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Understanding sweet-liking phenotypes and their implications for obesity: narrative review and future directions.

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Abstract

Building on a series of recent studies that challenge the universality of sweet liking, here we review the evidence for multiple sweet-liking phenotypes which strongly suggest, humans fall into three hedonic response patterns: extreme sweet likers (ESL), where liking increases with sweetness, moderate sweet likers (MSL), who like moderate but not intense sweetness, and sweet dislikers (SD), who show increasing aversion as sweetness increases. This review contrasts how these phenotypes differ in body size and composition, dietary intake and behavioural measures to test the widely held view that sweet liking may be a key driver of obesity. Apart from increased consumption of sugar-sweetened beverages in ESL, we found no clear evidence that sweet liking was associated with obesity and actually found some evidence that SD, rather than ESL, may have slightly higher body fat. We conclude that ESL may have heightened awareness of internal appetite cues that could protect against overconsumption and increased sensitivity to wider reward. We note many gaps in knowledge and the need for future studies to contrast these phenotypes in terms of genetics, neural processing of reward and broader measures of behaviour. There is also the need for more extensive longitudinal studies to determine the extent to which these phenotypes are modified by exposure to sweet stimuli in the context of the obesogenic environment.

Key words:
Sweet taste, liking, hedonics, individual differences, obesity, sweet-liking phenotypes

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1. Understanding sweet liking in humans

Since our earliest recorded history, forms of sweetened food and drinks have been part of the human diet, with cane sugar used for over 6000 years [1]. Throughout history and in modern popular culture, there is a widely held belief that individuals with a strong liking for sweet taste are prone to overeat and consequently are at greater risk of obesity [2]. There is no doubting that an imbalance between energy intake and expenditure will lead to weight change, with a positive imbalance leading to weight gain. And as many sugar-sweetened products are energy-dense (for example, cakes, biscuits and confectionery), it is clear that excess intake of these types of products will contribute to this imbalance. However, the key question addressed in this review is the extent to which different patterns of hedonic responses to the sweet taste of sugar (defined as sweet-liking phenotypes) are a plausible driver of over-consumption and consequent weight gain, revisiting the view that evidence for a clear link between sweet liking and obesity is weak [3-5].

Sweet liking has long been considered an innate preference, evidenced through infants’ positive facial reactions to the presence of sweet-tasting substances [6-8] and even observed in the womb before birth [9]. However, a growing body of research sparked by the classic work of Pangborn [10] has challenged the universality of sweet taste liking. Detailed analysis of the subsequent literature on how rated liking relates to sweetness concentration (reviewed in Section 2) suggests that humans fall into three distinct phenotypic response patterns: those whose liking increases with sweetness intensity (here referred to as extreme sweet likers: ESL), those who show mild liking for moderate levels of sweetness (moderate sweet likers: MSL) and those who show increasing dislike as sweetness increases (sweet dislikers: SD).
This review considers potential explanations as to why there are different sweet-liking phenotypes (Section 3) and contrasts how they differ in body-size and composition (Section 4), in use and consumption of different foods, drinks and broader flavour preferences (Section 5) and on psychological measures (Section 6) to test the widely held view that liking for the sweet taste of sugars may be a key driver of obesity. To achieve this, we focussed only on human studies that classified sweet-liking phenotypes based on actual hedonic (i.e. liking) measurements and not measures of relative preference. A great deal of that literature has focussed on responses to sweet taste in children [e.g. 11, 12-14] who are less able to engage conceptually with continuous ratings of liking (for a detailed review of methods for defining sweet-liking phenotypes see [15]). However, the absence of a specific measure of liking in most of those studies makes it difficult to determine whether responses were driven by actual liking or more by incentive motivation (motivation due to desire for a reward). Indeed, one of the most widely used tools to more broadly assess liking and wanting in humans explicitly uses a choice measure (between different foods) to assess wanting and uses rated liking for these foods to measure hedonic motivation [16]. For this reason, we only discuss these studies when we consider the drivers of overconsumption beyond sweet hedonics (Section 7) and note where future research is needed (Section 8). As we discuss later, it may be that excessive incentive motivation (wanting) but not liking that may predict excess consumption, a conclusion that contradicts the simple view that sweet liking drives obesity.

The focus of this review is on liking for the sweet taste of sugars. Sweetness is, of course, also experienced from an ever-increasing range of non-nutritive sweeteners (NNS), and both
the range of products sweetened with NNS [e.g. 17] and overall NNS intake have increased in recent years [18]. However, we concentrate here on sweetness in relation to sugars for two specific reasons. Firstly, the majority of studies exploring individual differences in sweet liking in humans have focussed primarily on responses to sugar, typically using sucrose to identify different phenotypes (reviewed in Section 2). Secondly, if sweetness increases intake, then this will be most evident for sugars because of their caloric content.

A further reason why reconsideration of the role of sweetness liking in driving obesity is needed is the increased focus on the intake of sugar-rich products to counter the worldwide increase in obesity. Across the globe, people live in diverse food environments with varying access to resources to make informed decisions about food choice [19-22], and where often the most accessible food is unhealthy, containing high levels of fat, salt and sugar [23-25]. As such, many countries have enforced legislation, including specific sugar taxes [26-28], that aims to reduce sugar intake on the assumption that sweet liking drives overconsumption. By comparing how the sweet-liking phenotypes differ on measures that relate to obesity (i.e., body size and composition, intake of sweetened products), we hope to shed new light on this key issue.

2. What is the evidence for multiple sweet-liking phenotypes?

As we note above, the idea that there are clear individual differences in the expression of sweet liking started with the classic work of Pangborn [10]. Based on visual inspection of individual profiles of rated liking as a function of sugar concentration, she identified the three distinct phenotypes noted earlier (extreme sweet likers, ESL; moderate sweet-likers, MSL; sweet dislikers, SD). That observation of consistent individual differences has
subsequently been replicated in numerous studies (reviewed in [15]). However, from the early 1970s until recently, most studies used a simpler two group distinction, classifying individuals as either sweet likers (SL, also referred to as Type 2 responders in some studies) or sweet dislikers (SD, or Type 1 responders). More recently, the use of hierarchical cluster analysis of liking ratings and perceived sweetness intensity for a wide range of sucrose solutions has allowed a more robust and statistically-based method for assessing how many distinguishable patterns of response are seen. These analyses strongly suggest that there are three distinct phenotypic liking patterns (Figure 1) of ESL, MSL (also often referred to as inverted-U responses) and SD which have been found across adult populations in the UK, US and Asia (e.g. [29-32]), statistically validating the impression Pangborn had from visual inspection of individual responses 50 years ago.

One of the key differences between studies of hedonic responses to sucrose solutions is the range of concentrations tested (as discussed in more detail in a recent review [15]). As shown in Figure 1, only at very high sucrose concentrations (i.e., > 0.5 M sucrose) do all three hedonic response profiles clearly emerge, with the most explicit distinction at 1.0 M sucrose. Notably, sucrose concentrations below 0.1 M are neither strongly liked nor disliked by any group, but differences start to be seen at 0.25 M, just below the typical levels in sugar-sweetened beverages (c. 0.3 M). Studies that used a simple dichotic classification of sweet likers/dislikers typically used 10% sucrose (c. 0.29 M), a concentration when MSL are not readily discernible from the other groups.

