exposure → sweet taste liking) exists, but is obscured by limitations in research design and methods related to the exposures or outcome measures. For example, the variation in sweetness exposures in intervention trials may have been too narrow in size and scope, often being limited to just a single food or beverage format. However, similar results (absence of effect) have come from studies involving variation in whole-diet sweetness exposures[25]. In observational studies, reported intake data may not be a valid reflection of habitual diet intakes and must further be translated into a measure of orosensory perceptual exposure to sweet taste. Use of intakes of added sugars or sweet foods and beverages as a proxy indicator of sweet taste liking is highly problematic. Food choices, especially in children, may reflect household food offerings or availability/affordability, and specific 'sweet' or sweetener-containing products may vary greatly in their actual sweetness. The availability of food sensory profile databases[57,58] is a major improvement over earlier research, which made assumptions of sweetness based on the presence of sugars and sweeteners in the diet. Nevertheless, there is no standardised approach for measuring the sweetness of the total diet, making it difficult to combine and compare data across different studies[11,59]. Mean sweetness ratings from trained panels in an isolated setting cannot fully capture the momentary time-intensity profile of sweetness experienced by an individual eating the same food or beverage under real-life conditions.

There are also differences in the methods used to measure individual sweet taste 'liking'. For the purpose of this review and others[25], these methods included sensory hedonic testing, as well as the reported liking, desire or choice and intake of sweet (relative to non-sweet) foods. This diversity of outcome measures reflects the nature of the primary evidence base, and it appears here that the results from different outcome measures generated similar (or at least not clearly dissimilar) conclusions. Nevertheless, variation in how 'liking' is operationalised leaves questions as to what measures are most sensitive, appropriate or meaningful (e.g. relevant to behaviour) and impedes direct comparisons and quantitative meta-analyses of primary research. Conceptual distinctions can be made amongst 'liking', 'desire' (wanting or incentive motivation) and 'preference' (choice), and there are different ways to operationalise these in research[60,61]. Although the practical relevance of these distinctions may only be apparent under certain conditions, further attention to alternative methods and greater standardisation across studies may advance the field. Sensory hedonic (taste) testing under controlled testing conditions is often seen as a 'gold standard', but has important limitations as a measure of generalised sweetness liking, particularly where only a single test medium is used (e.g. sugar in water). Individual differences in the perception of sweetness can vary with sweetener type and concentrations, the context and methods used to present stimuli and collect ratings, and food matrix in which the taste stimuli are delivered[11]. Recent evidence also suggests specific differences in methodologies for determining preferred sweetness levels may also influence apparent relationships with dietary intakes[62].

Underlying much of this research is a presumed (causal) relationship between sweet taste perception and diet, particularly sweet taste liking and free sugar intakes. While this seems intuitive, it has proven difficult to demonstrate robust, consistent relationships in practice. A recent, comprehensive systematic review concluded that measures of preferred sweetness concentrations had inconsistent associations with diet[12]. Measures of taste preferences based on preferences for real foods (choice tasks) may be more ecologically relevant and perhaps predictive of habitual diet, but are also open to more sources of variability and confounding[14].

In addition to the general methodological issues, all the evidence here has come from populations in the USA, western Europe and Australia, with the exception of 2 related studies in Ghanaian children[33,34]. It is possible that other populations, with perhaps much lower or higher habitual consumption of sweetened foods and beverages, may respond differently to changes in sweetness exposures.

Despite the possible methodological limitations, the general research findings are presumed to be valid, suggesting that exposure to sweetness has little impact on subsequent generalised liking for sweetness. There are a number of mechanisms that could explain why that may be true and why presumed analogies to salt exposure may not be appropriate.

Developmental changes and interindividual differences

There is a wide range of within-person factors that have been shown to have an influence on sweet taste liking[15]. Taste cells and receptors start to develop before birth, and an innate unlearned general preference for sweet-tasting stimuli is observed not only in infancy but even *in utero*[63,64]. It may simply be difficult to see the effects of exposure against a strong background of universal liking for sweetness and established individual phenotypic variation within that. Preferences for sweet-tasting foods are observed in children across all cultures, declining from mid-adolescence for reasons that are not clear[63] and increasing again in older adults (> 60 years), possibly linked to reduced taste sensitivity and discrimination[15].

