

Palatability: response to nutritional need or need-free stimulation of appetite?

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The traditional view of palatability was that it reflected some underlying nutritional deficit and was part of a homeostatically driven motivational system. However, this idea does not fit with the common observation that palatability can lead to short-term overconsumption. Here, we attempt to re-evaluate the basis of palatability, first by reviewing the role of salt-need both in the expression of liking for salty tastes, and paradoxically, in dissociating need from palatability, and second by examining the role of palatability in short-term control of appetite. Despite the clarity of this system in animals, however, most salt (NaCl) intake in man occurs in a need-free state. Similar conclusions can be drawn in relation to the palatability of food in general. Importantly, the neural systems underlying the hedonic system relating to palatability and homeostatic controls of eating are separate, involving distinct brain structures and neurochemicals. If palatability was a component of homeostatic control, reducing need-state should reduce palatability. However, this is not so, and if anything palatability exerts a stronger stimulatory effect on eating when sated, and over-consumption induced by palatability may contribute to obesity. Differential responsiveness to palatability may be a component of the obese phenotype, perhaps through sensitisation of the neural structures related to hedonic aspects of eating. Together, these disparate data clearly indicate that palatability is not a simple reflection of need state, but acts to promote intake through a distinct hedonic system, which has inputs from a variety of other systems, including those regulating need. This conclusion leads to the possibility of novel therapies for obesity based on modulation of hedonic rather than homeostatic controls. Potential developments are discussed.

Palatability: Salt: Appetite

What makes a food palatable? Does palatability reflect internal nutritional state? Or does hedonism promote intake independent of nutritional needs? These and related questions about the relationship between palatability and controls of nutrient intake are central to our understanding of how sensory factors are involved in appetite regulation. However, despite many reviews (Young, 1967; Kissileff, 1976; Le Magnen, 1987; Naim & Kare, 1991; Drewnowski, 1998; Yeomans, 1998), theories (Davis & Levine, 1977; Cabanac, 1989; Berridge, 1996; Berridge & Robinson, 1998) and debates (Kissileff, 1990; Ramirez, 1990; Rogers, 1990), there is still a lack of consensus on the nature of palatability. The recognition that a positive energy balance is a contributory factor in the current increased incidence of obesity (Doucet & Tremblay, 1997; Jequier & Tappy, 1999), and that over-consumption of palatable foods may contribute to this positive energy balance (Blundell & Cooling, 2000), make resolution of the nature of palatability an urgent issue.

Theories about the nature of palatability fall into two broad groups. One group of theories suggests that palatability reflects an underlying biological need for the nutrient predicted by the sensory properties of the ingestant. Accordingly, liking for sweet tastes when

hungry can be interpreted as an expression of energetic needs (Cabanac, 1971, 1989), while salt deprivation may enhance palatability of salty tastes (Denton, 1982; Berridge *et al.* 1984). The second group of theories relates palatability to reward processes that may operate, at least to some extent, independently of need state. Both groups of theories have contributed to the notion of allostasis, wherein need-states can be anticipated in the absence of current need. The first two sections of the current review evaluate the recent literature relating to these different theoretical positions, initially by reviewing evidence for palatability of salty tastes as a reflection of need-state, and then extending this discussion to foods where the relationship between sensory properties and nutrient consequences are mainly acquired. The general conclusion is that in neither case can palatability be explained adequately by need-state models alone, and a more integrative model combining hedonic and need-state-driven components is required. This then leads into a discussion of the implications of need-free stimulation of appetite by palatability for obesity, and potential treatments of obesity.

One problem in evaluating effects of palatability is defining the specific sensory component that is being evaluated. For primary tastes, which have a direct relationship

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with a specific nutrient (thus salty tastes always predict Na), this definition is clear. For more complex flavours, there is little evidence that palatability reflects innate flavour preferences, with the exception of sweet tastes (Steiner *et al.* 2001; Beauchamp *et al.* 2002; Drewnowski, 2002), and thus palatability must reflect the outcome of past experience. A full discussion of the mechanisms underlying the development of palatability is beyond the scope of the present review, and have been reviewed elsewhere (Rozin & Vollmecke, 1986; Zellner, 1991; Sclafani, 1999; Mela, 2000). Instead, we concentrate on the mechanisms relating to the expression of palatability, and its effects on immediate appetite.

The biological determinants of salt palatability

The beauty of the phenomenon of increased palatability of salt consequent on bodily Na deficit stems from its patent adaptive significance, the unequivocal definition, to the ion, of the object of the palatability changes, and the mystery of how a naive animal can find the remedy to its specific affliction: by taste. Yet studies on human subjects on the determinants of individual variability in salt palatability and intake have concentrated on acculturation and learning, especially in infancy and childhood. These have shown how a particular salty food becomes preferred, but they have not revealed the determinants of individual variability in the palatability of salt (Harris *et al.* 1990; Beauchamp *et al.* 1991; Kanarek *et al.* 1995; Leshem & Rudoy, 1997).

