Advances in Nutrition: Perspective

Measuring sweetness in foods, beverages, and diets: toward understanding the role of sweetness in health

Paula R. Trumbo,[1]* Katherine M. Appleton,[2] Kees de Graaf,[3] John E. Hayes,[4] David J. Baer,[5] Gary K. Beauchamp,[6] Johanna T. Dwyer,[7] John D. Fernstrom,[8] David M. Klurfeld,[5] Richard D. Mattes,[9] and Paul M. Wise[6]

[1]Department of Food Science and Nutrition, University of Minnesota, St. Paul, MN, USA

[2]Department of Psychology, Bournemouth University, Dorset, UK

[3]Division of Human Nutrition and Health, Wageningen University, Wageningen, The Netherlands

[4]Department of Food Science, Pennsylvania State University, University Park, PA, USA

[5]U.S. Department of Agriculture Agricultural Research Service, Beltsville, MD, USA

[6]Monell Chemical Senses Center, Philadelphia, PA, USA

[7]School of Medicine and Friedman School of Nutrition Science and Policy, Tufts University, Boston, MA, USA

[8]School of Medicine, University of Pittsburgh, Pittsburgh, PA, USA

[9]Purdue University, West Lafayette, IN, USA

***Corresponding author:** Paula R. Trumbo, 2217 Beckenham Dr., Mt. Pleasant, SC 29466. Telephone: 843-972-8965; e-mail: paulatrumbo@yahoo.com

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Conflicts of interest

PRT serves as an independent consultant on projects supported by the ILSI North America Carbohydrate Committee. She has served as a consultant to PepsiCo, Ocean Spray, Bioneutra, Lantmännen, Hayashibara, GlaxoSmithKline, and 8Greens, and received speaker travel expenses from the Council for Responsible Nutrition that are not related to sweetness or sweeteners. In connection with research on sweetness, KMA has received funding from Unilever R&D Vlaardingen, Netherlands; has current funding from TIFN, Netherlands (in collaboration with Arla Foods, Denmark; American Beverage Association, United States; Cargill, United States; Dutch Knowledge Centre for Sugar, Netherlands; Firmenich, Switzerland; the International Sweeteners Association, Belgium; SinoSweet, China; and Unilever, Netherlands), and from the

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Committees of ILSI North America. She served on the Conagra scientific advisory board until 2018 and on a scientific advisory group for Gerber Nestle until 2019, and advised Motif Foodworks in 2019. She holds stock in several food and drug companies. She is editor of *Nutrition Today*, a nutrition journal, and is a professor at Tufts University School of Medicine and Senior Scientist at the Jean Mayer USDA Human Nutrition Research Center on Aging. JDF is a scientific advisor to the International Glutamate Technical Committee (Brussels, Belgium) and to ILSI North America (Washington, DC). RDM has received research and travel support as well as honoraria from various sources related to sweeteners but has no current support relevant to the topic of this manuscript. DJB and DMK serve as government liaisons to the ILSI North America Lipids and Carbohydrates Committees, respectively, and DJB serves as an unpaid member of the Sabra Wellness and Nutrition Advisory Board, Avocado Nutrition Science Advisory Group, and the California Walnut Commission Health Research Advisory Group, and funding research on sweetness research supported by a competitive grant from the US NIH (National Institute on Deafness and Other Communication Disorders) (other funding is unrelated to sweetness or other topics of this manuscript).

Abbreviations: CS, category scaling; CSIRO, Commonwealth Scientific and Industrial Research Organisation; DA, descriptive analysis; DNF, Dutch National Food; gLMS, general labeled magnitude scale; LMS, labeled magnitude scale; ME, magnitude estimation; NQ+, Nutrition Questionnaires plus; QDA, quantitative descriptive analysis; VAS, visual analogue scale.

Abstract

Various global public health agencies recommend minimizing exposure to sweet-tasting foods or beverages. The underlying rationale is that reducing exposure to the perception of sweet tastes, without regard to the source of sweetness, may reduce preferences for sweetness, added sugar intake, caloric intake, and body weight. However, the veracity of this sequence of outcomes has yet to be documented, as revealed by findings from recent systematic reviews on the topic. Efforts to examine and document the effects of sweetness exposure are needed to support evidence-based recommendations. They require a generally agreed-upon methodology for measuring sweetness in foods, beverages, and in the overall diet. Although well-established sensory evaluation techniques exist for individual foods in laboratory settings, they are expensive and time consuming, and agreement on the optimal approach for measuring the sweetness of the total diet is lacking. If such a measure could be developed, it would permit researchers to combine data from different studies and populations and facilitate the design and conduct of new studies to address unresolved research questions about dietary sweetness. This narrative review includes an overview of available sensory techniques, their strengths and limitations, recent efforts to measure the sweetness of foods and diets across countries and cultures, and a proposed future direction for improving methods for measuring sweetness toward developing the data required to support evidence-based recommendations around dietary sweetness.