Since there have now been a small number of studies that have reported the three sweet-liking phenotype pattern, it is possible to start to consider whether the relative distributions
of these three phenotypes are stable or vary depending on age, racial ancestry, culture and sex. To date, a larger community sample study in the US is the only study that has used the three-phenotype model to examine a wide range of ages [29]. In their sample of adults, they reported fewer SDs (ESL 34%, MSL 58%, SD 9%), whereas, in children, the cluster analysis only revealed two groups, SL (78%) and SD (22%). This may be partly explained by the difficulties children have when trying to scale liking as a continuous variable, but also a relatively low concentration of sucrose was used as the highest level tested (0.4 M sucrose). At that concentration, there is clear separation of SD from liker groups, but the distinction between ESL and MSL is likely to be less apparent (Figure 1).

Studies using preference rather than liking methods have also consistently reported stronger sweetness preferences in children and adolescents than in their mothers [13, 33] and between children and young adults [12, 34-36]. While the SD phenotype is still seen, this enhanced sweet preference amongst children classified as sweet likers is thought to reflect the increased energy demands for growth in childhood [37, 38], making the distinction between ELS and MSL less clear. There is also some evidence that the ability to detect sweet taste changes with age, with children having lower sensitivity to sweet taste than adolescents and adults [39]. Notably, in that study, although overall children preferred higher sucrose concentrations, individual differences in sweet-taste sensitivity did not predict preferences. This is in line with broader conclusions that sweet preference is not readily explained by differences in ability to detect sweetness [40]. Overall, these observations reveal two key findings in the context of this review: firstly, that even in young children, there is evidence of a substantial minority that dislike sweet taste, and secondly that the strong liking (and/or preference) for sweet taste exhibited by many people when
younger reduces with age, perhaps suggesting individual expression of ESL may change across development.

It is also now possible to make some preliminary conclusions about how these phenotypes differ across populations based on their racial ancestry and the culture through which a person is exposed to sweetened foods and drinks. Ideally, cross-cultural studies should contrast populations with markedly different food and drink environments. However, to date only one study has explicitly contrasted sweet-phenotypes between cultures, examining similar populations in the UK and USA [15], and found roughly similar proportions of the three phenotypes (ESL: UK 32%, US 23%; MSL: UK 50%, US 50%; SD: UK 19%, US 26%). Although these two cultures are broadly similar, there is evidence for higher consumption of key diet components like sugar-sweetened drinks in the US than UK [41]. Data also suggest that the relative proportions of these three phenotypes may vary with racial ancestry. Specifically, the SD phenotype seems to be more common in people of Asian ancestry in comparison to those who are of Caucasian or other ancestries [32, 42-44]. Although some caution is needed as ancestry and culture are confounded in some of these studies. This is however, consistent with research without phenotyping which also suggests differences in sweet preference between groups depending on ancestry and culture [see 45 for an overview] and supports findings from a recent genome-wide association study (a large scale study exploring genetic variations) which suggested key genetic variants implicated in sweet taste perception may differ depending on racial ancestry [46]. Sex differences also support a genetic basis. Biological males consistently show higher liking for sweet tastes than do females, and are much more likely to be classified as ESL [e.g. 32, 42].
In summary, recent detailed statistical analyses provide strong evidence that there are meaningful, measurable individual differences in sweet liking, with a clear sweet disliker phenotype that is evident in children and may also vary across cultures and races. As well as challenging the idea of universality of sweet taste liking in humans, these distinct phenotypes offer an opportunity to further clarify the extent to which sweet liking is a risk factor for overconsumption and consequent obesity.

3. Understanding sweet-liking phenotypes.

A key question is why there are consistent, distinct phenotypic differences in liking for sweetness? At present, there is no clear explanation for these differences, but it is possible to construct alternative explanations based on what we know to date in relation to wider theories of appetite control and sensory reward.

Classically it was argued that the momentary expression of liking for sweet taste could reflect an underlying physiologically sensed nutrient deficit. This is often interpreted as a homeostatic need state, based around set-point theories of motivation [47] and typically supported by evidence that liking for sweetness was expressed more strongly when hungry than sated (full) [47-50]. However, not all studies have found hunger state to modify liking for sweet taste [51]. One idea might then be that individual differences in sweet liking reflect variations in underlying sensitivity to appetite signalling and reflect state rather than trait differences. Evidence that supports this idea includes the observation that ESL score higher on the TFEQ hunger scale [42], a scale that was conceived as a measure of sensitivity to internal hunger cues [52]. A more direct way of testing individual differences in internal sensitivity would be to use standardised tests of interoceptive awareness (the awareness of
internal body sensations) [53], based on evidence that these measures correlate with experienced hunger [54] and relate to homeostatically-driven eating styles [55, 56]. Recently, ESL and SD’s performance on these tests were investigated, and ESL displayed enhanced interoceptive performance on all measures [57]. Likewise, it is now becoming clear that the experience of hunger is more closely related to changes in free-fat mass than to overall body size [58]. The lastest observation that SD have higher fat mass (detailed in Section 4) and that older ESL a higher free-fat mass [42], coupled with greater interoceptive awareness, could suggest that ESL express a strong liking for sweet taste because they are more aware of acute energy demands.

Sensitivity to internal appetite cues have been conceptualised as “intuitive eating” [59], and specific psychometric tools developed to assess this construct [60, 61]. ESL were recently reported to score higher on measures of intuitive eating than SD [57]. Overall, these different pieces of evidence all point to higher sensitivity to internal appetite cues in ESL. The corollary of this suggestion would be that SD express dislike because they are less sensitive to internal regulatory cues. These suggestions also fit with Schachter's externality theory that obesity is related to individual differences in sensitivity to internal and external signals relating to appetite control [62, 63], with those more sensitive to internal cues being less prone to obesity. This would, surprisingly, suggest that ESL would therefore be less prone to obesity and SD more and the findings (reviewed in Section 4) that SD may have higher percentage body fat and the wider suggestion that obesity may be associated with reduced sweet liking [e.g. 4, 64], both fit with this suggestion. Overall, the current data are far from conclusive, but do suggest that differences in internal appetite sensitivity are a plausible explanation for the existence of these different sweet-liking phenotypes.
However, although the previous discussion highlights what may be different about different sweet-liking phenotypes, it does not explain why these phenotypes exist. Here we offer two opposing views, contrasting nature and nurture. The observation that the SD phenotype is evident at all ages and in all racial groups tested to date might suggest that this reflects a fundamental difference between individuals that could be grounded in genetics. Indeed, the three-phenotype model, with smaller proportions of SD and ESL compared with a larger population of MSL, would fit with a genetic model. However, currently, no published studies are testing this hypothesis using the three-phenotype model. There have been a few studies that have examined genetic differences in sweet liking as a continuous variable. The rated pleasantness of the strongest of three tested sucrose solutions (19% sucrose) was reported to be 41% heritable [65], and a follow-up study found similar heritability for sweet liking and for preference for a range of sweet foods and drinks [66]. Keskitalo and colleagues suggested that the likely variation was on chromosome 16 but could not predict which genes might be involved. However, it is possible to predict where these differences might lie. As the data suggest that sweet likers phenotypes differ purely in their hedonic appraisal of sweetness, one candidate system could be the genetic coding of some aspect of the μ-opioid receptor, where there are known polymorphisms (a common genetic variation of a single DNA base pair) implicated in sweet taste/liking [67]. Opioid peptides seem a potential candidate based on studies implicating opioid peptides in the perception of liking for foods based on opioid receptor antagonism [68, 69] and broader evidence for a critical role of opioids in the neural systems underlying liking [70, 71]. To date, only one study has specifically investigated the effects of μ-opioid stimulation on perception of liking and intensity of sweet tastes in different sweet-liking phenotypes [72]. However, no significant
difference was found between SL and SD in that study, although the authors did note that the study may have been underpowered.