This directs us to consider biological determinants of salt palatability. In many animals, including primates (Denton, 1982; Denton *et al.* 1993, 1995), the palatability of salt varies inversely with its availability to the body, and it is believed to be the primary mechanism driving increased Na intake (Denton, 1982; Berridge *et al.* 1984; Berridge & Schulkin, 1989; Epstein, 1991; Schulkin, 1991; Johnson & Thunhorst, 1997). But natriophilic animals also have a spontaneous avidity in the absence of immediate physiological need (Denton, 1982; Epstein, 1991) that can bear the traces of perinatal (Denton, 1982; Nicolaidis *et al.* 1990; Crystal & Bernstein, 1995; Leshem *et al.* 1996; Vijande *et al.* 1996; Arguelles *et al.* 1999; Leshem, 1999) or adult Na-loss as a long-term enhancement of salt palatability (Falk, 1966; Sakai *et al.* 1987, 1989; Rowland & Fregly, 1988). A coherent physiological model of the determinants of salt intake has emerged, including the notion that acute activation of the brain renin-angiotensin system conjointly with peripheral aldosterone, as by Na deficit, can induce both the acute and enduring increases in Na palatability (Fluharty & Epstein, 1983; Sakai *et al.* 1987, 1989; Epstein, 1991; Schulkin, 1991; Johnson & Thunhorst, 1997), possibly involving changes in dendritic morphology and neurochemistry (Roitman *et al.* 2002).

Sodium deficit and palatability

Perhaps the most evocative demonstration of this change in palatability is the rat's response to the taste of salt when in Na-deficit: its oral, lingual and forelimb movements become similar to those expressed in response to sugared water

(Berridge *et al.* 1984; Berridge & Schulkin, 1989; Curtis *et al.* 2001) and its neurons respond analogously (Jacobs *et al.* 1988). Since the same circumstances bring about increased intake of Na, herein, our working assumption is that increased intake is driven by increased palatability. The taxonomy of Na palatability and intake is outlined in Fig. 1. It requires some clarification: both Na hunger and spontaneous Na appetite are considered to be innate responses. The enhanced spontaneous appetite enduringly replaces the spontaneous appetite as a consequence of experienced Na deficit, and is viewed as an expression of biological preparedness triggered by the earlier deficit (Epstein, 1991; Schulkin, 1991). Actually, expression of Na hunger, or even frank Na deficit, are not necessary for induction of enhancement: surging of the hormones from a state of Na loss is a sufficient condition (Sakai *et al.* 1989). This is important, as we shall see later, because it releases us from positing a frank Na deficit as the antecedent of long-term enhanced palatability.

The functional significance of these palatability changes differs: the acute increase in Na palatability enables resolution of the immediate natriuretic challenge. Epstein (1991) has suggested that the need-free spontaneous avidity for salt is also regulatory, motivating the Na-dependent animal to seek and learn about sources of Na in its surroundings, and to maintain adequate intake. He also suggested that the enhanced appetite is an expression of biological preparedness, hormonally organised, working as a hedge against salt deficit in an environment of proven scarcity, by further prioritising the seeking and memorising of Na resources (Epstein, 1991). Environmental scarcity might be extended to include an individual vulnerability to Na privation, for example, a tendency to dehydration, perspiration, diarrhoea or vomiting, whether of constitutional or behavioural origins. Schulkin (2003) has recently argued elegantly for the enhanced spontaneous Na appetite as a prime example of allostasis: homeostasis broadened to encompass preparedness and anticipatory responses. This broader view clarifies how Na need, long past, nevertheless determines contemporary Na palatability.

Do physiological mechanisms regulate sodium palatability in human subjects?

Similarities to salt appetite in animals are suggestive: in both human subjects and animals, Na is a basic taste

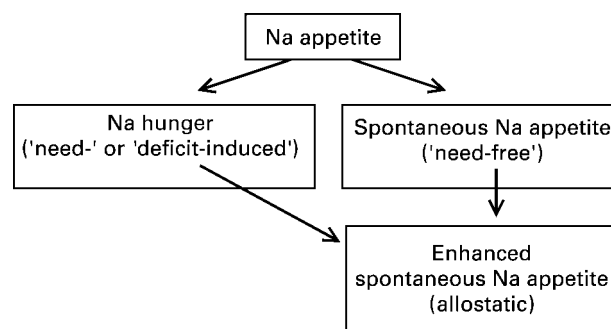


Fig. 1. Taxonomy of Na appetite. Spontaneous Na appetite becomes enhanced enduringly if Na hunger is experienced. (See p. S4.)

modality, and the hormones of Na conservation, aldosterone and angiotensin II, regulate Na balance (Nose *et al.* 1988; Verbalis, 1990). Like animals, man appears to have the spontaneous avidity for salt, and as in rats, perinatal mineralo-fluid loss causes a long-term enhancement of Na palatability (Crystal & Bernstein, 1995, 1998; Stein *et al.* 1996; Leshem, 1998; Leshem *et al.* 1998; Crystal *et al.* 1999; Kochli *et al.* 2002).

Sodium need in human subjects

Human instances of Na privation are consequent upon adrenal or hormonal pathology, haemorrhage, dehydration, diarrhoea, vomiting, neonatal hyponatraemia and exertion-induced Na losses. However, unlike animals, Na-deficient human subjects have generally failed to show a robust increase in salt intake after severe Na restriction (Mattes, 1997). The most cited reports of such a response in human subjects are practically anecdotal: a posthumous case report (Wilkins & Richeter, 1940), a statement in a study of Addison's disease (Henkin *et al.* 1963) and a report that one of four Na-deficient volunteers craved salt (McCance, 1936).