Keywords: sweetness, sensory measure(s), taste, diet, nutrition

Introduction

The WHO currently recommends that the intake of free sugars (defined as monosaccharides and disaccharides added to foods, plus sugars that are naturally present in honey, syrups, and fruit juices) be reduced to less than 10% of total energy intake (1, 2). This recommendation is based on moderate evidence from observational studies on risk of dental caries. However, overconsumption of sugar, a high-calorie, low nutrient-density food ingredient, is widely assumed to contribute to obesity and associated health conditions, through the energy it provides directly and, perhaps more importantly, also through enhancing the overall appeal of a broader portion of the diet. Thus, weight control is another presumed benefit of reduced sugar intake.

To assist in reducing sugar consumption, various governmental organizations currently recommend reducing the consumption of sweet-tasting foods and beverages, regardless of the source of the sweet taste (i.e., caloric and low/no-calorie sweeteners) (2-6). The *Cambridge English Dictionary* (7) defines sweet as having a taste similar to that of sugar (not bitter or salty). The *Oxford Learner's Dictionary* (8) defines sweetness as the quality of being pleasant, or the quality of tasting or smelling sweet. Both a specific ingredient or a quality or sensation are elements of these various definitions and both aspects appear to be important. From a physiological perspective, one could consider sweetness to be the generally appetitive sensation that arises when sugars or other sweet compounds stimulate specialized receptor proteins expressed in a subset of cells in taste buds. The rationale for these recommendations is the hypothesis that reduced exposure to sweetness will lead to reduced preferences for sweet-tasting foods and beverages, reduced preferences will lead to reduced consumption of sweet-tasting foods and beverages, and ultimately reduced consumption will decrease caloric intake and favor weight management. However, many links in this presumed causal chain still require empirical confirmation. Elsewhere, a substantial body of research demonstrates that a reduction in dietary sodium intake for a period of several months reduces the preferred saltiness of foods, facilitating the reduction of subsequent sodium intake in the entire diet (9, 10). Interestingly, exposure altered liking, but not sensitivity ratings. These observations are referenced in support of the current CDC (11) and FDA (12) policies recommending gradual reductions in the sodium content of foods and the overall food supply. By analogy, it is assumed that parallel adjustments may also occur for sweetness, but empirical evidence to support this assumption is lacking. The situation is more complicated with sweet ingredients than with sodium, an ingredient that does not contribute to energy intake. Energy-yielding sweeteners may contribute positive energy balance via two primary mechanisms. First, processed sweet food may be energy dense, not so much because of the sugar itself, but because sugar is often combined with fat, a primary driver of energy density. Small quantities of these products can contribute a disproportionate amount of energy. Second, in children and adults, 41% and 33% of added sugars are obtained from sugar-sweetened beverages (13, 14), which are extremely energy dilute but are consumed in high quantities. Reductions in the preferred sweetness level of foods and beverages in the diet could modify the appeal of both types of products and help to moderate energy intake and body weight.

It has been hypothesized that dietary exposure to sweetness influences the way individuals perceive foods and beverages, what and how much is consumed, and/or how the body processes and reacts to what is consumed (15-18). Indeed, an ability to detect and savor simple sugars, the major source of sweetness in nature, reflects the importance of glucose as the major energy source in humans and many other species (19). For example, a strong attraction to honey as a food source in many primates, particularly humans, is consistent with its high levels of glucose and fructose and hence honey's intense sweetness (20, 21).

Appleton et al. (15) conducted a systematic review of published data on the influence of dietary exposure to sweet-tasting foods or beverages on the subsequent generalized acceptance, preference, or choice of sweet foods and beverages in the diet. These studies provided no consistent support for a relationship between sweet taste exposure and subsequent preferences or subsequent sweet food intake. (15)(15)Public Health England (4) reached a similar conclusion based on a literature review. Thus, empirical evidence about the relationship between consumption of sweet-tasting foods and subsequent preferences for or consumption of sweet foods is lacking, as is the assumption that consumption of lesser amounts of sweet foods (apart from all other intake) will bring about decreased caloric intake and decreased body weight. Whether the incongruous responses to salt and sweet exposure reflect a true mechanistic difference is not known. However, it is notable that unlike the case with salt, preliminary evidence suggests that exposure effects for sweetness alter intensity ratings but not hedonic responses (22). If sweet intensity perception does not result in a shift in the preferred sweetness of foods, it is not clear that food choice will be altered.

Numerous studies over several decades have found that overweight and obese individuals have similar sweetness perception and preferences compared to normal-weight individuals (23-26), but the WHO (1) found evidence from observational studies conducted in adults and children (moderate and low strength, respectively) for an association between body weight and intake of free sugars, primarily from sugar-sweetened beverages. Less is known about the association between the sweetness of the *whole diet* and energy intake and health-related outcomes.

Clearly, further work is needed to elucidate putative effects of dietary sweetness on preference for sweet foods, intake of sweet foods, body weight, and associated health outcomes.

Critically, the perception of sweetness cannot be measured simply by quantifying concentrations of sugars in the diet and therefore must be measured by the experiences of human observers. First, a generally agreed-upon and validated measure of dietary sweetness is needed. Methods to measure the effects of sweetness on consumption have generally used a combination of measures including sweetness intensity or preference ratings of individual food items with a measure of food intake.