The alternative to a genetic explanation is that sweet-liking phenotypes are more a manifestation of differences in exposure to sweetness in the environment, particularly in the context of the obesogenic environment. The key test here would be to measure how increased or decreased sweetness levels in the diet altered sweet perception and liking, particularly contrasting these effects across the sweet-liking phenotypes. Studies adopting that approach have been subject to a detailed recent review [73], which identified 21 studies. They concluded that there was no evidence of effects of exposure in population cohort studies, but some evidence that increased exposure to sweetness reduced preference for sweet foods. Notably, none of these studies classified participants by sweet-liking phenotype and most measured changes in preference rather than liking per se. Thus, the idea that the observed sweet-liking phenotypes are a consequence of differences in habitual intake of sweet foods seems unlikely, especially given the limited differences in the actual use of sweetened products between phenotypes (reviewed in Section 5), but the specific tests needed to assess this properly have not been published.

Overall, the current state of knowledge does not give a clear explanation why individuals exhibit such strikingly different hedonic responses to sweet tastes as those exhibited by ESL and SD groups and further investigation is needed (as discussed in Section 8).
4. Do sweet-liking phenotypes differ in body size and composition?

This section's key aim was to explore the strength of evidence that differences in sweet liking are associated with differences in body size and composition. Researchers have reported various measures of body size, most commonly body-mass index (BMI), in many studies that have examined individual differences in sweet liking, either because the paper was specifically interested in potential effects of sweet liking on body size, or simply when reporting the characteristics of their participants. A large number of these studies have examined the relationship between overall sweet liking (as a continuous variable) and some measure of body size and/or composition: as these studies treated sweet liking as a continuous variable, and did not categorise individuals according to the different sweet-liking phenotypes, we do not review these studies here in detail. However, we could only find one study which reported that people with a higher BMI showed an increased liking for sweetness [74]. In contrast, many studies reported the opposite, that obese individuals expressed a lower overall liking for sweetness [e.g. 4, 64, 75]. Likewise, a large cross-sectional population study in France reported that self-reported liking for natural sweetness (assessed using a questionnaire measure) was negatively associated with self-reported BMI [76]. Overall, these cross-sectional studies provide minimal evidence to support the hypothesis that sweet liking drives obesity, and indeed appear to suggest the opposite, but crucially in the context of this review, these studies all treated sweet liking as a continuous variable, which we know now is not the case.

If sweet liking is a driver of obesity, it would be predicted that ESL would be most at risk of weight gain and consequent obesity. Therefore, here we focus in detail on studies which
classified participants according to their sweet-liking status and measured one or more aspects of body size or composition.

Table 1 summarises differences in body size measures from 11 studies using the traditional, older dichotomous phenotyping of participants into sweet liker (SL) and sweet disliker (SD) groups, based on hedonic ratings for sucrose solutions. Although some studies noted a trend towards SL having higher BMI [77, 78] only one study reported a significant difference between these groups, with SD having a significantly higher BMI and body fat percentage than SL [79], contrary to the view that sweet liking drives obesity. Although, a cautionary note in interpreting the lack of consistent differences in body size between SL and SD across these studies is that many used small sample sizes, and there was variation in phenotyping method, classification criteria, the range of sweet concentrations tested as well as variation in the extent to which potential confounding factors (e.g. smoking, stage of the menstrual cycle, medication, eating disorders etc.) were controlled for (Table 1). However, inspection of actual data (where reported) does not give any clear indication that any differences between SL and SD had been missed due to lack of power. One study contrasted BMI in a sample of obese adults on a weight-loss programme and found no significant difference in BMI between SL and SD [80], but notably, there were nearly twice as many people classified as SD (n=127) than SL (n=69), again contrary to what might be predicted if sweet liking was a key driver of obesity. Thus, studies defining people as SL versus SD have not found any clear evidence that SL tend to have higher body size, and if anything, imply that obesity is associated with reduced liking for sweet taste, as suggested by Drewnowski in particular [4, 5].
But could it also be that people were wrongly classified? As the recent analyses using hierarchical cluster analysis (Figure 1) show that there is a distinction between moderate likers (MSL phenotype: c. 50% of the population) and extreme sweet likers (ESL: c. 25-30%), it might be that potential effects of extreme sweet liking are hidden when SD and MSL are combined, as is likely to the case with dichotomous classification. However, to date, only 5 studies have reported BMI or body composition based on the three-phenotype model, and 4/5 reported no significant differences between groups, giving no clear overall support for the idea that sweet liking by ESL drives weight gain (Table 2). It should be noted that although the two earlier studies [31, 43] classified into three groups, they only reported data and analyses for the extreme SL and SD groups, but found no significant differences. Likewise, the study with the largest sample size (based on opportunity sampling in a museum-based science project: [29]) found no evidence of differences in body size or composition.

The most recent study did, however, find significant differences. Iatridi et al. [42] explored the effects of sweet-liking phenotypes on body-size and composition and found an interaction between age and anthropometric measures. For those under 21 SD had significantly higher body fat whereas for those over 21 ESL had the highest BMI and also had significantly higher fat free mass (FFM) but SDs still tended to have higher fat mass. Overall, these data do not provide strong support for a simple model where sweet liking alone is a risk factor for obesity, with only one study reporting significant differences. The outcome of Iatridi et al. [42] suggests BMI may be higher in people with a strong liking for sweetness, but this could result from a larger FFM. Considering the well-established positive association between FFM and energy requirements, the above finding fits with longstanding ideas that
expression of sweet liking may reflect homeostatic needs for energy [e.g. 47, 79, 81, 82]. In contrast body fat was higher in SD, consistent with the earlier findings of Thompson et al. [79]. These findings suggest that there needs to be a more nuanced approach to the discussion of how sweet liking impacts body composition, and that wider reliance on BMI is problematic. Overall, these data question the idea that sweet liking may be a key driver of obesity.

An alternative approach is to measure individual sweet liking and test whether that predicted subsequent weight gain. One study that took that approach focussed on an obesity-prone sample of Pima Indians, and reported that sweet (and fat) liking was a predictor of subsequent weight gain [83]. However, we are not aware of similar findings in other populations. In contrast, a large community-based survey in France found no relationship between self-reported sweet liking and changes in BMI over 5 years, but did find that liking for fat predicted weight gain [84]. Although more studies like these are needed, these data further question the role of sweet liking as a cause of overconsumption.