More recent and empirical reports are accumulating modest evidence for physiologically bound Na palatability in human subjects. Although some studies found that haemodialysis, during which Na levels are reduced from high-normal to low-normal, did not increase Na palatability (Shepherd *et al.* 1986; Farleigh *et al.* 1987), others found suggestive effects of haemodialysis (Leshem & Rudoy, 1997) and of neonatal or adult natriuretic treatment (Beauchamp *et al.* 1990; Mattes *et al.* 1990; Leshem *et al.* 1998). Exercise does seem to increase Na palatability (Takamata *et al.* 1994; Leshem *et al.* 1999) and conditioning of a Na preference after exercise may be related to the amount of perspiration, suggesting a relationship between Na lost and increased palatability conditioned via the restorative role of Na on hydration and electrolyte balance (Wald & Leshem, 2003). Most recently, we have found increased Na palatability in those congenital adrenal hyperplasia patients who are salt-wasting and not stabilised by medication (Kochli *et al.* 2002). Together with a report that insensible Na preload reduces salt intake (Jacobs *et al.* 1988), these studies constitute fair, but not overwhelming, evidence that salt palatability is modulated by bodily Na availability.

Enhancement of spontaneous salt palatability

Surprisingly, the most replicated effect is not of Na hunger, but that of the enduring enhancement of Na palatability following on putative perinatal Na privation *in utero* by maternal vomiting during pregnancy (Crystal & Bernstein, 1995, 1998; Leshem, 1998; Crystal *et al.* 1999; Kochli *et al.* 2002) or due to infantile vomiting and diarrhoea (Leshem, 1998) or to electrolyte-deficient infant formula (Stein *et al.* 1996) (recall that frank Na loss is not necessary for enhancement, a surge of the hormones is a sufficient condition (Sakai *et al.* 1989)). Negative results from a series of studies examining Na palatability in human subjects who suffered some form of putative Na privation in

adulthood, as by hyperhidrosis, multiple blood donations, multiple births or dehydration during military training, showed no increases in Na palatability (M Leshem, unpublished results). Together, therefore, these findings suggest that variability in spontaneous Na palatability may be largely determined by early physiological events.

Sodium appetite and the palatability of salt in human subjects

These are interesting advances in charting the similarities between animals and human subjects, and they impart biological credence to the phenomenon. Yet they rest on the assumption that man has a Na appetite. But do we? The rationale for a human salt appetite rests on the widespread use of salt in food, but mere reflection reveals the inadequacy of this argument that could equally be applied to sugar, pepper or ketchup. Alternative interpretations might emphasise the utility of salt as a 'taste enhancer' or taste modulator (Epstein, 1991; Breslin & Beauchamp, 1995). Moreover, the fact that unlike animals, human subjects do not find pure salt or its aqueous solution palatable (Pangborn & Pecore, 1982; Huggins *et al.* 1992) is troublesome for the proposition of a human salt appetite.

To advocate a human salt appetite, it would be necessary to demonstrate a commonality of palatability changes among the multiple forms of ingested Na. Indeed, determining the palatability of salt in human subjects is complicated by the absence of a ubiquitous definition of salt appetite. Palatability of NaCl in aqueous solution (used in animal research) may not be a good predictor of palatability of salt in food (Pangborn & Pecore, 1982; Huggins *et al.* 1992).

Moreover, if there is commonality of salt intake, it should extend to both conscious and unconscious Na intake that characterises human subjects (Shepherd *et al.* 1989). Unconscious intake includes Na inherent in foods or added in industrial processing or cooking, and insofar as the food choices an individual makes may be conditioned by post-ingestive consequences of, *inter alia*, their Na content, unconscious Na preference may be partly conditioned (Wald & Leshem, 2003). Conscious salt intake comes from a number of sources, e.g. salting at table, choice of salty food items in meals and consumption of salty snacks.

Because of these considerations, to examine 'Na appetite' in human subjects, we employ a number of tests of salt palatability and combine them to provide a measure of the overall 'appetite' for salt. A test of salting of soup provides a measure of conscious salt use. The technique we employ, of mixing solutions, ensures that the result is driven by palatability rather than habit (Pangborn & Pecore, 1982; Greenfield *et al.* 1983; Beauchamp *et al.* 1987; Shepherd *et al.* 1989). Conscious salt use is also evaluated by asking participants how much salt they add to each of fifty food categories or items (Leshem, 1998). To evaluate their conception of the palatability of salt relative to others, we ask how much they like salt; to obtain a measure of palatability for high salt concentrations, we monitor intake of salty snacks (Crystal & Bernstein, 1995); to obtain an indication of unconscious salt intake,

we use dietary recall. We derive the fractional excretion of Na, an index sampling recent Na intake. Finally, to measure the hedonic response to NaCl we spray six concentrations into the mouth and score the responses on a linear scales. As a control, we obtain scores of sweet palatability in analogous tests.

