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Gustatory hedonic value: Potential function for forebrain control of brainstem taste processing

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Abstract

Among well-nourished populations, eating beyond homeostatic needs when presented with caloric-dense palatable food evidences the assertion that an increasing proportion of consumption is driven by pleasure, not just by the need for calories. This presents a major health crisis because the affective component of foods constitutes a behavioral risk factor that promotes over consumption [Sorensen, L.B., Moller, P., Flint, A., Martens, M., Raben, A., 2003. Effect of sensory perception of foods on appetite and food intake: a review of studies on humans. Int. J. Obes. Relat. Metab. Disord. 27, 1152–1166; Yeomans, M.R., Blundell, J.E., Leshem, M., 2004. Palatability: response to nutritional need or need-free stimulation of appetite? Br. J. Nutr. 92 (Suppl. 1), S3–S14]. Overweight or obese individuals have an increased risk of developing hypertension, stroke, heart disease, chronic musculoskeletal problems, type-2 diabetes, and certain types of cancers [Hill, J.O., Catenacci, V., Wyatt, H.R., 2005. Obesity: overview of an epidemic. Psychiatr. Clin. N. Am. 28, 1–23, vii]. The etiology of obesity is complex involving genetic, metabolic, and behavioral factors, but ultimately results from long-term energy imbalance. Evidence indicates that learned and some forms of unlearned control of ingestive behavior driven by palatability (i.e. hedonic value) are critically dependent on reciprocal interactions between brainstem gustatory nuclei and the ventral forebrain. This review discusses the current understanding of centrifugal control of taste processing in subcortical gustatory nuclei and the potential role of such modulation in hedonic responding.

Keywords

Taste; Amygdala; Cortex; Parabrachial; Solitary nucleus

1. Introduction

Although palatability (i.e. hedonic value) is unquestionably a key factor in guiding food choice and amount consumed, we know little about the neural bases of hedonic tone. We know that the influence of palatability is at least dependent upon the sensory characteristics of food, which involves the taste, trigeminal, and olfactory systems. Of these systems, the taste system offers a powerful model for studying the neural basis of hedonic value. A notable advantage of the taste system is that the adequate stimuli for the sense of taste are simple soluble chemicals, some of which have inherent hedonic value that epitomize ingestion and rejection (e.g. sucrose and quinine). This provides a benchmark against which the neural and behavioral responses to other stimuli can be judged. Further, the hedonic and behavioral response to a taste stimulus

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can be readily modified. For example, learning and nutritional status can change taste-guided behavior from ingestion to rejection and vice versa.

Taste-guided behavior begins with the interaction between a chemical stimulus and receptors located on the membrane of specialized epithelial cells. In mammals, receptor cells for the sense of taste are distributed primarily in the epithelium of the tongue, palate, and pharynx. They are located in discrete end organs called taste buds that are segregated in subpopulations and differ in size, innervation, chemical sensitivity, and presumably function. Most receptor cells are in 3 subpopulations of taste buds on the dorsal surface of the tongue, the fungiform, foliate, and circumvallate papillae. The fungiform papillae are scattered across the anterior two-thirds of the tongue, the circumvallate papillae on the posterior one-third of the tongue, and the foliate along the posterior edge of the tongue. Taste-evoked activity of fungiform receptors is carried centrally by the axons of the chorda tympani branch of the facial nerve, and that of most receptors in the foliate papillae, and all those in the circumvallate papillae by axons of the glossopharyngeal nerve.

On the palate, subpopulations of taste buds occur from the opening of the oral cavity on the hard palate back to the middle third of the soft palate near the opening of the nasopharynx. The greater superficial petrosal branch of the facial nerve innervates the vast majority of these receptor subpopulations. The other subpopulation of receptor cells is situated in the pharynx and larynx and innervated by the superior laryngeal branch of the vagus nerve (SLN). The afferent neural activity carried by the SLN apparently functions to prevent passage of food and fluid into the airway rather than ingestive behavior per se (Bradley, 2000).

A fundamental role of the taste system is to identify the components of foods and fluids. On a basic level this provides a means to initiate ingestion of those compounds an organism needs for survival and rejection of those that are potentially toxic. The sensory neural code for some sapid stimuli, then, provides an excitatory input to feeding circuits, while the code for other taste stimuli provides an inhibitory input. The influence of taste on feeding behavior, however, is dynamic because learning and physiological signals related to nutritional status can switch the behavioral response to a taste stimulus from ingestion to rejection or vice versa. The underlying mechanism for such compensatory responses appears to involve a change in gustatory hedonic value, i.e. palatability, rather than taste quality.