In summary, contrary to the widespread belief that sweet liking is a key driver of obesity, detailed analysis of the body size and composition of different sweet-liking phenotypes provides little evidence that sweet liking is associated with larger body size.

5. Do sweet-liking phenotypes differ in dietary intake?

Taste hedonics have important influences on eating behaviour, informing food preference, selection and consequently nutritional intake and health [reviewed in 85]. Therefore, greater understanding of individual differences in sweet liking may help to reveal
predispositions to diet-related health outcomes to better support public health strategies and treatments to prevent obesity and non-communicable diseases [86, 87]. Liking for sweet taste is commonly thought to have developed as a mechanism to identify sources of carbohydrates, a key energy-rich nutrient. However, although sweetness intensity can be a reliable predictor of sugar content [e.g. 88, 89], the reliability of sweet taste as a predictor of overall energy content is questionable [90]. Once scarcely available, an abundance of highly palatable, inexpensive, energy-dense and nutrient-poor food and beverages with high concentrations of added sugars are now increasingly accessible and could therefore play a key role in the obesity epidemic [91-93].

Here we collate differences in dietary intake of people classified into either of the hedonic sweet-liking phenotypes only (SL/SD or ESL/MSL/SD). Though, it is worth noting that a recent review [40], which included studies with a wider variety of psychophysical tests for sweet taste liking (i.e., liking, preference, intensity and taste sensitivity), and included studies using sucrose, glucose, fructose and non-nutritive sweeteners, found that out of all the tests, liking measures were best correlated with dietary intake but most notably in studies which classified participants according to sweet-liking phenotypes. However, relatively few studies have used this approach (summarised in Table 3).

Among the only three studies which contrasted dietary patterns using the dichotomous phenotype (SL/SD) approach (Table 3), two reported some significant differences in dietary intake. SL had higher intake of refined sugars in one study [94] and increased intake of sugar sweetened beverages (SSB) and reduced intake of dietary fibre in the other [80]. The third study [95] noted that although they did not find any significant differences, this may have
been due to lack of power. Only two studies have explored measures of dietary intake using the three-phenotyping method (Table 3). Both found SSB intake was higher in ESL [29, 42], although this was only significant for participants aged over 21 in one study [42]. Notably, no other dietary contrasts were significant. These data, therefore, provide minimal support for the idea that sweet liking per se drives overconsumption since no differences in intake in many of the foods implicated in obesity (foods high in sugar, salt and fat) were found.

Rather than focusing on self-report usage of sweetened products, an alternative approach is to explore differences in wider flavour preferences between sweet-liking phenotypes. During our lifetime, every human develops a unique set of individual food preferences. The majority of which are learned through exposure to novel foods and drinks, underpinned by multiple learning mechanisms [96, 97]. Although the five basic tastes, including sweetness, directly impact liking for foods and drinks, associations between these tastes and other flavour components also shape our broader food preferences. Two learning models have dominated our understanding of how ingestion of sugar can contribute to wider flavour preferences: flavour-flavour learning (FFL), where liking for a novel flavour component may be modified by association with a second known liked or disliked component, and flavour-consequence learning, where liking for a novel flavour is modified by the experienced consequences of ingestion [96]. In FFL, the prediction would be that individual differences in liking for sweet tastes would transfer to other flavour components. To date, 6 studies have contrasted FFL between participants classified as sweet likers or dislikers, although these studies all predated the more recent 3-phenotype model and used a simpler dichotomous classification of sweet likers versus dislikers. In all of these studies, where sweet likers were exposed to a novel flavour paired with a liked sweet stimulus, liking for the novel flavour
increased [98-103], whereas where both phenotypes were tested, liking increased for a novel flavour paired with sweetness for sweet likers, but decreased for sweet dislikers [Experiment 3 in 98, 103]. One study in particular is notable since it showed that pairing a novel flavoured with sweetness subsequently increased liking, sweetness and intake of a product with the sweet-associated flavour even when the sweetness was not present [99]. Thus sweet likers may differ in their wider liking for sweet-associated flavours, and so may have a more varied diet. Therefore, focusing on intake of sweetened products alone may underestimate the broader impact of different sweet-liking phenotypes on food and drink intake.

6. Do sweet-liking phenotypes differ in personality and reward sensitivity?

Given the breadth of research which has occurred in the 50 years since Pangborn’s discovery of the sweet-liking phenotypes, remarkably few studies which have assessed sweet liking have contrasted the ways phenotypes differ in broader personality and behavioural measures. There is, however, a much larger literature that assessed sweet preference and reported important associations with alcohol use and addiction [e.g. 104, 105-107] and broader reward sensitivity [108, 109]. Although those important findings may, however, relate to how increased wanting for sweet taste is associated with broader behavioural risks, an issue we return to later (see Section 7), but here we focus purely on studies that assessed sweet liking.

We found only six studies: four using the dichotomous phenotyping approach [103, 110-112] and two using the statistically-based clustering method with three phenotypes [42, 43]. Of these, individual differences in trait measures of eating behaviour were most commonly
assessed. Three studies used the Three Factor Eating Questionnaire (TFEQ) [52], which measures restrained eating (controlling body weight through restriction of food intake), disinhibition (thought to assess opportunistic and emotional eating) and trait hunger (the extent to which perceived feelings of hunger drive eating). No significant differences in dietary restraint were found between the dichotomous phenotypes on either the TFEQ restraint [103, 112] or Herman Restraint scale [110, 111]. This lack of difference in restraint between phenotypes also counters concerns of demand effects impacting self-report liking for sweetness: here it could be argued that claiming not to like sweetness could be consistent with a wider restrained attitude to eating, but there is no evidence to support that concern.

A later study also found no difference between SL and SD on the TFEQ disinhibition scale [103]. However, more recent research using the three phenotypes model, found ESL scored higher on the TFEQ hunger scale, but again not on TFEQ restraint or disinhibition [42]. This implies enhanced interoceptive abilities due to heightened awareness of hunger driven signals. That study also found ESL scored higher on the intensity subscale of Arnett’s Inventory of Sensation Seeking (AISS) [113], which can be understood as a potential indicator of behavioural adaptation to internal body signals [114]. ESL also scored more highly on the reward sensitivity subscale of the Sensitivity to Punishment and Sensitivity to Reward Questionnaire [115], supporting the idea that the pleasurable ‘rewarding’ attribute of sweetness could be an important distinction between ESL and SD. Specifically, this could render ESL less resilient to highly rewarding sweet food and drinks [42], which could partly explain why Kim and colleagues found a tendency for ESL to over-eat sweet and energy-dense foods in response to negatively aroused emotions [43].
Overall, the small amount of data contrasting the different sweet-liking phenotypes psychological profiles suggests extreme liking may combine enhanced sensitivity to internal hunger signals coupled with a degree of sensation-seeking. However, more research is needed to clarify this fully.

7. Why might evidence that sweet-liking drives overconsumption be weak?

The conclusion from our review of both the body size and eating behaviour of the different sweet-liking phenotypes is that these data provide no clear support for the wide assumption that sweet liking drives overconsumption and obesity and, if anything, provides evidence to the contrary. Here we briefly consider possible reasons why sweet liking may not emerge as a strong driver of overconsumption and associated obesity.