The intercorrelations of these different indices can indicate the validity of a general salt palatability. Factor analysis of data obtained from eighty-two young people (half of them diagnosed with congenital adrenal hyperplasia) provided two main factors accounting for the palatability of salt, and, importantly, they were distinct from that accounting for the palatability of sweet (Table 1; Kochli *et al.* 2002; for another example, see Leshem 1998). Since the factors include questionnaires, behavioural tests and physiological measures of palatability, representing conscious and unconscious modes of salt intake in different ingestive contexts (snacks, meals), this commonality suggests that to some extent salt palatability is assessed independently of its food vehicle. This is further support for regulated Na palatability.

Thus, of the two appetitive mechanisms for combating Na deficit, Na hunger may be rarely observed in human subjects (if only because of our salt-redundant environment), but the spontaneous, need-free appetite, which may prevent deficit arising, is more evident. Human subjects seem to regulate this latter appetite for salt by taste and habit (Bertino *et al.* 1982, 1986; Pangborn & Pecore, 1982; Greenfield *et al.* 1983; Cowart & Beauchamp, 1986; Beauchamp *et al.* 1987, 1991; Harris *et al.* 1990; Ayya & Beauchamp, 1992; Huggins *et al.* 1992; Kanarek *et al.* 1995). However, evidence is accumulating that it may also be regulated by alterations within the normal range of body salt levels (Huggins *et al.* 1992; Takamata *et al.* 1994; Leshem & Rudoy, 1997; Leshem *et al.* 1999; Kochli *et al.* 2002; Wald & Leshem, 2003), and that it can be enhanced enduringly by early Na challenge (Crystal & Bernstein, 1995, 1998; Stein *et al.* 1996; Leshem, 1998; Leshem *et al.* 1998; Crystal *et al.* 1999; Kochli *et al.*

2002). Thus, physiological Na need, within normal limits or below, past or present, may contribute to the palatability of salt. We should note that there are other possible physiological determinants of salt palatability: the hormones of reproduction and the density of lingual papillae (Brown & Toma, 1986; Bowen, 1992; Frye & Demolar, 1994; Bartoshuk *et al.* 1998; Bartoshuk 2000; Duffy *et al.* 1998), but it is not currently known how these might interact with Na need.

Palatability of salt in human subjects: nature or nurture?

Yet more careful studies are certainly required to bolster the case for need-regulated palatability in human subjects, but the question of whether salt palatability is nature or nurture is as restrictive as that discussion ever was. Adolescent salt-wasting patients with congenital adrenal hyperplasia have a greater salt appetite: they find it more palatable, less aversive at high concentrations and ingest more of it than their siblings, but only when they are not therapeutically balanced because of non-compliance. They are thus responding to their Na loss, possibly via an adrenocorticotropic hormone stimulatory action, since their adrenocorticotropic hormone levels and salt appetite correlate. But on questioning, most report initiation of salt intake in childhood rather than infancy: half report that they learned to do so from others and half discovered they liked salt themselves. For example, one salt-wasting patient told us she discovered she liked salt in a kindergarten taste experiment. This could be taken to suggest that eating salt to ameliorate hyponatraemic crisis, as well as to prevent it, is an acquired strategy, possibly reinforced by heightened palatability. Moreover, most of the patients seem to prefer this living on the edge to taking their medicine (Kochli *et al.* 2002). Thus, self-medication with palatable salt might be inbred in man too.

Palatability of food in relation to biological needs

The discussion of Na-specific appetites highlights how a nutritional need for Na induces increases in the palatability of Na-rich items in many animals, and shows how similar mechanisms might apply in man. Yet, importantly, it also resolves the apparent paradox of how the palatability of salt can be dissociated from need, i.e. need may increase the palatability of salt when it is long dissociated from the need state.

The same principle of nutritional need leading to increased palatability has long been discussed in the more general context of why foods that are a reliable source of energy are generally liked. Indeed, such arguments were central to classic models of appetite regulation, especially those who saw body weight set-point as central concepts in appetite control (Nisbett, 1972; Cabanac, 1989). The notion that energetic need is integrated with sensory evaluation to determine palatability and so direct food choice and intake has obvious attractions, since it provides an elegant, testable model. Critical to models that have developed from this basic idea is the general principle that when the body is in need of energy, the palatability of

Table 1. Rotated factor matrix of tests of salt and sweet palatability

Factor...	1	2	3	4
Variance explained (%)...	21	16	13	11
Hedonics of oral NaCl spray†	0.724			
Amount of salt added to soup†	0.721			
Licking pure salt*	0.710			
Sweeten food*		0.845		
Love sweet food*		0.807		
Amount of sugar added to tea†		0.621		
Dietary sweet carbohydrates*			0.833	
Dietary Na content*			0.800	
FE _{Na}				0.681
Salty snacks eaten (relative to sweet snacks)†				0.598
Salting food*	0.468			0.570
Love salty food*	0.551			0.552

FE_{Na}, Fractional excretion of NaCl.

* Questionnaire scores.