2. Central gustatory pathways

Prior research has demonstrated that the isolated brainstem contains not only the sensory and motor apparatus necessary to produce feeding behavior, but also the integrative capacity to organize normal acceptance and rejection responses to appropriate gustatory stimuli. For instance, chronically decerebrate rats, in which all neural connections between the forebrain and the brainstem are severed, are competent in producing innate discriminative responses to appropriate sapid stimuli (Grill and Norgren, 1978b,c) as well as in the integration of taste and gastrointestinal signals that determine intake in the short term (e.g. gastric preload, insulin, bombesin, cholecystokinin) (Kaplan et al., 2000; Grill and Kaplan, 2001). Decerebrate rats are, however, unable to learn a conditioned taste aversion (CTA) or express a sodium appetite (Grill and Norgren, 1978a; Grill et al., 1986). Generally, induction of a CTA occurs following experience with negative gastrointestinal consequences of ingesting a taste stimulus (e.g. nausea, sickness, or vomiting), which produces a switch from acceptance to avoidance of that and any like tasting stimulus. In contrast, a switch from avoidance of concentrated sodium salt to avid ingestion characterizes sodium appetite, the behavioral manifestation of a negative sodium balance. Decerebrate rats also fail to integrate signals like 24-h food deprivation that influence intake in the long term (Kaplan et al., 2000; Grill and Kaplan, 2001). Together, these results indicate that learned and some forms of unlearned control of taste-guided behavior are

critically dependent on connections between brainstem gustatory nuclei and the ventral forebrain.

2.1. Nucleus of the solitary tract

The first central synapse of gustatory axons supplying innervation to the oral cavity occurs in the nucleus of the solitary tract (NST). These afferent axons distribute in an overlapping order with input from the two branches of the facial nerve (e.g. chorda tympani and greater superficial petrosal) occupying the most rostral portion of the NST and that from the glossopharyngeal concentrated most caudally.

As would be expected, input to the NST is important in an animal's ability to use taste information to guide behavior. For example, rats with bilateral lesions in the gustatory area of the NST respond inappropriately to sapid stimuli compared with controls (Shimura et al., 1997b). Specifically, concentration-dependent intake of normally preferred and avoided taste stimuli is abolished. Altered concentration–response functions to taste stimuli following NST gustatory lesions are not due simply to an inability to modify ingestive behavior because the same NST lesioned animals responded normally to increases in the concentration of the trigeminal stimulus capsaicin. Even though the lesions produced a substantial deficit in preference–aversion functions, i.e. unconditioned hedonic responding, these same animals were competent in other taste-guided behaviors like CTA acquisition and sodium appetite expression (Grigson et al., 1997).

The disjunction of behavioral deficits that result from lesions of the gustatory NST presents a great paradox, because expression of a CTA and sodium appetite require that gustatory information reach more rostral forebrain sites and, consequently, information transfer from the NST to the PBN. One possibility is that certain behaviors like concentration-dependent intake of normally preferred and avoided taste stimuli is more vulnerable to a certain amount of damage compared to CTA and sodium appetite. This assertion gains support from the fact that the lesions of the NST discussed above were never complete suggesting that the residual taste neurons are sufficient to make the gross discrimination between the absence and presence of a taste stimulus and to transmit this neural information to the PBN (Grigson et al., 1997). From a sensory perspective, unconditioned concentration-dependent intake is a more complex behavior requiring subtle discrimination between different concentrations of a taste. However, unlike CTA and sodium appetite, innate concentration-dependent intake does not appear to require information transfer to more rostral structures via NST input to the PBN.

2.2. Pontine parabrachial nucleus

In lower vertebrates like rodents, the most widely used species in gustatory research; the primary rostral target of axons from the gustatory NST is the caudomedial pontine parabrachial nucleus (PBN). From there, gustatory projections diverge with one pathway sending axons to the gustatory cortical area (GC) via the thalamus and the other a direct route into the ventral forebrain providing gustatory information to areas like the lateral hypothalamus (LH), central nucleus of the amygdala (CeA), and bed nucleus of the stria terminalis (BNST) (Norgren, 1976; Nishijo et al., 1998; Li and Cho, 2006).