The first possibility we explore is that rated liking is not the critical component of sweet perception that drives sugar intake and explore in brief the evidence that sweet preference or reward and sweet perception better predict overconsumption and/or obesity. Throughout this review, we have not analysed in detail studies that used the relative preference method as a measure of “sweet liking” as it is possible to prefer a higher level of sweetness over a low level, but not to like (i.e. to rate liking above neutral) either option [15]. However, a recent review that examined how sweet preference related to obesity found similar results to those reported here: that is, that sweet preference was not reliably associated with higher weight [45]. In practice, while focusing on studies that used liking ratings allow us to give a more precise test of sweet-liking, studies that classified participants by both liking ratings and preferred sugar concentration found a similar pattern
of results. Although classifying by sweet preference reduces the accuracy in discriminating ESL from MSL [e.g. 31]. Overall, there does not seem strong evidence that studies that used the sweet-preference method (many of which report that approach as assessing liking) have found clearer relationships between sweet preference and the key outcomes of body size and wider intake of sweetened products. However, as noted in a recent review [45], sweet preference is complex and is influenced by many factors beyond the immediate gustatory experience of sweetness. There is also broader evidence that although liking is a key component of food choice [116], individual liking does not map well onto actual consumption in general [117], and that more recent concepts such as nutrient-sensing of sugars independent of the sensed taste quality may drive aspects of ingestion [118, 119]. It may also be worth considering the opposite, how disliking certain tastes and textures lead to avoidance of specific foods and dietary components which in turn may also drive overconsumption of other foods resulting in potential energy and nutritional imbalances and adverse health outcomes.

Data at a population level have suggested that sweet-preferences parallel estimated sugar intake. Thus, in a review of sugar consumption from nationally representative dietary surveys across the world [120], intake of total sugars was estimated to be highest among children (20-38% and 15-30% of total energy intake in toddlers and schoolchildren/adolescents, respectively), but lower in adults (14-25% of total energy intake). These findings do not, however, provide a conclusive test of a causal link between liking and overconsumption, and as much of the evidence is based on self-report data, it must be treated with caution. Other data question such a link: for example, intake of sugar-
sweetened beverages has decreased [121, 122], but there has been no concomitant
decrease in obesity.

Many studies have also examined how the ability to perceive sweetness (both with sugars
and NNS) may also impact on diet choice, intake and consequent body size, as tested by
detection thresholds (the lowest concentration of the sweet substance that could be
reliably discriminated), sweet recognition thresholds (the lowest concentration of a sweet
substance that was perceived as sweet) or supra-threshold intensity ratings (the perceived
intensity of stimuli above the threshold) [reviewed by 40, 123, 124]. Notably, studies have
generally failed to find consistent evidence that sweet-detection or recognition thresholds
reliably predict dietary intake of sweetened products (reviewed in [40, 125]). However,
although most studies reported no significant relationship between sweet taste detection or
recognition thresholds and body size [e.g. 64, 126, 127-132], some studies reported higher
detection thresholds in obese patients [133, 134], but others lower sweet detection
thresholds [135, 136], and when these results were averaged in a recent meta-analysis,
there was only a small overall association between sweet detection thresholds and body
size, but no such relationship for sweet taste recognition [137].

In terms of supra-threshold intensity, again some studies reported differences based on
body size: obese children rated the sweetness of sucrose solutions as less intense [134], and
weight loss was associated with increased sensitivity to sweet taste in some studies [138],
yet reduced sensitivity to sweet taste in others [139]. But, other studies reported no
significant associations between sweet intensity [e.g. 64, 127] and body weight. Overall,
there is little compelling evidence that sweet taste perception is related to body size.
Importantly in the context of this paper, the majority of studies that classified participants into different sweet-liking phenotypes reported no corresponding differences in sweet-perception [e.g. 29, 30, 79, 81, 98, 112]. Some studies have reported higher supra-threshold sweet intensity for SD [140, 141], but this appears to reflect a tendency for SL to be more insensitive to the bitter taste of 6-n-propylthiouracil (PROP) [112], a widely known genetic marker of broader taste sensitivity. Notably, detailed analysis confirms that the different sweet-liking phenotypes are still evident when sweetness intensity is controlled for [30, 31]. Therefore, the evidence suggests that the different sweet-liking phenotypes do not seem to be a consequence of differences in ability to perceive sweetness per se but instead purely reflect differences in hedonic tone (pleasantness) of the experienced sweetness. Overall, there is no convincing evidence that broader measures of sweet perception and preference support the idea that sweet liking drives overconsumption.

The second possibility is that other drivers of overconsumption mask any impacts of sweet taste liking. Although our ability to detect sweet taste is an important component of chemosensory perception, sweetness is experienced in the context of many other sensory factors, including the tastes of salt, umami and possibly fat, other orosensory cues and retronasal odours [142, 143]. It was notable that none of the studies contrasting food choice and intake between sweet likers (either SL or ESL) and dislikers found consistent differences in intake of products that were both sweet and high fat (Section 5). Dietary differences were restricted to purely sweet dietary components such as SSB, and these products contribute a relatively small proportion (<10%) of overall energy intake [144], which has consistently decreased over the last decade, particularly in the US [145]. Other studies that looked more broadly at the role of taste as a predictor of body size (but which did not look specifically at
sweet-liking phenotypes) suggested that it was individual differences in liking for [125, 146],
and sensitivity to [147-150] fatty tastes that most reliably predict higher body size and/or
obesity. Likewise, individual liking for fatty tastes predicted subsequent weight gain [83],
and in the longitudinal NutriNet-Santé study, where self-reported liking and use of foods
and drinks across a wide range of tastes were assessed, sensory liking for fat predicted an
increased risk of obesity, whereas liking for sweetness predicted a reduced obesity risk [84].
Thus, it may be that it liking for fatty rather than sweet taste is the more important sensory
driver of overconsumption.

There are also strong arguments that differences in habitual protein intake [151], driven in
part by sensory factors including umami taste [152], may also contribute to obesity risk, as
might liking for salty taste [153, 154]. Thus, the lack of clear evidence for sweet liking,
specifically driving intake, may because the effects of other sensory drivers hide any effects
of sweetness. Moreover, overall liking for flavour goes beyond the contribution of taste
alone, and there remains the possibility of sweet liking increasing broader flavour
preferences (see Section 5), thereby impacting dietary variety and indirectly increasing
intake.

The final possibility is that liking is not the key motivational component driving sugar intake,
building on the broader roles of wanting and liking in motivating behaviour. Detailed
analysis of responses to sweet taste in rodents [reviewed in 155, 156] led to the widespread
acceptance that the neural circuitry which underlies motivated behaviour can be divided
conceptually into an affective dimension, liking, and an incentive component, wanting, that
relates more to motivation and decision making [157]. Notably, the study of rodents'
reactions to sweet taste was pivotal in the initial dissociation of liking from wanting and later in identifying specific neural “hedonic hotspots”, brain areas that are key components of the neural circuitry underlying liking [158, 159], and more recently “hedonic coldspots” which may underpin disliking responses [70, 160]. Nevertheless, studies of liking and wanting in relation to drug addiction suggest that increased drug use can increase wanting but a simultaneous decrease in liking [161, 162]. If this were also the case with responses to sugars, then sweet wanting rather than liking would be predicted to be the stronger driver of overconsumption. Nevertheless, the relationship between liking and wanting is complex, and in humans, hard to disentangle [163].