† Behavioural tests.

any food that is a potential source of energy will be enhanced and, conversely, when no such need states exist palatability will be reduced. Arguably, the most explicit version of these models is the concept of negative gustatory alliesthesia, where a liking particularly for sweet tastes has been shown to vary as a function of level of satiety (Cabanac, 1989). The similarity between the concept of negative gustatory alliesthesia for sweet tastes and the concept of enhanced liking for salty tastes when in salt-need is compelling and fits with a broader view of the physiological role of pleasure (Cabanac, 1971). However, as with the earlier evaluation of human salt appetite, there is an alternative view of palatability that divorces, at least to some extent, the sensory stimulation of appetite through palatability and the notion that palatability simply reflects internal needs states. Thus, the concept of spontaneous (need-free) salt appetite may relate to a broader, hedonic model of palatability. The next section therefore evaluates in detail the case for need-free hedonic components to appetite control.

Palatability and the hedonics of eating

The observation that palatability is associated with greater food intake is well documented in studies on human subjects (Bellisle *et al.* 1984; Bobroff & Kissileff, 1986; Guy-Grand *et al.* 1989; Spiegel *et al.* 1989; Helleman & Tuorila, 1991; Tuorila *et al.* 1994; Yeomans, 1996; Yeomans *et al.* 1997; de Graaf *et al.* 1999; De Castro *et al.* 2000a,b) and has been widely reviewed (Young, 1967; Kissileff, 1976; Le Magnen, 1987; Drewnowski, 1998; Yeomans, 1998). This observation can be tautological: palatability is defined as the sensory stimulation of appetite, but without an independent measure of palatability (particularly in animal studies), increased intake is the evidence both for the difference in palatability and the effect of palatability on intake. However, this circularity can be avoided either if differences in palatability (in terms of hedonic evaluation for example) are established before the intake test, or if a specific mechanism underlying the short-term enhancement of food intake through palatability is evident. Human studies have provided evidence to meet both these criteria. The most common method for achieving differences in palatability independent of nutritional content is to simply alter the flavour of the ingested food (Bellisle *et al.* 1984; Bobroff & Kissileff, 1986; Spiegel *et al.* 1989; Yeomans, 1996; Yeomans *et al.* 1997). In all cases, the degree to which flavour is rated as palatable (based on hedonic evaluation) at the start of a meal predicts overall food consumption. Moreover, the relationship appears to follow a linear function between the degree of difference in rated palatability at the start and overall intake (Bobroff & Kissileff, 1986; Yeomans *et al.* 1997). Thus, manipulations of palatability in the absence of differences in nutrition have predictable effects on short-term intake. At a behavioural level, these changes in flavour also produce measurable differences in the pattern of change of rated appetite within a meal (Yeomans, 1996; Yeomans *et al.* 2001b), with hunger tending to increase in the early stages of meals that are rated above neutral in terms of palatability (Fig. 2). Rated appetite

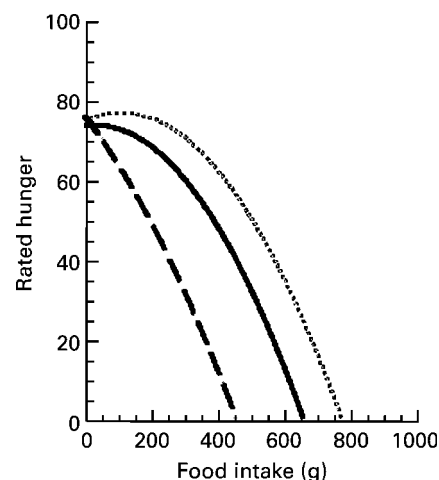


Fig. 2. Changes in rated hunger for normal-weight men eating a palatable (....), bland (—) or overly strong-flavoured (— — —) test meal. (Modified from Yeomans 1996.)

can also be enhanced merely by the sight of a preferred food (Hill *et al.* 1984), suggesting immediate modulation of appetite by palatability. Manipulations that increase food pleasantness also enhance eating rate (Bellisle & Le Magnen, 1980; Spiegel *et al.* 1989; Yeomans, 1996), as well as overall length of meals (Spiegel *et al.* 1989; Yeomans, 1996).

If this stimulatory effect of palatability was the consequence of stimulation of brain pathways associated with orosensory reward mechanisms, then disruption of these pathways should modify the response to palatability. Models of reward highlight three putative neurotransmitter systems: dopamine (Berridge, 1996), endogenous opioid peptides (Cooper & Kirkham, 1990; Kelley *et al.* 2002; Yeomans & Gray, 2002) and most recently endocannabinoids (Kirkham & Williams, 2001). Of these, only opioid systems have been explored using pharmacological modulation in human subjects, but the outcome of these studies supports the idea that palatability reflects stimulation of central reward pathways by orosensory cues. Thus, opiate receptor antagonists reduce the rated pleasantness of food flavours (Yeomans *et al.* 1990; Bertino *et al.* 1991; Yeomans & Wright, 1991; Drewnowski *et al.* 1992; Yeomans & Gray, 1996; Arbisi *et al.* 1999), and the opioid antagonist naltrexone reversed the stimulatory effects of palatability on appetite (Yeomans & Gray, 1997). The idea that palatability operates through orosensory reward is also well supported by animal studies (Berridge, 1996). Future human studies might usefully evaluate the contributions of other components of putative brain-reward pathways and the specific neuroanatomy of orosensory reward.