In contrast to lesions of the NST, bilateral lesions of the PBN can distort or blunt gustatory preference–aversion functions but fail to eliminate them (Flynn et al., 1991; Spector et al., 1992, 1993; Scalera et al., 1995). Nevertheless, the lesioned animals were unable to acquire a CTA or express a sodium appetite (Spector et al., 1992; Reilly et al., 1993; Scalera et al., 1995; Grigson et al., 1998; Reilly and Trifunovic, 2000). Disruption of CTA learning reflects a specific inability to associate taste and visceral afferent cues (Spector et al., 1992; Reilly et al., 1993; Grigson et al., 1998). Lesions in the thalamus, one synapse further along in the central

gustatory system, had no obvious effect on any of these taste-guided behaviors suggesting that the PBN–thalamocortical connection is not critical (Reilly and Pritchard, 1996a,b; Scalera et al., 1997). These and other data further suggest that the axons necessary for assigning hedonic value to taste stimuli relay through direct projections from the PBN to the ventral forebrain (Hajnal and Norgren, 2005; Norgren et al., 2006).

In summary, lesions of the brainstem gustatory nuclei interfere with conditioned and unconditioned gustatory hedonic responding as does disrupting afferent and efferent pathways between the forebrain and brainstem. However, damage at the level of NST and PBN produce a different constellation of symptoms. The NST seems to be more involved in the direct sensory control of ingestive behavior while the PBN may function in taste–visceral associations that are critical for assigning new hedonic value to tastants. Importantly, the forebrain regions that receive gustatory information like the GC, BNST, CeA, and LH send projections back to the NST and PBN (Veening et al., 1984; van der et al., 1984) and, thus, provide an anatomical substrate for critical forebrain/brainstem interactions.

3. Modulation of brainstem taste processing

3.1. CTA and sodium appetite

In addition to taste quality and intensity, the responses of brainstem taste neurons are modulated by prior experience and physiological state. In normal animals, for instance, CTA and sodium appetite selectively alter the responses of taste neurons in the NST and the PBN (Chang and Scott, 1984; Jacobs et al., 1988; Nakamura and Norgren, 1995; McCaughey et al., 1996, 1997; Shimura et al., 1997a,c; McCaughey and Scott, 2000). A common finding is an enhanced neural response to the conditioned taste stimulus after acquisition. In the case of sodium appetite, the common finding is decreased sensitivity of NST and PBN taste cells to sodium salt, particularly at the higher concentrations that are normally avoided. Whether these neural changes reflect a causal relationship is unsettled, although altered PBN taste responses induced by CTA acquisition are abolished following decerebration (Tokita et al., 2004). As mentioned earlier, PBN lesions and decerebration disrupt the ability of animals to acquire a CTA.

Although the basis of such neural modulation is not well understood, it likely depends upon dynamic modulation of gustatory-evoked responses by descending forebrain inputs. In fact, stimulation of the GC, BNST, CeA, and LH has been shown to modulate taste-evoked neural activity in the NST and PBN. This centrifugal modulation is often differential, which is consistent with lesion-behavioral data showing that damage at the level of the NST and PBN produce a different constellation of taste-guided behavioral symptoms.

3.2. Nucleus of the solitary tract

Depending on the source of descending input, the predominant effect is often either inhibition or augmentation of NST taste-responsive neurons. The most common effect of CeA (91–93%) and LH (66–100%) stimulation was excitatory; BNST stimulation was predominantly inhibitory (80%), while GC activation induced a more equal distribution of excitation (47%) and inhibition (53%) (Matsuo et al., 1984; Murzi et al., 1986; Dilorenzo and Monroe, 1995; Smith and Li, 2000; Li et al., 2002; Cho et al., 2002, 2003; Smith et al., 2005). In one study that produced temporary inactivation of GC with procaine infusions (Dilorenzo and Monroe, 1995), inhibition of medullary taste cells was reported to be the primary influence. In the few studies that tested the influence of forebrain activation on taste-evoked responses, the excitatory influence of LH and CeA activation was shown to increase responses of NST neurons to all taste stimuli tested (Li et al., 2002; Cho et al., 2002). Presumably, the increased signal-to-noise ratio would increase the discriminatory capability of the gustatory system because neural discrimination is dependent on the relationship between signal and noise (Cho et al.,

2002). This is consistent with findings resulting from temporary removal of cortical input or chronic decerebration where taste-evoked responses were suppressed (Mark et al., 1988; Dilorenzo and Monroe, 1995).