Suppose it is possible to incorporate wider use of carefully constructed measures of both liking and wanting into human studies, it could provide greater insights into the nature of phenotypic differences in sweet liking. For example, recently, a study assessed sweet liking and wanting separately in obese patients prior to Roux-en-Y gastric bypass (RYGB) or vertical sleeve gastrectomy (VSG) surgery [164]. Their sweet-wanting, but not sweet-liking, rating predicted weight loss in their RYGB, but not VSG, patients. In this context, another exciting set of recent studies attempted to assess individual differences in general eating behaviour based on the relationships between self-reported measures of liking and wanting [165]. They also identified three distinct phenotypes, which they labelled “reward lovers”, “half epicurious” and “non-indulgents”, and reported greater variation on wanting than on liking measures. It is intriguing to ask then whether these broader phenotypic descriptions are manifestations at a whole-diet level of the three sweet-liking phenotypes that are the focus of this review. However, both these studies relied on self-report measures of wanting, and the use of such measures remains controversial, partly because participants may more
broadly confuse incentive salience with pleasure [166], making it hard to disentangle rated wanting from expected pleasure [167], and since it has been argued that liking and wanting may operate below the level of consciousness [168]. Methods involving effort to gain a reward, such as the measure of reinforcement value developed by Epstein and colleagues, where participants work to gain food rewards using a progressive-ratio schedule [e.g. 169], may better measure wanting but have not yet been examined in relation to the behaviour of sweet-liking phenotypes. Nevertheless, it remains plausible that sweet wanting could be more influential in driving sugar intake than liking for sweet tastes. However, the idea that eating can be driven by sensory pleasure alone, most obviously captured in the concept of hedonic hunger [170], challenges the view that wanting may drive intake more strongly than does liking, and provides an alternative perspective through which sensory pleasure may drive short-term intake independently of homeostatic need or broader incentive motivation [171]. Hedonic hunger suggests that the anticipation and need for pleasure from eating can by itself promote intake, but how hedonic hunger differs between sweet-liking phenotypes is untested.

8. Filling the Gaps: What don’t we know, and need to know?

This brief review has highlighted the state of knowledge about sweet-liking phenotypes. It is clear that there are consistent differences in sweet liking, which cross cultures, ethnicities and age groups, but our understanding of why these differences exist remains very limited. One key issue which has held this area back is the inconsistent way different sweet-liking phenotypes have been defined (see Section 2 and [15]). There is an urgent need for a statistically robust classification criterion to be applied across future studies to help find
consensus on how these differences in sweet-liking phenotypes relate to key behavioural, dietary and anthropometric measures. A new approach for refining and standardising phenotypes' characterisation has been suggested, which could help resolve this [30]. The test involves rating liking on a visual analogue scale (VAS) ranging from extreme dislike (-50) to extreme like (50) for a 1.0 M sucrose. This approach has been shown to reliably distinguish MSL, who give a liking rating between −15 and +15, from both SD (−50 to −15) and ESL (+15 to +50), however it needs to be validated more widely. If widely adopted, the simplicity of this test, coupled with the statistical evidence that underpins it, may allow much greater comparability across future studies while being simple enough to be incorporated into the large-scale and longitudinal studies the area needs to resolve some of the key contentious issues.

In discussing potential explanations for different sweet-liking phenotypes, we suggested that the consistency in the proportions of the three sweet-liking phenotypes implies these differences may have a genetic basis, but that no study has tested for genetic differences. Here we suggest where such studies might focus.

Differences in the peripheral taste system could explain some of the phenotypic differences through single nucleotide polymorphisms (a common genetic variation of a single DNA base pair) on sweet taste receptor genes TAS1R2 and TAS1R3 [13, 172-174]. However, due to the complexity of ingestive behaviour and the similarity in intensity ratings between the sweet-liking phenotypes, it is likely that additional genes beyond sweet taste receptors account for individual variation in sweet liking. This could include polymorphisms in the GNAT3 gene which encodes gustducin, a protein that helps to convert sweet taste stimuli into nerve
impulses that can be sent to the brain [175], the ‘fat mass and obesity’ FTO gene [46] and its
potential mediator IRX3 [176], which have all been implicated in affecting sweet taste but
have yet to be tested in relation to sweet-liking phenotypes.

Another possibility is that individual differences in sweet taste liking may be a manifestation
of other taste preferences, for example in the bitter taste receptor TAS2R38 gene [177].
Although no study has yet examined variations in the TAS2R38 gene between sweet-liking
phenotypes, this has been tested using the dichotomous sweet-liking phenotypes with
sensitivity to the bitter tasting 6-n-propylthiouracil (PROP), which is in-part mediated by
variations in TAS2R38 [178], where there are also three phenotypes: non-tasters (low
sensitivity), medium tasters (medium sensitivity) and super tasters (high sensitivity).
However, results have been inconsistent and non-significant [111, 179] and although two
studies did find SL were more likely to be PROP non-tasters [112, 141], there were still PROP
supertasters who were classified as SL. Genetically only Mennella et al. [180] has tested this
in relation to sweet preference with children and their mothers, however, this was using
forced-choice preference procedure, and they only found a significant association with
sweet preference and the homozygous bitter insensitive allele (i.e., two copies of the
insensitive allele) in children but not with their mothers. Interestingly, they noted an effect
of ethnicity and environmental exposure on TAS2T38 genotype, sweet preference, and food
habits. In conclusion, limited evidence currently exists concerning the bitter taste receptor
affecting sweet taste liking, but this has also not been explored using the three-phenotyping
method or genetically with the hedonic sweet-liking phenotypes.
There is also a need to explore the role of genes not directly implicated in taste perception and their potential role in mediating sweet-liking [181], particularly those involved in the processing of motivation ‘wanting’ and reward ‘liking’ by central reward mechanisms and the pleasure generating brain systems [182] as partly discussed in Section 6 in relation to μ opioids. Several neurotransmitters and their receptors are already known to modulate the rewarding effects of food, making the coding genes prime candidates for investigation with sweet-liking phenotypes. This includes dopamine via DRD2 [183] often implicated in ‘wanting’ alongside μ-opioids via MOR [184] and cannabinoids via CB1 [185, 186] in food ‘liking’.

Another approach to enhance understanding would be to contrast neural responses to sweet taste in these different sweet-liking phenotypes. To date, only one study, Rudenga and Small [187], has explored this, using functional magnetic resonance imaging (fMRI) and the dichotic classification as SL/SD. They found greater activation in the ventromedial prefrontal cortex (vmPCF) in sweet likers compared to sweet dislikers, an area implicated in reward processing [188]. However, since the nature of the difference between phenotypes lies in hedonic processing, and the earlier study used the dichotic classification and may have been underpowered, future studies should contrast the three phenotypes, focusing on the now well-characterised reward system. This would implicate the dopamine lead mesocorticolimbic system (ventral tegmental area to the nucleus accumbens (NAc) and prefrontal cortex) as well as additional limbic systems (e.g., amygdala and hippocampus), cortical regions (orbitofrontal cortex (OFC), cingulate gyrus and insula) and the hypothalamus which all play an important part in the convergence of the sensory, emotive and post-ingestive consequences of eating [157]. Areas of particular interest include the
dopaminergic “hedonic hotspots” that are mediated by μ opioids and endocannabinoids such as the NAc [189] along with the ventral pallidum which may serve as a key area for driving the ‘disgust’ rather than ‘reward’ response that sweet dislikers experience with sweet taste through “hedonic coldspots” [160]. Research exploring cortical responses to sweet taste without phenotyping found activation in the reward regions such as the OFC [107, 190, 191] and the right ventral striatum [107], as well as the NAc and the ventral pallidum [192].