In the homeostatic approach to energy balance, drives (such as hunger) that arise in part from biological needs are balanced by physiological satiety signalling systems. The substrate comprises a network of neuropeptides and biogenic aminergic neurotransmitters that links peripheral and central components. This system has been well characterised (Hellström *et al.* 2004), and involves insulin, leptin, neuropeptide Y, agouti gene-related peptide, α -melanocyte stimulating hormone, cocaine- and amphetamine-regulated

transcript, orexins, ghrelins, peptide YY and other peptides, along with serotonin pathways and other aminergic systems. Are the circuits for energy homeostasis and hedonic mediation independent of each other? Pharmacological evidence suggests that the circuits are rather separate. For example, in obese subjects administration of the serotonin drug d-fenfluramine (Blundell & Hill, 1987) suppressed the sensation of hunger, but had no effect on the appreciation of the pleasantness of food. Conversely, opioid antagonists reduce the rated pleasantness of palatable foods, but have no effect on hunger (Yeomans & Gray, 2002). This double dissociation indicates that appreciation of palatability is associated with a specific biological substrate that can be pharmacologically dissected from the substrate mediating hunger (Blundell & Rogers, 1991). However, it is still possible for a functional interaction to occur when the manipulation is made through the natural commodity (namely food) rather than through a more selective artificial pharmaceutical manipulation.

Palatability, satiation and satiety

If neural system underlying orosensory reward and homeostatic controls of eating are dissociable, how then do these systems interact? Orosensory reward and satiety may operate independently, and therefore manipulations of these two systems should have additive effects. Alternatively, homeostatic needs (low levels of satiety) might magnify the effects of orosensory reward and thereby enhance the effects of palatability. One strategy for addressing this issue is to examine how manipulations of pre-test energy consumption modulate both the pleasantness of a subsequent test meal and the relationship between pleasantness and intake within that meal. This approach is clearest in preload studies, where a fixed energy load is followed by an *ad libitum* test meal, especially where differences in pre-test preload energy are appropriately disguised. If food pleasantness reflects the current level of need for energy, pleasantness of a test meal should be lower after a high-energy than a low-energy preload. However, while there have been some studies where test meal pleasantness was reduced after high-energy preloads (Booth *et al.* 1982; Johnson & Vickers, 1993; Kim & Kissileff, 1996), other studies report no effect of preload energy on the rated pleasantness of a test meal, despite compensatory reductions in subsequent energy intake (Birch & Deysher, 1986; Vandewater & Vickers, 1996; Yeomans *et al.* 1998, 2001*a,b*; Raynor & Epstein, 2000). Thus, enhanced satiety does not reliably produce reductions in subsequent food pleasantness.

The same preloading design has also been combined with manipulations of palatability at the test meal to explore the interactive effects of palatability and satiety (Yeomans *et al.* 2001*b*; Robinson *et al.* 2004). The results suggest that orosensory stimulation decreases the ability of short-term satiety cues generated by moderate energy preloads to reduce intake, resulting in an increase in overall energy intake in conditions where moderate-energy fat or carbohydrate preloads were combined with a test meal with enhanced flavour (Fig. 3). These results not only confirm that satiety and orosensory stimulation have opposing effects on short-term food intake, but also suggest that palatability

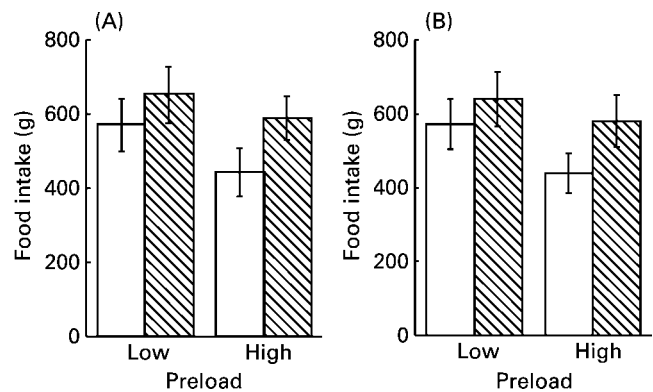


Fig. 3. Intake of a palatable (□) and bland (▨) food after low- and high-energy carbohydrate (A) and fat (B) preloads. (Modified from Yeomans *et al.* 2001.)

has a greater influence in conditions where satiety is enhanced, contradicting ideas that satiety and orosensory reward have either additive or positively interacting effects. The implication is that palatability may lead to over-consumption, particularly when sated. This conclusion is further supported by the observation that when intake of a preload was enhanced through a palatability manipulation, adequate compensatory reductions in intake were not seen at a subsequent test, resulting in over-consumption following high-palatability preloads (de Graaf *et al.* 1999).

An alternative to preloading as a manipulation of need-state is simply to increase the time since the previous meal (deprivation state). As with satiety, the effects of deprivation state on palatability are ambiguous. Some studies report enhanced increased palatability of food under conditions of deprivation (Spiegel *et al.* 1989), but an interesting recent study that attempted to separate reinforcing value from hedonic evaluation of food suggested that deprivation enhanced the reinforcing properties of foods without altering hedonic evaluations (Epstein *et al.* 2003). This distinction between reinforcement and hedonic influences fits well with theories of motivation originating in the drug-abuse literature (Berridge & Robinson, 1998), and fits with the increasing belief that food and drugs share a common underlying reward system (Berridge, 1996; Carr, 1996; Grigson, 2002).