3.3. Parabrachial nucleus

One synapse further along in the ascending gustatory system, forebrain activity produces a somewhat different pattern of effects on taste cells in the PBN. Here activation of the BNST was entirely inhibitory; CeA (85%) and GC (71%) most often produced inhibition, while inhibition and excitation occurred equally often during LH stimulation (Dilorenzo and Monroe, 1992; Lundy and Norgren, 2001, 2004; Li et al., 2005; Li and Cho, 2006). It should be noted that one study reported that the predominant influence of GC stimulation on PBN taste cells was excitatory rather than inhibitory (Dilorenzo and Monroe, 1992). The stimulating procedures in this study, however, appeared to predispose the identification of excitatory effects because PBN neurons that showed evoked action potentials time-locked to GC stimulation were the sample of interest. Thus, the inhibitory component of descending GC projections might have been underestimated.

Again, only a few studies have examined the influence of descending forebrain inputs on taste-evoked responses in the PBN. The most thorough characterization was conducted in rats and will be discussed here further. The net effect of LH, CeA, and GC activation on PBN taste cells was to sharpen the distinction between different classes of taste stimuli (Lundy and Norgren, 2001, 2004). Inhibition accomplished this shift in chemical sensitivity by suppressing the overall response level of PBN neurons to sapid stimuli irrespective of a neuron's response profile to qualitatively distinct stimuli (e.g. best-stimulus category). This reduced the number of tastants to which a given unit responded, but the magnitude of inhibition was often differential so that the response to the best-stimulus ended up even larger with respect to the other stimuli. The excitatory influence, on the other hand, was rather specific; sharpening the response profile of neurons most responsive to NaCl (e.g. NaCl-best cells) through stimulus specific enhancement of responsiveness to NaCl. In fact, the spontaneous discharge and the response to other qualitatively distinct stimuli were often suppressed.

Prior research also demonstrates that descending projections from multiple forebrain sites can converge onto individual brainstem gustatory neurons. In the NST, nearly half of the forebrain responsive neurons were influenced by stimulation of both the LH and CeA (Cho et al., 2003). In the PBN, convergence of descending input from the LH, CeA, and GC was examined (Lundy and Norgren, 2004). Forty-two of the 60 PBN taste neurons tested for convergence were influenced by stimulation of at least 2 of the 3 forebrain sites. Similar to dually responsive NST cells, a common effect was produced on PBN cells responsive to stimulation of only 2 forebrain sites, either inhibitory or excitatory. However, the neurons responsive to stimulation at all 3 sites were often differentially influenced. Thus, ongoing activity in higher-order nuclei might produce independent or coordinated modulation of earlier stages of gustatory processing.

In the awake-behaving animal, the forebrain areas discussed above presumably influences the same gustatory activity continuously and dynamically. Thus, gustatory neural activity recorded in the awake, behaving state might be expected to differ from responses in anesthetized animals. Indeed, the response profiles of PBN taste neurons have been shown to be sharper (e.g. more stimulus selective) than similar activity recorded in anesthetized preparations (Nishijo and Norgren, 1997), which might result from a general suppression of forebrain circuits caused by anesthesia. This raises the question of whether the general nature of artificial electrical activation of the forebrain reflects specific patterns of descending activity present in the awake, behaving animal. It might be that specific patterns of descending activity are associated with different internal and external environmental signals that can selectively amplify certain signals (e.g. selective increase in neural response to the CS following CTA induction). In fact, electrical

forebrain stimulation in an anesthetized preparation sharpened the response profile of PBN neurons to sapid chemicals, which often was specific to a single class of taste stimulus (Lundy and Norgren, 2001, 2004). Moreover, altered PBN taste responses induced by CTA acquisition are abolished following decerebration, which removes the influence of descending input on brainstem taste processing (Tokita et al., 2004). Given the vast differences between a few pulses of electricity for a few seconds versus dynamic activity of the entire forebrain, the similarity in overall effect is striking and reflects the value of simplifying the activity in an awake, behaving brain to uncover specific synaptic mechanisms.