Within the innate general liking for sweetness, there are also sweet 'likers' and 'dislikers', and others showing intermediate responses, as defined by their acceptance of increasing concentrations of sucrose or other sweet tastants[8,62,65]. Sweet 'likers' show rises in liking with increasing sucrose concentrations until an eventual plateau, while sweet 'dislikers' show an increasing aversion to higher concentrations. Between these extremes are patterns of liking that are relatively stable or follow an inverted U-shape across rising concentrations. These differences in sweet-liking phenotypes have been observed across different cultures[66], and a key question here is whether this variation reflects differential exposures. The genetic basis for sweet liker phenotypes and sweet liking in general appear to be complex, but factors including polymorphisms in the TAS1R3 sweet receptor gene may explain up to 50 % of the variation of individuals' liking for sweetness[15,65,67–70]. Numerous studies have also investigated the cross-sectional relationships between sweet taste liking phenotypes and dietary intake of sugars or sweet foods, but the results have been inconsistent, and differences speculated to be attributable to habitual diets, variation in the methods used to define these phenotypes or genetic background[59,66–68,70]. Unfortunately, the paucity of longitudinal data limits conclusions on the possible direction of causality of associations with dietary sweetness exposures[8].

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Sweet v. *Salt taste: differences in perception and biology*

Preferences for salty taste can be altered after sustained changes in sodium intakes, although corresponding changes or dietary associations with the perceived intensity of salty stimuli are not consistently observed[71–74]. Some studies have reported that reductions in sweet taste exposure led to enhanced ratings of sweetness intensity, despite having no significant effects on liking[38,75]. There is not a clear explanation for the lack of corresponding effects of exposure interventions on liking and perceived intensity in some studies, either for saltiness or sweetness[73,75]. Although parallels may be assumed between the effects of sweet and salty taste exposures, there are important differences in their nature and mechanisms. This may be related to the suggested evolutionary relevance of sweetness and saltiness; that is as signals for sources of sugars and sodium, respectively[76]. While sodium is a nutrient required for maintenance of electrolyte balance and other functions, sugars are not essential in the diet. Also, in contrast to sugars, salty stimuli do not contribute to energy intake and are only required in low amounts, and higher concentrations become aversive by recruiting sour and bitter pathways[77].

From a molecular perspective, sweet tastants, through their multiple binding sites situated either at the extra-cellular and/or transmembrane regions, are captured in taste cells by G protein-coupled receptors, mainly taste receptor type 1 (TAS1R), members 2 (T1R2) and 3 (T1R3). This generates a complex intracellular signalling pathway that finally leads to depolarisation and nerve signals interpreted centrally as 'sweet' messages[78]. In contrast, salty tastants are conveyed through ion channels, with entry of sodium (Na^+) triggering depolarisation and a 'salty' message[77,78]. Thus, sweet stimuli interact with dedicated receptors to generate second messengers while the salty stimulus itself is transported into the cell, involving different neurons and brain activation patterns[79]. Lastly, while salt intake is strictly regulated through a highly selective and saturable sodium transport mechanism, the broad range of sweet-tasting stimuli is less strictly regulated and mainly limited by availability and post-ingestive satiety[79,80]. These differences in the biology of sweet and salt taste might underlie differences in the observed effects of variations in tastant exposure on measures of liking in human studies.

Low-energy sweeteners v. *Sugars*

There are trends toward continuing increases in global sales of LES and their relative contribution toward sweetness in the diet[5]. It is therefore relevant to consider whether the relationship between sweetness exposures and liking is influenced by the source of sweetness. Based largely on a subset of animal studies it has been suggested that exposure to LES specifically (*v.* sugars) may specifically influence the development of sweet taste perception and liking[81–83]. A statement that early consumption of LES may affect later preferences for sugars is also expressed in recent child-feeding guidance from the WHO[24]. The leading hypotheses posit that LES consumption may alter the development of sweet taste receptor expression and glucose sensing, or 'uncouple' sweet taste from the energy value of sweet foods in nature[81,83,84]. However, many of the underpinning elements of these hypotheses have limited or equivocal empirical support, and their replicability and interpretation have been challenged[85–87].

The types of compounds that may elicit a sweet taste (not only sugars and LES but also specific fibres, proteins and amino acids) are diverse in their energy value, chemistry, sweetness profiles, bioactivity and metabolism. While they activate the same taste receptors, they do not necessarily share the same binding sites or affinities[88]. Recent systematic reviews of brain imaging studies data indicate uncertainty as to possible differences in neural responses to LES and caloric sweeteners; however, there are many limitations to that evidence base, and questions around the robustness and interpretation of results[89,90]. It is not yet clear how these types of observations might be associated with subsequent physiological or behavioural responses. There is also mixed evidence regarding the stimulation of cephalic phase responses by specific LES relative to caloric sweeteners[91–93], though LES in general appear to have limited effects on post-prandial gut hormone or other physiological responses[94]. The post-ingestive responses to sugars reflect the nature of the carbohydrate, not the perceived sweetness[95]. Lastly, while it has been suggested that LES corrupt the natural relationship between sweetness and energy content, sweetness is poorly predictive of the energy content of human foods and diets, even when LES are excluded[96,97].