Although the idea that satiation and palatability operate independently is well supported by the results reviewed so far, one counter-argument is to highlight the subtlety of these interactions. In contrast, rated palatability, or more precisely rated pleasantness (Yeomans & Symes, 1999), declines in a predictable manner within a meal, an observation consistent with Cabanac's concept of alliesthesia, and could be interpreted as palatability reflecting underlying homeostatic needs. However, the observation that liking for the consumed item declines more than for uneaten items (Rolls *et al.* 1981) contradicts this conclusion, since in a sated state any energy-rich food should be liked less than when hungry. Since changes in homeostatic needs following ingestion should peak some time after the end of a meal, sensory-specific satiety appears the more plausible mechanism to explain decreases in pleasantness during a meal, possibly as a means to counter palatability-induced over-consumption.

Pleasure of eating: a risk factor for weight gain?

At the outset it is useful to pose some questions in order to focus attention on certain key issues. First, do people who gain weight and become obese have a different response to the palatability of food compared with people who remain lean? If the answer to this question is yes, then do obese people perceive food as being *more* or *less* pleasant than lean people? Put another way, do obese people have a suppressed or a super-sensitive response to the palatability of food? These questions are theoretically important, since both possibilities could account for over-eating among obese people. If food is perceived as being low in pleasantness, then it could be argued that people would need to eat *more* food in order to gain an adequate level of pleasure. Conversely, if food is perceived as being very pleasant, then this would stimulate more eating in order to gain maximal pleasure. The attraction of foods probably involves motives of 'liking' (reward) and 'wanting' (incentive salience) (Berridge & Robinson, 1998), qualities that are difficult to dissect in human subjects.

Second, how can the biological purpose of eating be reconciled with the strong social, cultural and psychological aspects? As noted in the recent National Nutrition Health Programme (2001–2005) in France, an individual's food choice is a 'free act' and eating is recognised as a moment of pure pleasure. 'Must we from now on sacrifice the gentle principle of pleasure to the all powerful precautionary principle?'

A key proposal is that the palatability of foods constitutes a behavioural risk factor that promotes over-consumption. Although 'sedentariness' is widespread, there is also much evidence that weight-gaining individuals consume excessive amounts of food (Pearcey & de Castro, 2002) and that weight gain is associated with specific food habits, including the consumption of fatty foods, eating outside the home and the availability of fast foods. Physiological satiety signals can be overwhelmed by the potency of energy-dense highly palatable foods (Blundell *et al.* 1996) and preferences for these foods are expressed as behavioural traits or risk factors (Blundell & Gillett, 2001). Do these particular food habits stimulate eating either wholly or in part via the high palatability that forms an important part of their appeal?

Food choice, palatability and obesity

In addition to an interaction between palatability and hunger, the perceived pleasantness of foods could also modulate appetite control indirectly by influencing the choice of foods. There is considerable evidence that this is the case. In an experiment in which subjects sampled a range of foods containing varying amounts of fat and rated their sensory preferences, there was a positive relationship between the rated pleasantness of the fat content of the foods and measures of the adiposity of the subjects (Mela & Sacchetti, 1991). The fatter the subjects, the greater their ratings of pleasantness for the fatty foods. More recently, the food choices of monozygotic twins discordant for body weight have been assessed (Rissanen *et al.* 2002). The twins with the highest degree of fatness

displayed a significantly higher preference for fatty foods. If it is assumed that the expression of food preferences is influenced at least in part by the pleasure yielded by the foods, then these studies have demonstrated that levels of body fat are associated with a greater rating of pleasantness of fat-containing foods. In addition, female obese subjects have demonstrated a significantly higher preference for sweet high-fat foods than lean subjects (Drewnowski, 1992). In addition, using the database from a national food survey in the UK, it has been shown that obese subjects (BMI ≥ 30 kg/m²) reported a greater consumption of sweet high-fat foods than subjects with lower BMI (Macdiarmid *et al.* 1996). However, this relationship only emerged after the suspected under-reporters had been removed from the database, leaving only subjects whose reports were likely to be more valid. Taken together, these findings indicate that palatability of foods promotes the choice of foods (high in fat) that are known to favour the attainment of a positive energy balance. Obese individuals appear to be particularly vulnerable to display this maladaptive food choice process.