3.4. Neural coding of hedonic value

The brain extracts information about quality, intensity, and hedonic value from gustatory neuronal responses, thus all of these psychological attributes must be coded by the neural activity in the taste pathways. In general, two primary theories have emerged to explain how taste information is represented in the activity of afferent neurons; a labeled-line and an across-neuron pattern theory (Pfaffmann, 1955; Erickson, 1968; Smith et al., 1983; Frank et al., 1988). Briefly, the former theory is critically dependent upon the existence of neuron types and assumes that a particular type carries information about only one class of tastant. In fact, a large body of electrophysiological data has demonstrated that gustatory neurons can be meaningfully divided into groups on the basis of their sensitivity to different classes of chemical stimuli (Frank, 1974; Chang and Scott, 1984; Boudreau et al., 1985; Nishijo and Norgren, 1997; Lundy and Contreras, 1999; Smith et al., 2000). The latter theory, on the other hand, emphasizes that individual neurons respond to many different compounds and coding is accomplished through differential activation of large ensembles of neurons with distinct response profiles (for a critical review, see Spector and Travers, 2005).

As mentioned earlier, a common finding following induction of a CTA is an enhanced neural response to the conditioned taste stimulus. In the NST, this altered neural response to the CS (e.g. Na-saccharin) was shown to be differential, so that the clear distinction between the neural patterns elicited by the normally accepted CS and normally avoided stimuli (e.g. QHCl and acids) were disrupted (Chang and Scott, 1984). That is, the across-neuron pattern of activity elicited by Na-saccharin, QHCl and acids were more similar following CTA acquisition. Recently, we have reported an altered population code for sucrose in an animal model for obesity and type-2 diabetes (Lundy et al., 2006).

Otsuka Long-Evans Tokushima fatty (OLETF) rats lack functional cholecystokinin-1 (CCK-1) receptors and develop hyperphagia, obesity and type-2 diabetes over about a 28-week time period (Kawano et al., 1992). With advancing age, OLETF rats show increased preference for sugars and monosodium glutamate compared to age-matched Long-Evans Tokushima Otsuka (LETO) lean controls during sham feeding and brief access licking (De Jonghe et al., 2005; Hajnal et al., 2005). Thus, OLETF rats display a progressive increase in behavioral sensitivity to palatable tastants that coincides with the progression of obesity and development of diabetes. Since central taste processing in this strain has not been studied, we investigated whether taste processing of sucrose in the PBN varied with the progression of obesity and diabetes.

Advancing age in OLETF rats, but not LETO rats, increased the neural response of sucrose-best neurons to sucrose and correspondingly decreased it in NaCl-best cells. In terms of an across-neuron pattern, the development of hyperphagia and obesity in OLETF rats was accompanied by an increase in the proportion of sucrose-evoked activity carried by the class of neurons most responsive to sucrose (e.g. sucrose-best cells). In this framework, biasing the population output towards a greater proportion of the total taste-evoked activity being carried by neurons most responsive to normally preferred stimuli might signal increased positive hedonic value and augment subsequent intake, and vice versa. This coding scheme is consistent with the opposite shift in the PBN across-neuron pattern evoked by sucrose observed following

intraduodenal lipid infusion (Hajnal et al., 1999), which reduces intake of sucrose (Foster et al., 1996). Thus, groups of neurons with unique response profiles to different classes of tastants are critical for defining distinctive ensemble patterns of activity for different stimuli (Smith et al., 1983, 2000). Since the relative responsiveness to different stimuli in specific classes of taste neurons ismalleable, the across-neuron pattern of activation consequently changes and, thus, might perception and behavior.

Of import, forebrain activation can produce similar alterations in the across-neuron pattern elicited by specific gustatory stimuli (Dilorenzo and Monroe, 1995). In a prior study from our lab, we showed that forebrain stimulation increased the relative contribution of a given stimulus to overall evoked activity in specific classes of gustatory neurons (Lundy and Norgren, 2004). When this data was re-analyzed to determine the effects on the across-neuron pattern elicited by taste stimuli (unpublished), we found that forebrain stimulation increased the proportion of overall sucrose-evoked activity carried by sucrose-best neurons and, consequently, decreased it in NaCl- and acid-best neurons. A similar result was evident for citric acid and NaCl where the proportion of overall citric acid- and NaCl-evoked activity carried by acid- and NaCl-best neurons, respectively, was increased during forebrain stimulation.