Given clear evidence that dietary patterns are relevant to long-term health, an effective measure would need to capture the sweetness of an entire diet or dietary pattern, not merely the sweetness of specific foods or food categories. The 2015–2020 Dietary Guidelines for Americans (27), as well as the Scientific Report of the 2020 Dietary Guidelines Advisory Committee (28), emphasize the importance of overall eating patterns for health, as compared to a focus on individual foods. This narrative review sets the stage for examination of 1) the current approaches for measuring perceived sweetness of individual foods and diets and 2) the extant databases related to the sweetness of whole diets. Based on this review, research questions are identified for improving the measurement of the perception of sweetness.

Available methods to measure perception of sweetness of individual foods and diets

To support the collection of data on the relationships between sweetness and diet, validated measures of sweetness are needed that are well accepted across the scientific and public health communities. The most relevant parameters of exposure remain unknown but may include mean sweetness across foods in the diet, maximum sweetness among all items consumed, and frequency with which people consume items of some minimum level of sweetness. Because the most important parameters are unknown, an ideal method would capture as much information as possible about the sensory properties of the diet. Ideally, the measurement method should 1) be easy for participants, experimenters, and possibly clinicians to complete, 2) be low cost, and 3) allow valid comparisons between groups of people with different cultures, numeracy, and literacy.

Sweetness measurement theory

Before discussing specific techniques to measure sweetness, it may be useful to consider a general concept from theory of measurement, viz. that some measures provide more information than others. In 1946, Stevens (29) proposed a hierarchical framework to describe various levels of measurement and types of data: nominal, ordinal, interval, and ratio (**Table 1**). Ordered data (ordinal scale) provide a ranking but no indication of spacing between items. Interval data are equally spaced, but the zero value may not have a real meaning (e.g., 20°F is not twice as warm as 10°F). The most informative approach to measure perceived sweetness intensity of sweet substances is to use a ratio-level measurement with a true zero, because this allows for meaningful ratios to be constructed and for more powerful statistical evaluation. For example, a liquid at 310K does in fact have 14% more heat than a 273K liquid, because the zero is meaningful on a Kelvin scale. Only with ratio-level measurement can it be determined that, for example, a food assigned a number twice as high has twice the perceived sweetness. Why might this matter? As discussed in the paragraph above, the most relevant parameters of exposure to sweetness remain unknown. The ability, for example, to perform valid calculations of the ratio of minimum to maximum sweetness for foods consumed within a meal or over the course of some period of time may not prove important for understanding the impact of exposure to sweetness. However, all else being equal, a measure that provides more information will allow more options for valid analyses.

Examples of techniques for measuring sweetness: direct and indirect methods

Perception is an internalized experience that cannot be directly observed by another individual. Some indirect methods infer perceived sweetness from observable behaviors (e.g., how well people can discriminate between different concentrations of a sweetener). Despite the advantage of being based on objective data, such techniques are not practical for assessing the sweetness of a large number of foods and beverages, due in large part to their intensive nature. For example, indirect measurement of an intensity versus concentration function for sucrose in water required 3600 judgments collected over months (30). In contrast, direct methods rely on the observer to report how intense a sensation is. A number of such techniques for measuring sweetness are discussed below and a general summary of each, including the limitations, is provided in **Table 2**.

Magnitude estimation (ME) is perhaps the "gold standard" direct method for ratio-level measurement. In various forms of ME, subjects assign numbers to sensations proportional to perceived intensity. Thus, a sugar solution that tastes twice as sweet as another would be assigned a number twice as large, while a solution that tastes half as sweet would be assigned a number half as large (31). ME has been cross-validated, in part, via comparisons across different sensory modalities and to neural activity recorded from taste nerves (32, 33). ME has played an important role in developing and validating other indirect methods (including the general labeled magnitude scale [gLMS], discussed below). However, ME is probably not ideal for measuring sweetness in the diet since it provides only relative information regarding perceived intensity (no semantic information regarding intensity is provided) and ME can be difficult for participants with low numeracy.

Because researchers often desire semantic information that ME cannot provide, another widely used direct method is category scaling (CS). In CS, participants select one of a fixed number of responses; the response options may or may not have numbers visible to participants, but researchers typically code these with integers to provide ordinal data. For taste intensity, various CS approaches have been used (e.g., a 9-point scale with labels "no sweetness" at 1, "slightly sweet" at 3, moderately sweet" at 5, "strongly sweet" at 7, and "extremely sweet" at 9) (34, 35). For measurements of sweetness using a CS, one can reasonably conclude that a sample scored 4 tastes sweeter than a sample scored 2. Critically, however, it cannot be assumed that the intensity is twice as large, unlike a ratio-level measure like ME. However, labels associated with the categories provide some useful semantic information about the absolute level of sweetness, and category scales tend to be easy and intuitive for participants to use, so they remain popular despite this limitation. Also, it should be noted that the semantic labels may not indicate the same level of sensation across individuals or between groups that differ systematically (e.g., by age, dietary exposure, or genetics) (36-38).