The trials described in Table 1 tested foods or beverages containing sugars[28,30,31,33,34,40], LES[29,32,36] or (separately) both LES and sugars[32,35,37–39] as exposures and compared these to unsweetened controls. The general pattern of results was similar for LES and sugar exposures, and the examples where these deviated (all using beverages) generated inconsistent results. Kendig et al. found reductions in liking for higher sugar concentrations following sustained exposure to water or SSB, but not LES[37]. In contrast, Ebbeling et al. reported significant decreases in preferred sugar concentrations following sustained exposure to LES and water, but not SSB[38]. Appleton reported significantly lower percent energy from sweet foods following a single exposure to SSB but not LES relative to water (but no comparison of LES to SSB)[35]. The literature search also identified two additional recent trials that specifically compared the effects of LES *v.* sugar exposures, but had no non-sweet comparators. Dalenberg et al. found no differences in repeated exposure to LES *v.* sugar on the preference for or perceived intensity of sucrose solutions[98]. Casperson et al. reported that following a single acute exposure to LES or sugar with a meal, LES comparatively increased the relative reward value of sweet *v.* salty/savoury snacks, but with no differences between LES and sugar in their effects on ratings of desire to eat sweet, salty, savoury or fatty foods, nor amounts of sugar or of sweet *v.* salty/savoury foods consumed[99]. Taken together, most of the evidence here from human trials on sweetness exposure and liking indicates largely similar results for LES and sugars. However, there are exceptions to this, and there remains active debate around this question, as well as whether effects might differ for specific LES. Given widespread public health guidance focused on reducing sugars and an increasing use of LES in some product sectors, this remains a relevant topic for further research.

Limitations of this review

This was not a formal systematic review of literature, though an effort was made using multiple approaches to identify any potentially relevant publications, and no publication testing the research question as framed was intentionally excluded. However, it is possible some relevant sources have been overlooked, in part because taste or liking measures are usually not a primary outcome in studies on sugars or sweeteners. There was also no attempt to grade the evidence, for example using a quality assessment tool or weighting of the included studies. Over the next few years, results are expected from a number of studies where testing for effects of exposures on sweet taste liking is an *a priori* objective, and those results may solidify or shift the current balance of evidence.

Research recommendations

- Given the volume of newer research and ongoing studies, it would be timely to undertake new high-quality, formal systematic reviews of this research question (with meta-analysis if possible) in the next 2–4 years. Where possible, these should also consider the source of sweetness (sugars or specific LES).
- Research using sweetness exposure as an independent variable should be based on objective data on perceived sweetness and consider the sources of sweetness, rather than using intakes of sugars or sweeteners as a proxy for the sweetness of foods or diets[11,25]. Recent advances in the availability of large data sets profiling the sensory attributes of common foods are already facilitating analyses of taste-diet-health relationships[41].
- Measures to assess generalised sweet taste liking should include a range of sweet and non-sweet stimuli. The comparability of research and its use in quantitative meta-analyses would be facilitated by greater standardisation and validation of hedonic (liking, preference, choice) methodologies.
- The priority for observational research should be on longitudinal cohort data where available. Data analysis approaches should be pre-planned and registered, with careful consideration given to the selection of comparisons, covariates and models, and sources of potential confounding. Although not reviewed here, there is a gap in retrospective or prospective analyses assessing infant and child taste preferences in relation to prior maternal exposures to LES. Where possible these analyses would benefit from consideration of specific LES (due to differences in the potential for foetal or infant exposures).

Conclusions

Despite the widespread presumption of a 'sweet exposure → sweet tooth' causal pathway, the balance of evidence from recent primary research publications, added to evidence captured in earlier systematic reviews, does not provide empirical support that direction of relationship. Or, at best, the evidence for such a relationship is equivocal. The present conclusions are similar for research in adults and children, for LES and sugars, and from both intervention and cohort studies. Moreover, at least in the short term, sweetness exposure consistently suppresses the desire for sweetness. There are a number of limitations to the available research base, which may in part be addressed by future studies; however, there are also a number of plausible bio-behavioural explanations why sweet taste exposure may explain little of the observed variance in sweet taste liking in humans.

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Author D. J. M. is a former employee and current shareholder in Unilever and has carried out consultancy work for Unilever, Cargill Inc., Danone, CBC Israel and Tate & Lyle PLC, providing scientific expertise in the areas of sugars and sweeteners. He is an (unpaid) member of the Scientific Industrial Advisory Board for the European Commission project SWEET, which studies the benefits and risks of sweeteners and sweetness enhancers. He was a co-author of a systematic review (Appleton et al., 2018) cited in this review. Author D. R. is employed at Tate & Lyle PLC.

Both authors shared in formulating the research question, interpreting the evidence and drafting the manuscript. Author D. J. M. was primarily responsible for carrying out systematic searches of the literature and research registries. Both authors take responsibility for the final content.

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