Behaviourally, since relatively few studies have tested the three-phenotype model, there needs to be more studies in diverse populations and age groups to determine more clearly the universality and stability of these phenotypes. Section 5 noted some evidence of consistent differences in reward processing between different phenotypes, but future studies need to elaborate on these findings, using wider reward sensitivity and impulsivity measures. Likewise, the recent finding of enhanced interoceptive awareness in ESL [57] needs to be replicated and ideally related to altered neural responses to sweet tastes and associated genetic profiles. Most critically, future studies should include measures of both hedonic and incentive responses to sweet taste to allow the relative importance of liking and wanting to be better elucidated. This may involve the combination of the optimal test to define sweet-liking phenotypes [30] with the sweet-preference measure widely used by Mennella [193] and Kampov-Polevy [105, 194], and either the separate use of evaluations of explicit liking and wanting measures [e.g. 164] or measures of food reinforcement [169].

Perhaps the most critical question that needs answering is the extent to which exposure to sweet foods alters the behaviour of the different sweet-liking phenotypes. The analysis of
the limited longitudinal data to date, especially involving the different sweet-liking phenotypes, greatly limits what can conclude about the nature of the different phenotypes, and incorporation of sweet liking measures into ongoing cohort studies would be the ideal way to rectify this lack of knowledge.

9. Summary and conclusions

Overall, this review sets out for the first time to explore the nature of phenotypic differences in sweet-liking in humans. The evidence that there are consistent individual differences in sweet liking appears convincing, with the three phenotype-model (ESL, MSL and SD) emerging as the most accurate description of these differences. However, evaluation of body size measures and dietary intake of these different phenotypes provides no clear support for the wider belief that sweet liking is a major risk factor for obesity. It is most surprising, however, that these phenotypic differences in liking for pure sweet tastes are not a clearer predictor of wider use of sugar in the diet: ESL tend to consume more SSB, but the limited literature to date does not suggest they consume significantly more of the products high in sugar, salt and fat that are implicated more widely in obesity risk. As yet, we only have a limited understanding of how these phenotypes differ behaviourally, with a suggestion that ESL may be more sensitive to broader rewards and sensations and may have greater awareness of internal appetite regulation. But most importantly, this review highlights a shortage of research contrasting these phenotypes in terms of genetic, neural and broader behavioural differences. Our hope is that this review will encourage researchers around the world to look at some of these issues.
10. References


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Table 1. Studies assessing differences in body size measures between people classified into dichotomous, SL and SD sweet-liking phenotypes.

<table>
<thead>
<tr>
<th>Study</th>
<th>Phenotyping Method</th>
<th>Participants</th>
<th>Body size measures</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thompson et al. [79]</td>
<td>Magnitude estimates of intensity and liking of 7 sucrose solutions (0.06, 0.1, 0.25, 0.4, 0.7, 1 or 2M or 0.075, 0.15, 0.3, 0.6, 0.9, 1.2, 1.5M)</td>
<td>77 (22M 55F) US – Obese and lean</td>
<td>26 SL &amp; 51 SD</td>
<td>Significant difference in BMI and BF% between Type 1 (SD) and type 2 (SL) for both normal weight and obese participants. With SD having higher BMI and BF%.</td>
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<tr>
<td>Drewnowski &amp; Schwartz [110]</td>
<td>Rated (9-point scale) intensity and liking of 4 sucrose solutions (2% 8%, 16% &amp; 32% w/v)</td>
<td>50F US</td>
<td>32 SL = 18 SD</td>
<td>No significant differences, exact figures not reported</td>
</tr>
<tr>
<td>Drewnowski et al. [111]</td>
<td>Rated (9-point scale) intensity and liking of 5 sucrose solutions (0.058, 0.12, 0.23, 0.47, &amp; 0.93 mol/l)</td>
<td>148F US</td>
<td>66 SL = 82 SD</td>
<td>No significant differences BMI (SEM) SL: 22.9 ± 0.5 SD: 23.2 ± 0.5</td>
</tr>
<tr>
<td>Holt et al. [94]</td>
<td>Rated (VAS) intensity and liking for 5 sucrose solutions (2%, 4%, 8%, 16% &amp; 32% w/v)</td>
<td>132 (76F, 56M) Australia &amp; 63 Malaysians</td>
<td>16 SL = 11 SD</td>
<td>No significant differences, exact figures not reported</td>
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<tr>
<td>Yeomans, Tepper, &amp;</td>
<td>Rated (VAS and gLMS) intensity and liking of 4 sucrose solutions (2% 4% 8% 16% &amp; 32% w/v)</td>
<td>60 (40F, 20M) UK</td>
<td>40 SL = 20 SD</td>
<td>No significant differences BMI Females SL: 22.2 ± 0.7</td>
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<tr>
<td>Authors</td>
<td>Description</td>
<td>Ratings</td>
<td>Participants</td>
<td>BMI</td>
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<tr>
<td>Prescott [112]</td>
<td>Sucrose solutions (0.05, 0.21, 0.42, &amp; 0.83 mol/l)</td>
<td>Malaysia, SL: 22.8 ± 0.5 SD: 26.5 ± 4.2</td>
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<tr>
<td>Thai et al. [195]</td>
<td>Rated intensity (gLMS) and liking (VAS) of 3 sucrose solutions (3, 7.5 &amp; 18.75%w/v)</td>
<td>Malaysia – Overweight and lean</td>
<td>325 (166F, 159M)</td>
<td>Mdn = 21.0, R = 18-77</td>
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<tr>
<td>Asao et al. [77]</td>
<td>Rated (VAS) intensity and liking of 10 sucrose solutions (0.035, 0.053, 0.079, 0.118, 0.177, 0.266, 0.399, 0.598, 0.897, &amp; 1.346M w/v)</td>
<td>US</td>
<td>26 (14F, 12M)</td>
<td>32</td>
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<tr>
<td>Eikemo et al. [72]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (0.05, 0.10, 0.20, 0.42, &amp; 0.65 M)</td>
<td>Norway</td>
<td>49M</td>
<td>326</td>
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<tr>
<td>Methven et al. [95]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (3%, 6%, 12%, 24% &amp; 36% w/v)</td>
<td>UK</td>
<td>35 (23F, 12M)</td>
<td>Mdn = 26, R = 18-50)</td>
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<tr>
<td>Yeomans &amp; Prescott, [103]</td>
<td>Rated (VAS) intensity and liking of 1 sucrose solution (10%w/v) and water control</td>
<td>UK</td>
<td>85F</td>
<td>61 23</td>
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<tr>
<td>Lim et al. [78]</td>
<td>Rated (VAS) liking of 2 sucrose solutions (17%, 34% w/v) and water control</td>
<td>66F</td>
<td>Singapore</td>
<td>18</td>
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</tbody>
</table>

**Abbreviations:** Body Composition Analysis [BCA]; Body Mass Index [BMI]; Body Fat [BF]; Female [F]; Male [M]; Median [Mdn]; Standard Deviation [SD]; United Kingdom [UK]; United States [US]; Visual analogue scale [VAS]; Waist circumference [WC]; Weight to volume [w/v]
Table 2. Differences in body size measures between people classified into ESL/SL, MSL (IU) and SD, sweet-liking phenotypes. Note all sweet liking phenotypes were allocated based on cluster analysis.