The line scale/visual analogue scale (VAS) is another widely used direct scaling method. In this method, participants rate sensation by marking a line segment with anchored endpoints at the extremes (e.g., minimum and maximum). These differ from CS in that participants can mark at any point on the line resulting in the data being roughly continuous rather than being discrete. These scales may yield better resolution, and some empirical work is consistent with this idea (39-41), although other work finds that a 9-point category scale, a VAS, and ME are comparable in their reliability and ability to resolve small differences among stimuli (42, 43). Regardless, participants are not usually instructed to make ratio judgments, and therefore ratio-level data are not typically assumed. However, some variant of the VAS may yield ratio-level data with appropriate construction and orientation (44, 45).

Another direct scaling technique, the labeled magnitude scale (LMS), attempts to combine the semantic information of CS, the continuous response properties of the VAS, and the ratio measurement of ME. This scale has semantic intensity labels (barely detectable and strongest imaginable [taste or oral] sensation at the extremes, with intermediate labels such as moderate). Unlike CS, spacing of descriptors is empirically determined according to ME ratings for these labels, and therefore nonlinear (46-48). Slopes of intensity versus concentration ("psychophysical functions") measured using a LMS agree well with slopes measured using ME (44, 47, 49), suggesting that a LMS yields ratio-level data. A common variant called the gLMS anchors the top of the scale with "the strongest imaginable sensation of any kind," which was intended in part to allow valid comparisons between groups of people who differ in sensitivity to taste or oral sensations (36, 38). Thus, the gLMS combines the strengths of various other direct methods outlined above, although there is a tendency for participants to cluster ratings near the verbal labels (44), suggesting that some participants may use it in a manner similar to a CS. Further, the gLMS requires more extensive training and instructions than CS.

All of the methods mentioned above have originated in the academic literature and have been used largely in studies using naïve participants. These methods will now be contrasted with another set of methods that first arose in industrial practice, discussed below, which rely on highly trained observers.

Descriptive analysis methods for measurement of sweetness

As a family of methods, descriptive analysis (DA) techniques were initially created by practitioners to meet the needs of food and consumer goods companies [e.g., (50, 51)] who, unlike academic psychophysicists, had a practical need to quantify the sensations from foods and consumer products (52). The basic approach includes 1) selection of panelists, 2) development of a common language that comprehensively and accurately describes product attributes, 3) training panelists to align use of these common product attributes and the use of intensity scales in the products being tested, and 4) blinded evaluation of the products (52).

To quantify sweetness, a simplified version of DA is sometimes used where participants are trained to rate sweetness relative to standard reference solutions of sucrose, often from 0 to 20% sucrose by weight (or "brix," a measure of the sugar content of an aqueous solution). Thus, a sample that tastes as sweet as 8% sucrose is rated as 8, a sample that tastes as sweet as 12% sucrose is rated as 12, and so forth [e.g., (53)]. Using such physical referents instead of semantic intensity labels provide an unambiguous means to communicate results and, within the context of a particular product, can provide simple direct information to guide concentration adjustments to match a target level of sweetness. Repeated resampling of the references during blind testing may reduce the amount of training needed beforehand, but their addition might also cause sensory adaptation that alters the accuracy of the rating; with practice, participants are able to rely less on references. However, even if performance was functionally perfect, using a physical concentration as a reference would not result in ratio properties in regard to perceived sweetness, since intensity is usually a nonlinear function of concentration (i.e., doubling the concentration of sucrose does not double perceived sweetness) (49).

More broadly, two major approaches to DA emerged in the 1970s: Quantitative Descriptive Analysis (QDA) and Spectrum Descriptive Analysis (Spectrum). These two methods use the same general approach—trained panelists are aligned on descriptors, and then products are rated blind for intensity of each descriptor—but they have some nuanced differences in their implementation (54). In QDA, all intensity ratings are considered relative to the other items tested, whereas Spectrum uses what is termed a "universal scale." Typically, this is a 150-point scale (classically 15 cm, measured to one decimal point) meant to encompass the entire range of sensations one might encounter in commercial food products. Participants then receive extensive training on use of this scale, with intensity anchors tied back to specific references, which may be simple model systems or real commercial products as this method arose from industrial practice (54). For sweetness, a 2 would be 2% sucrose, a 7 would be the sweetness of lemonade, and a 9 would be a specific national brand of soft drink. In Spectrum scaling, a 6 for intensity is meant to be equal across qualities, so a 6 for sourness should equal the intensity of a 6 for sweetness. A putative strength of this approach is that training with references that evoke multiple qualities (i.e., lemonade is both sweet and sour) should encourage an analytic mindset while rating but also clarify distinctions between attributes (55). Regardless of whether Spectrum or QDA is used, heavy use of exemplars during training helps reduce conceptual ambiguity of what panelists are rating in perceptually complex foods. Information on multiple sensation qualities can also allow analyses of how other flavors modulate perceived sweetness and how well the overall flavor profile predicts nutrient content. The scales used in QDA and Spectrum are rarely discussed within Stevens' measurement typology (29), but ratio-level data cannot be assumed.