3.5. Neurochemical mediators

Despite the substantial data characterizing the influence of feedback from the LH, CeA, BNST, and GC on brainstem taste processing, the identification of the neurochemicals subserving centrifugal modulation remains in its infancy. In the PBN, the predominant inhibitory influence suggests a role for the inhibitory neurotransmitter GABA. Previous studies demonstrated that GABAergic neurons are present in these forebrain regions (Sun et al., 1994; Jia et al., 2005) and GABA produces a concentration-dependent reduction in input resistance of neurons in the caudomedial gustatory zone of the PBN (Kobashi and Bradley, 1998). Nevertheless, a recent study showed that GC, BNST, CeA, and LH neurons retrogradely labeled with fluorogold following small iontophoretic injections into the physiologically identified gustatory PBN do not contain glutamic acid decarboxylase, the enzyme responsible for the conversion of glutamic acid to GABA (Saggu and Lundy, 2007). Thus, the inhibitory influence of forebrain inputs on PBN taste processing does not appear to be mediated by direct input from GABAergic forebrain neurons onto PBN taste responsive cells.

Other neurochemicals might play a role in centrifugal modulation including somatostatin, neurotensin, corticotrophin-releasing factor, cholecystokinin, enkephalin, substance P, and galanin. PBN projecting neurons originating in the LH, CeA, and BNST are immunoreactive for these neurochemicals (Moga and Gray, 1985; Moga et al., 1989, 1990). In fact, substance P and cholecystokinin have been shown to inhibit evoked excitatory postsynaptic current in PBN cells, while neurotensin enhanced excitatory postsynaptic current (Saleh and Cechetto, 1993; Saleh et al., 1996, 1997). Whether these effects on excitatory transmission in the PBN are related to gustation per se is unknown because the PBN consists of different regions processing gustatory, visceral, and somatosensory signals. The same holds for the anatomical studies that used stereotaxic coordinates alone to place tracer injections. Valuable information was provided, however, the distinction between gustatory, visceral, and somatosensory regions of the PBN was not possible.

In the gustatory region of the NST, several neuroactive substances have been identified including substance P, neurotensin, somatostatin, tyrosine hydroxylase, enkephalin, and GABA (Mantyh and Hunt, 1984; Leonard et al., 1999). Some of these are known to influence the neural discharge of gustatory NST cells. For instance, local injection of GABA and met-enkephalin decreased the response of hamster NST cells to gustatory stimulation (Smith et al., 1994; Li et al., 2003). These effects were blocked by application of the $GABA_A$ receptor

antagonist bicuculline methiodide (BICM) or the non-selective opioid receptor antagonist naltrexone (NLTX), respectively. Application of BICM alone, but not NLTX, excited taste cells suggesting a tonic GABAergic inhibition, which when released results in an increase in chemical sensitivity (Smith et al., 1994; Smith and Li, 2000). In the case of BICM, microinjection into the NST blocked the cortical-induced inhibitory effect on taste cells, but not the excitatory effect (Smith and Li, 2000). Substance P also has been shown to influence NST gustatory neurons producing primarily enhancement of taste responses. Whether these neurochemicals are contained in the terminals originating from the forebrain and released upon activation or are part of local circuits engaged by descending input remains to be established.

4. Summary

The forebrain plays a prominent role in the hedonic value that the brain attaches to gustatory activity originating from the oral cavity. Specifically, the brainstem gustatory nuclei in isolation are not sufficient to support learned and some forms of unlearned control of taste-guided behavior that involve assigning new hedonic value. Moreover, recent evidence suggests that the axons necessary for assigning hedonic value to taste stimuli relay through direct projections into the ventral forebrain rather than relaying through thalamocortical projections. These same fore-brain structures including the LH, CeA, BNST, and GC, which are known to receive gustatory information, project back to the brainstem to modulate afferent taste-evoked activity in the NST and PBN. Because brainstem gustatory neural activity, particularly across-neuron patterns of activation, also is altered by forebrain stimulation and conditions that change gustatory hedonic value, these prominent reciprocal connections between the brainstem and the forebrain likely play a significant role in determining preference for and aversion to taste stimuli.

Clearly, additional research is needed to gain a better understanding of the neural basis of hedonic responding. Further research should be directed toward determining the neurochemicals and precise neural circuitry that mediates centrifugal control of brainstem taste processing. Another area of research involves identifying how these pathways are engaged by alterations in physiological status and experience. With this information in hand, it might be possible to pharmacologically increase the palatability of less caloric-dense foods (e.g. low sugar/low fat). A lofty goal indeed, but one day we should all be able to say, “Healthy food tastes so good.”

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