<table>
<thead>
<tr>
<th>Study</th>
<th>Phenotyping Method</th>
<th>Participants</th>
<th>Body size measures</th>
<th>Outcome</th>
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<tr>
<td>Kim et al. [31]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (3%, 6%, 12%, 24%, &amp; 36% w/v)</td>
<td>No. &amp; sex: 200F South Korea 99 63 38 22; R = 18-32 R = 15.6-27.9</td>
<td>BMI</td>
<td>No significant difference between ESL and SD, exact figures not reported.</td>
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<tr>
<td>Kim et al [43]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (3%, 6%, 12%, 24%, &amp; 36% w/v)</td>
<td>No. &amp; sex: 120F South Korea 39 43 38 23; R = 18-43</td>
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<td>BMI</td>
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<td>Garneau et al. [29]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (0.0–13.7% w/v)</td>
<td>No. &amp; sex: 650 (403F, 246M) US 21 8 37 7 55 41.8 27.2</td>
<td>BMI + BCA</td>
<td>No significant differences, exact figures not reported.</td>
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<tr>
<td>Iatridi et al. [30]</td>
<td>Rated intensity (gLMS) and liking (VAS) of 7 sucrose solutions (0.03125,</td>
<td>No. &amp; sex: 148 (10 UK 46 73 27 20.2; R = 22.1; R = BMI + BCA</td>
<td>No significant differences BMI:</td>
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<tr>
<td>Authors</td>
<td>Description</td>
<td>Rated intensity (gLMS) and liking (VAS) of 7 sucrose solutions (0.0, 10.7, 21.4, 42.8, 85.6, 171.2, 228.2 &amp; 342.3 w/v) and water control</td>
<td>BMI + BCA ESLs had the highest BMI and FFM</td>
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<tr>
<td>Iatridi et al. [42]</td>
<td></td>
<td>0.0625, 0.125, 0.25, 0.5, 0.67, &amp; 1 M) and water control</td>
<td>ESL: Mdn = 23; R = 17.9-29.1 MSL: Mdn = 21.6; R = 17.8–32.4 SD: Mdn = 22.7; R = 18.2–30.3</td>
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<td>5F, 43 M)</td>
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<td>ESL: Mdn = 23; R = 17.9-29.1</td>
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<td>MSL: Mdn = 21.6; R = 17.8–32.4</td>
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<td>SD: Mdn = 22.7; R = 18.2–30.3</td>
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<td>US: ESL: Mdn = 23.1</td>
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**Abbreviations:** Body Composition Analysis [BCA]; Body Mass Index [BMI]; Fat Free Mass [FFM]; Female [F]; Male [M]; Median [Mdn]; Standard Deviation [SD]; United Kingdom [UK]; United States [US]; Visual analogue scale [VAS]; Waist circumference [WC]; Weight to volume [w/v]
Table 3. Differences in dietary intake measures between people classified into dichotomous, SL and SD sweet-liking phenotypes or ESL/SL, MSL (IU) and SD, sweet-liking phenotypes based on cluster analysis.

<table>
<thead>
<tr>
<th>Study</th>
<th>Phenotyping Method</th>
<th>Participants</th>
<th>Dietary assessment</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. &amp; Sex</td>
<td>Origin of Sample</td>
</tr>
<tr>
<td>Holt et al. [94]</td>
<td>Rated (VAS) intensity and liking for 5 sucrose solutions (2%, 4%, 8%, 16% &amp; 32% w/v)</td>
<td>132 (76F, 56M)</td>
<td>Australia (69) &amp; Malaysia (63)</td>
<td>16</td>
</tr>
<tr>
<td>Turner-McGrievy et al. [80]</td>
<td>Rated (VAS) intensity and liking for 5 sucrose solutions (.05, .10, .21, .42, and .83 molars)</td>
<td>196 (164F; 32M)</td>
<td>US</td>
<td>85</td>
</tr>
<tr>
<td>Methven et al. [95]</td>
<td>Rated (VAS) intensity and liking for 5 sucrose solutions (3%, 6%, 12%, 24% &amp; 36% w/v)</td>
<td>36 (23F, 12M, 1 unknown)</td>
<td>UK</td>
<td>12</td>
</tr>
<tr>
<td>Garneau et al. [29]</td>
<td>Rated (VAS) intensity and liking of 5 sucrose solutions (0.0%, 2.4%, 4.3%, 7.7%, 13.7% w/v)</td>
<td>418</td>
<td>US</td>
<td>14</td>
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<td>-----------------------------------------------</td>
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<tr>
<td>Iatridi et al. [42]</td>
<td>Rated intensity (gLMS) and liking (VAS) of 7 sucrose solutions (0.0, 10.7, 21.4, 42.8, 85.6, 171.2, 228.2, &amp; 342.3 w/v)</td>
<td>274</td>
<td>UK (148) &amp; US (126)</td>
<td>74</td>
</tr>
</tbody>
</table>

**Abbreviations:** Food frequency questionnaire [FFQ]; Female [F]; Male [M]; generalised labelled magnitude scale [gLMS]; Median [Mdn]; Standard Deviation [SD]; Sugar sweetened beverages [SSB]; United Kingdom [UK]; United States [US]; Visual analogue scale [VAS]; Weight to volume [w/v]

**Notes.**
1. CSIRO FFQ (Baghurst et al., 1996)
2. CSIRO FFQ (Baghurst et al., 1996) with additional items from Siong et al. (1997)
3. European Prospective Investigation into Cancer and Nutrition study (EPIC) FFQ (Bingham et al., 2001)
4. Beverage intake questionnaire (BEVQ-15) (Hedrick et al., 2012)
Figure legends

Figure 1: Liking patterns for the three sweet-liking phenotypes defined by HCA (modified with permission from Iatridi et al., 2019a). ESL, whose liking increased with sweetness intensity, MSL, whose liking peaked at around 0.25M sucrose before decreasing and SD, whose liking decreased with sweetness intensity. The suggested liking cut-off at ± 15 for 1.0M sucrose was based on analysis of the sensitivity and specificity scores for all sucrose concentrations and possible cut-offs ranging from 0-20. The selected cutoffs had the highest combined sensitivity/specificity score for both the prediction of ESL (95.6%) and SD (92.4%) phenotypes compared with respective alternative phenotypes across all potential tested cut-of values: see Iatridi et al., 2019 for full specificity and sensitivity data.