Factors affecting ratings of perceived intensity

Numerous factors affect the perceived intensity of sweetness. Three important factors are discussed below. In addition to these, it may be useful to characterize color, as there is some evidence (albeit inconsistent) for an effect of color on sweetness perception (56).

Sweetener concentration

Most obviously, sweetener concentration is a major factor in the sensation of sweetness and it is routinely changed to alter sweetness intensity of products (57). Rated sweetness increases with sweetener concentration over a wide range of concentrations (22, 58-60). Ratings made using all of the methods outlined above increase with sweetener concentration to some point, suggesting that all offer at least ordinal measurements of sweetness. It is critical to distinguish between the amount of sugar in a product and the rated sweetness it evokes. As shown in **Figure 1**, the same amount of sucrose (920 mg) tastes roughly half as sweet when presented in twice the amount of water. Nutritionally, these samples are functionally identical from the amount of sugars and calories they provide, but perceptually, they are not.

Range of presented stimuli (context)

There are also other factors that affect ratings of intensity sensation. One important factor concerns the concentration range of stimuli that are experienced within a test session. For ME, exponents of rated intensity versus concentration functions are flatter when the range of presented stimuli is wide and steeper when the range of presented stimuli is narrow (35). Lawless and colleagues (61) showed that category scales, VASs, and two forms of LMS showed range bias as well. Participants also tend to rate a given stimulus as less intense in the presence of stronger stimuli and more intense in the presence of weaker stimuli (a contrast effect) (61). Sensory adaptation, or fatigue, could contribute to such effects, but they still occur when adaptation is controlled (61). Thus, intensity ratings ultimately cannot be regarded as simple reflections of underlying sensation outside the context of a particular method (58, 62). A key question here is whether these contexts affect how participants mentally map responses into sensations, or how the sensations are actually perceived. For example, if someone rates a 10% by weight sucrose solution as “moderate” when presented after a 5% solution, but “weak” when presented after a 20% solution, did the perceived sweetness of the solution really change, or did the rater simply choose a different response?

Food matrix

The same amount of a sweetener might taste very different depending on the food matrix. Taste differences may be due to physical effects, such as effectively sequestering sweeteners so that they are less able to dissolve in saliva and interact with sweet receptors. Although sweetness is clearly related to concentrations of sugars in foods, this relationship can be decoupled in several ways: sweetness is imparted by nonsugar ingredients (e.g., low-calorie sweeteners), or sweetness can be masked by other ingredients. Sweetness can be inhibited centrally (in the brain), as exemplified by mutual suppression of sweetness and bitterness, such that adding a bitter compound to a fixed concentration of sweetener makes the solution taste less sweet (63, 64). This is the reason, for example, why people might underestimate the sugar content of tonic water containing bitter quinine (see Figure 1). Enhancement effects, including synergy between different sweeteners, also occur (65) and such effects are part of what shapes rated sweetness during the consumption of foods and beverages. Assuming that rated sweetness reflects sweetness sensation, food matrix and enhancement effects are not problematic for measuring the sweetness of the diet. Such effects, however, may affect the influence of dietary sweetness on food choice, intake, and physiological responses to foods. Furthermore, these interactions highlight the point that added sugars and perceived sweetness are not interchangeable.

Individual differences and their effects on the measurement of sweetness

Even within a particular context, people differ markedly in how they rate sensations (35). If one person rates a given concentration of sugar as sweeter than does a second person, do the people differ in what they actually taste, differ in how they rate what they taste, or both? At least some individual differences in sensitivity to the sweetness of sugar are associated with differences in genes which encode sweet receptors expressed in taste buds (66-68). Thus, people probably do differ in what they actually taste. However, people are often consistent in their tendency to assign relatively high or low ratings across sensory modalities (69). Accordingly, researchers have proposed various ways to use cross-modal information to adjust for such individual idiosyncrasies (70, 71). An important assumption is that individual differences in the modality that is used to "control" for differences in how people use scales (e.g., the loudness of tones or the brightness of lights) are at least partially independent of individual differences in the modality of interest (in the current context, sweet taste). Regardless, measuring the intensity of sensation in more than one kind of sensory modality on the same scale can offer potential advantages in understanding individual differences (72).