These studies indicate that palatability can influence appetite control (and therefore food intake) via effects on food choice or on energy intake (via hunger). Recent investigations of behavioural phenotypes characterised by habitual food choices suggest that these phenomena can coexist. Groups of obese and lean young male subjects matched for age and the habitual high consumption of fat (high-fat phenotypes) were compared (Le Noury *et al.* 2002). Although both groups were eating a diet known to favour a positive energy balance, the obese phenotypes consumed greater amounts of the high-fat foods in a test meal and reported greater feelings of pleasantness, satisfaction and tastiness for the foods consumed. One interpretation of these results is that, for a least one group of obese people, they habitually self-select (fatty) foods with a high probability of generating a positive energy balance (on the basis of their energy density), consume these foods in greater amounts and derive greater pleasure from this eating. This outcome also demonstrates that obese people have a disposition to perceive foods as being more pleasant than their lean counterparts. This may indicate a super sensitivity in components of the neural circuitry forming the substrate for hedonic properties of foods. Given this capacity to obtain a high level of pleasure from foods (and eating), it is not surprising that obese people show a tendency to self-select high palatability foods. There is evidence that dopamine D2 receptors (implicated in hedonic processes) are altered in obese individuals (Wang *et al.* 2001) although the interpretation of these results may be complicated (Berridge & Robinson, 1998).

The palatability dilemma

The evidence indicating a role for palatability in appetite control creates a problem for nutritional strategies to deal with obesity. Within the field of functional foods (or nutraceuticals) there is a strong movement to produce foods that will enhance satiety. However, the food industry is also committed to producing foods that are highly palatable; this will have the intended effect of promoting acceptability and consumption (see results earlier). Palatability increases

the willingness of people to consume (and carries the potential to over-consume). This means that within a particular food, different components may enhance and diminish the disposition to eat. Is this achievable? Is it possible to design foods with enhanced palatability (to promote and ensure consumption) and at the same time to improve satiety (which implies a reduction in the desire to eat)?

Pharmaceutical strategies

Although low levels of physical activity contribute to body-weight gain, there is no doubt that many weight-gaining and obese individuals display behavioural risk factors, such as patterns of eating, food selection, weak satiety and a recurring drive to eat, which favour the attainment of a positive energy balance (Blundell & Cooling, 2000). To these risk factors should be added a super-sensitive hedonic capacity. Currently, pharmaceutical strategies for the treatment of obesity are concerned with the reduction of energy assimilated, by improving satiety (sibutramine) or by reducing fat intake and fat digestion (Orlistat). Given the evidence cited earlier, some consideration should be given to the concept of diminishing the hedonic response to foods, particularly in the light of the ever-increasing palatability of foods entering the market place. The strategy would counter one significant risk factor that predisposes people to gain weight. The identification of a neural substrate that mediates aspects of the hedonic response, reward value of foods or their incentive salience, identifies pharmacological targets. Of particular interest are the endocannabinoids, which are known to be involved in food consumption and especially the intake of highly palatable foods (Kirkham & Williams, 2001). CB1 receptor antagonists such as SR141716A (Rimonabant) may be effective in helping people to diminish consumption of high-risk foods, adapt to more appropriate food choices and resist cravings. This type of approach would add a useful dimension to pharmaceutical treatments and may be especially helpful for a subset of obese people who over-consume because of a potent hedonic response to food.

Summary

The overall conclusion from the present brief review is that homeostatic models that interpret palatability as a reflection of underlying need-state are inadequate. Whether we examine salt appetite, where the physiological imperative to relate the palatability of a specific ion (Na) to the bodily need-state for that ion, or look more broadly at the use of foods in general, the recurring theme in the present review is that the preference for specific foods in man appears to reflect need-free hedonic stimulation of appetite, rather than a specific appetite arising from a specific need-state.

An important issue is what makes a food taste palatable. The most widely cited models in appetite research suggest palatability arises through past associations between flavours and consequences, most explicitly in flavour preference conditioning (Booth, 1991; Capaldi, 1992; Sclafani, 1999). An important finding in the present review of

liking for salty tastes was the observation that even a single experience of salt deprivation in childhood can lead to an enduring increase in liking for salty tastes in the absence of salt-need in adulthood. Accordingly, need-state may result in acquired palatability, but need-state may not be necessary for the subsequent expression of palatability. Attractive though this idea is, the limited results on acquired flavour preferences in human subjects suggest that preferences for flavours acquired when hungry or in a protein-deprived state are not expressed when sated (Booth *et al.* 1982; Gibson *et al.* 1995). Similarly, association of a flavour with caffeine can result in increased liking for that flavour if in need of caffeine, but this acquired palatability is not expressed when in a caffeine-sated state (Yeomans *et al.* 2000). These limited results argue against a generalised rule that need-state may enhance palatability, but this acquired liking is then insensitive to subsequent need-state. However, further research is needed to verify this conclusion, especially since, as discussed here, over-consumption of palatable foods is implicated in the development of obesity.

The present review also highlights the need for treatment strategies for obesity that incorporate our understanding of obesity. While reducing the palatability of our diet should result in reduced food consumption, in practice this is clearly not an option. However, designing diets that maximise hedonic satisfaction, but enhance satiation and/or satiety, is a novel and potentially useful strategy. Likewise, accepting that obesity cannot easily be attributed to a breakdown of homeostatic control mechanisms (Hellström *et al.* 2004) suggests that alternative pharmaceutical strategies aimed at modifying hedonic components of eating is also a strategy worth pursuing, especially with the merging role of cannabinoids in appetite control. At the same time, some of the shortcomings in our understanding of the nature of palatability highlighted in the present review need addressing. Until we have a clear model of what makes a food palatable, and how this leads to over-consumption, we will not be in a position to utilise these ideas to properly develop novel treatment strategies for obesity.

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