The subject's concept of sweetness

Ratings of intensity depend, in part, on the raters' concept of the sensation to be rated. Few people with an otherwise normal sense of taste would fail to recognize sucrose (table sugar) as sweet. However, in sensory experiments, adding some nominally tasteless aromas, such as fruity esters or vanilla, can cause subjects to rate both simple sugar solutions and real foods as sweeter (73-76). In many studies, sweetness enhancement by aroma is less likely if the participants rate both sweetness and aroma (e.g., "fruitiness") than if they just rate sweetness (77-79). Clark and Lawless (77) have framed such enhancement effects as a scaling bias called "dumping." In this explanation, participants perceive a distinct sensation from the added aroma but, lacking an appropriate option to rate this aroma, they assign the sensation to ratings of sweetness. Notably, however, odors less congruent (or compatible) with sweetness like peanut butter do not enhance sweetness (80). Further, training raters to adopt an analytic approach (analyze sensation into components) rather than a synthetic approach (respond to flavor as a whole, a natural tendency for untrained consumers) (81) also makes it less likely for aroma to influence ratings of taste intensity, even if subjects rate sweetness but not aroma (82, 83). Accordingly, odor enhancement of sweetness is not purely an artifact of the rating task (84). Rather, it appears that the concept of "sweetness" can include compatible nontaste sensations, depending on how experimenters ask the question and how raters approach the task (83). While overall flavor is widely believed to be important for food choice and eating behavior (83), the relative importance of odor and taste in determining food choice and satiety is unclear (85); thus, additional research is needed. Ideally, ratings of sweetness would be obtained from both naïve consumers *and* more trained, analytically oriented panels, since both may convey important and potentially complementary information.

Conclusions and future directions regarding measurement of sweetness

Key features, strengths and weaknesses of the various techniques discussed above are presented in **Table 2**, and some directions for future work are presented in **Box 1**. Regarding the various subjective scales used (ME, category, VAS, gLMS), it is important to remember that all meet the most important criterion for validity, viz. that rated sweetness increases over a broad range of concentrations of sweetener. Thus, all provide potentially useful information. ME and gLMS may provide more information in Stevens' theoretical framework of level of measurement, and thus allow a broader array of valid analyses of parameters of dietary sweetness. However, ME might prove difficult for people of low numeracy to use, and gLMS labels might be difficult to translate for use across various cultures. VAS and the closely related scales used in the SPECTRUM-derived techniques do not have these limitations, but may or may not provide ratio-level measurement. However, relatively little effort would be required to validate a particular VAS for sweetness against ME to establish level of measurement.

Regardless of the particular scale used, ratings of sweetness will depend on factors such as context (crucially, the overall range of sweetness intensity among presented samples) and panelists' concept of the sensations they rate (e.g., how completely they separate "sweet" aroma from sweet taste). Since these factors are in turn methods-dependent, perhaps the most important consideration in developing a technique various laboratories can use to build a joint data-base is to establish a more comprehensive set of overall procedures for training and testing panelists. The SPECTRUM-derived techniques embody these principles, even if they have not been perfectly standardized to date. A possible area for further development is to determine if comparable data can be obtained with less intensive, long-term training of panelists.

Current taste databases for the measurement of sweetness in diets

Development of sensory databases

Three studies developed taste databases that measured the sweetness intensities of foods in Australia (86), France (87), and the Netherlands and Malaysia (88). These studies all used a modified Spectrum approach for measuring the perception of sweetness (89) using trained sensory panelists for developing the taste databases for each country. These standardized scales allow for a comparison of the data collected across studies, with multiple panels, and even allow for a comparison of the rated intensities of sensory attributes across the different types of foods (90, 91). These rigorous approaches have potential utility for evaluating the sweetness of diets on a population level but are likewise resource intensive. To note, sucrose and food standards, even if they were entirely consistent across panels, might not allow valid between-group comparisons if groups differ systematically in how they perceive the standards. Granted, the Spectrum-inspired techniques also include ratings of other sensation qualities, but all tend to be focused on taste or oral sensation, which might in turn be correlated with sweetness (92). A possible modification would be to include some uncorrelated sensations, such as loudness of sounds or brightness of lights, as in the method of magnitude matching.

Lease et al. (86) developed a Sensory-Diet database using an Australian children's national nutrition survey. Foods were selected as representing the total diet based on frequency, food grouping, nutritional, and/or sensory differences. Database development involved measuring basic taste intensities (sweet, salt, sour, bitter, umami) and texture profiles of 377 single foods based on the Australian food consumption survey. From the 377 foods, the researchers imputed the sensory profile of 3758 foods.

A similar approach was used by Teo et al. (88) for the Netherlands and Malaysia, where 469 Dutch and 423 Malaysian foods were profiled for the five basic taste intensities and fat sensation. In the Netherlands, mostly single foods were characterized, whereas in Malaysia, mixed dishes were profiled. The profiles of the measured intensities were used to create a taste database of 1407 Malaysian foods and 1346 Dutch foods, representative of 97% and 99% of energy intakes in Malaysia and the Netherlands, respectively.

Martin et al. (87) created a food "taste" database following intensive panel training similar to that conducted by Lease and colleagues (86). A slightly different approach was used, in that a trained panel profiled the five basic taste intensities and fat sensation of predominantly mixed dishes as eaten at home. In total, 590 foods/dishes were profiled. Using cluster analyses, the foods were categorized into six taste clusters: 1) salty, umami, fatty (253 foods; 43%); 2) sweet (155 foods); 3) sweet, sour, bitter (57 foods); 4) bitter (24 foods); 5) salt, umami, bitter, sour (58 foods); and 6) salt (43 foods).

The Dutch and Australian taste databases are based on single foods that are frequently consumed using the Dutch and Australian food consumption surveys. The Dutch database has also been validated using a food frequency questionnaire and biomarkers of nutrient exposure (93), and therefore would be useful in evaluating sweetness exposure and health outcomes in large prospective cohort studies. The French database is based on composite foods consumed by a group of about 15 trained subjects, which makes it more difficult to make a connection with the overall sweetness exposure of the French diet. The critical gap with all three databases is that they have not yet been used in relation to the large prospective cohort studies.

Panel training and performance

Teo et al. (88) aimed to assess the extent to which an extensive training procedure with two panels from different cultures yields similar results with respect to the taste profiles of 15 reference taste solutions and a selection of 19 identical control foods. Both taste panels were monitored for their discriminatory power, explanatory power agreement within the group, and repeatability. Panelists were checked on whether they used the same range of scale, scored the product in the same magnitude, discriminated the products, perceived the same taste attributes, and scored the products similarly to the rest of the panel during each training session. **Figure 2** shows the mean sweetness intensity ratings of 19 identical products of the Malaysian panel as a function of the mean sweetness ratings of the Dutch panel. The two panels yielded similar sweetness ratings for each food. This study demonstrates that extensive panel training resulted in similar taste evaluation results, regardless of cultural and geographical backgrounds. Whether such performance will be achievable with untrained consumers is not known.

Relationship between sweetness and nutrient content of foods

The taste database developed by Martin et al. (87) and a French Food Composition table were used to obtain a dataset combining sensory and nutritional information for 365 foods (94). The sweet taste intensity ratings correlated with the carbohydrate content ($r = 0.57$, $P < 0.0001$) and strongly correlated with the mono-disaccharide content ($r = 0.84$, $P < 0.0001$). No strong correlations were observed with other nutrients.

Sweetness exposure, energy intake, and diet quality

Van Langeveld et al. (94) assessed dietary taste patterns in the Netherlands by sex, BMI, age, and education. Six taste clusters were identified among 476 profiled foods: “neutral” (27%), “sweet and sour” (14%), “sweet and fat” (23%), “bitter” (4%), “salt/umami/fat” (24%), and “fat” (8%). Two population-based cohorts (Dutch National Food [DNF], $n = 1351$; and Nutrition Questionnaires plus [NQ+] study, $n = 944$) were used to calculate the contribution of each of these taste clusters to the overall energy intake of the diet. Women consumed a higher percentage of energy from sweet and fat–tasting (15% [DNF] and 15% [NQ+]) and sweet and sour–tasting (13% [DNF] and 12% [NQ+]) foods compared with men (sweet and fat: 13% [DNF] and 12% [NQ+], $P < 0.001$; sweet and sour: 13% [DNF] and 10% [NQ+], $P < 0.001$). Notably, energy intake from sweet and sour– and sweet and fat–tasting foods was relatively higher during snacking occasions compared with main meals, which corresponds with reported intakes of monosaccharides and disaccharides with snack consumption. The conclusion was that taste can be related to macronutrient intake of individual foods, as well as the total diet. The data also showed that the contribution of sweet-tasting foods to energy intake in the diet is generally similar among people with normal weight, overweight, and obesity (**Figure 3**).

Cox et al. (95) quantified the sensory profiles of different food groups (e.g., fruits, vegetables, grain, meats) in Australia using the validated Sensory-Diet tool database (89), representing the specific foods covered in each question of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Healthy Diet Score survey used to estimate food intake. The CSIRO Healthy Diet Score survey was also used to calculate a diet quality score. Average sensory scores (weighted by frequency of consumption) were calculated for each grouping of food covered per survey question. Reported intake of each food group was multiplied by the sensory scores for each food group. To determine the total sensory value of an individual's diet, sensory values of each food group were then summed to give a total dietary sensory score. Sweetness of the diet was quantified by multiplying grams of each food consumed by the sweetness intensity of that food. By dividing the sweetness value by the total energy intake, the sweetness density of the diet was calculated for approximately 10,000 adults and 2700 children. Higher diet quality was associated with higher sweet and bitter scores, but a greater proportion of this sweetness was from healthy core foods (e.g., fruit, vegetables, grains, and dairy) rather than discretionary foods (e.g., chocolate and confectionary, cakes and biscuits, pies and pastries).

Conclusions

Some governments and influential health organizations recommend diets low in sweetness based on a widespread and longstanding belief in a causal chain: a highly sweet diet leads to changes in perception of sweet foods and beverages, which in turn leads to overconsumption of sugar, which finally leads to negative health outcomes. However, no link in this proposed causal chain has strong empirical support. Empirical evaluation of at least the first two links will require measures of human perception of sweetness. Some of the important research questions that have been identified are provided in **Box 1**.

There are important challenges in measuring perceptions of sweetness of individual foods and beverages. The challenges are even more daunting when attempting to measure the sweetness of entire diets. Ratings of sweetness depend on the scale one uses, the context (i.e., the range of intensities presented in a test session and perhaps the level of sweetness raters experience in daily life), and how raters approach their task (e.g., whether their concept of sweetness includes “sweet” aromas like vanilla). In short, ratings of sweetness are not independent of the set of procedures that are used. Further, it is not known if differences are due to how a person perceives sweetness and/or how the person uses the rating tool/scale. Accordingly, agreement on a standard set of procedures to facilitate comparisons across studies toward an integrated database is one priority.

With a reliable method, studies related to the effects of sweetness on health-related outcomes could be evaluated. Although well-established sensory evaluation techniques in laboratory settings exist for individual foods, agreement on the optimal approach for measuring the sweetness of the total diet is lacking, particularly in settings other than in the laboratory. The development of such measures would permit researchers to combine data from different studies and populations. This would facilitate the design and conduct of new studies to address unresolved research questions about dietary sweetness in foods and diets and relationships to health outcomes. This is a second priority.

Future research, including longitudinal research, is needed to understand 1) the role, if any, of sweet-tasting foods, beverages, and diets, as well as sweetness intensity, in food preferences, energy intake, dietary intake, and health-related outcomes such as obesity and dental caries, and 2) if so, in what way these factors operate. Findings from the Netherlands using a taste database (94) indicate that it may be possible to profile diets based on their taste characteristics. If this is accomplished, the association between sweetness in the diet and food preferences and health-related outcomes could be evaluated, along with the role of sociodemographic/cultural variables. Addressing these is a third priority.

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Author contributions

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Figure 1. Sweetness ratings of three samples that each contain 920 mg of sucrose. Bars are group means and standard errors, and dots are the individual ratings. All samples were presented in a counterbalanced Williams design; ratings were obtained using a general labeled magnitude scale (gLMS) by 61 participants (Brodock, Alshouse, & Hayes, unpublished data). BD, barely detectable.

Figure 2. Mean sweetness intensity of 19 identical products rated by the trained Malaysian panel as a function of the mean sweetness intensity of the trained Dutch panel. Figure is based on data provided in Teo et al. (88).

Figure 3. Contribution of sweet-tasting foods to energy intake in the diet among individuals with normal weight, overweight, and obesity. Data adapted from van Langeveld et al. (94).

Table 1. Hierarchical levels of measurement

Levels of measurement	**Data description**
Nominal	Named variable No specific order A = B or A ≠ B
Ordinal	Named + ordered A > B
Interval	Named + ordered + proportionate interval between variables A is 2.3 units greater than B
Ratio-level	Named + ordered + proportionate interval between variables + can accommodate absolute zero A is 35% higher than B

Table 2. Available methods to measure perceptions of sweetness of individual foods and diets

Method	Direct, indirect, objective, or subjective	Easy to implement and score	Requires a large number of judgments	Other features, including challenges and limitations
Discrimination	Indirect Objective	No	Yes	For foods, fixed standard of comparison impossible Can be unclear about what cues people use to make the judgment Slow and labor intensive
Magnitude estimation	Direct Subjective	Yes	No	Considered the "gold standard" for ratio-level measurement of intensity Obtained values are only meaningful in relation to a fixed concentration (e.g., modulus), and provide no semantic information about absolute intensity Difficult for some raters to use, particularly those with low numeracy
Category scale	Direct Subjective	Yes	No	Only provides rank-order data Provides semantic information about absolute intensity (but is easy and intuitive for raters)
Visual analogue scale	Direct Subjective	Yes	No	Provides no semantic information about absolute intensity Usually does not provide ratio-level data (but is relatively easy and intuitive to use)
Spectrum method of descriptive analysis	Direct	No	No, once panelists are trained	Panelists are typically screened for sensory acuity and ability to make sensory judgments

and quantitative descriptive analysis				and undergo many hours of rigorous training before data collection begins
	Subjective			A concern is whether highly trained panels, selected and coached to uniformity, provide sensory profiles that reflect differences in the perception of randomly selected naïve consumers
				No effort is made to check or ensure ratio properties of ratings
Labeled magnitude scale	Direct	Yes	No	Provides ratio-level data and semantic information about absolute intensity
	Subjective	Can require more extensive instructions and practice compared to other methods		Translating the verbal intensity descriptors between languages and cultures might prove difficult
Magnitude matching	Direct	Easy to score	No	Less ambiguous language to communicate results
	Subjective; can include an objective component	Relatively more difficult to implement		Accuracy of the judgments depends in part on how well participants have been trained
				Ordinal measurement

Box 1. Key research questions about the measurement of sweetness to support evidence-based recommendations on dietary sweetness

- How should sweetness be defined?
- What are appropriate methods for judging sweetness intensity in individual foods?
- What are the key food matrix and processing effects that affect sweetness ratings of individual foods?
- How can quantitative data on sweetness from individual foods be translated to the sweetness of a meal, entire diet, or dietary pattern?
- For profiling dietary sweetness, what current or additional databases are available or needed?
- Does experience with different levels of sweetness influence subsequent sweet preferences? Does this influence operate similarly based on sweetness level, regardless of food type/category?
- Do preferences for the sweetness of individual foods and beverages predict long-term preferences for sweetness levels of foods and beverages?