Afferent Neural Coding in the Three Main Gustatory Nerves
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Abstract

A functional gustatory system is crucial to the survival of humans and animals. Because taste functions as a survival mechanism, it is important for animals to develop and maintain the ability to correctly distinguish between tastants of different chemical components and to avoid tastants that are dangerous. Because mammals encounter a wide array of tastants in the everyday environment, the mammalian taste system has evolved complex mechanisms to distinguish between tastants and adjust behavior based on those distinctions.

Three main nerves are involved in transmitting gustatory information to the brain. These nerves are the chorda tympani, the glossopharyngeal nerve, and the greater superficial petrosal nerve. Electrophysiological studies have shown that each nerve has widely-tuned neurons and narrowly-tuned neurons to different tastants. Behavioral studies have suggested that each nerve has a distinct ability to detect and avoid certain tastants and to discriminate between tastants. The compilation of behavioral and electrophysiological studies have allowed researchers to form theories about how each nerve contributes to taste perception. In this review, the afferent neural coding shown by electrophysiological and behavioral data from the CT, GL, and GSP nerves is discussed.
Introduction

As in any other sensory system, the gustatory system receives a stimulus and transduces it into a neural code that is sent to the brain and perceived as a specific sensation. The distinct process by which taste is transduced by the gustatory system begins when taste receptors on the tongue are stimulated by a particular taste stimuli. The tongue contains four different types of taste receptors called papillae. The filiform papillae are located over the entire surface of the tongue. The fungiform papillae are located at the anterior tip and the sides of the tongue. The foliate papillae are folds that are located along the sides of the tongue, and the circumvallate papillae are found on the posterior region of the tongue. The papillae contain taste buds, which contain taste cells. Stimulation of the taste buds occurs when chemicals interact with the taste cells of the taste buds. The effect of this interaction is the influx of ions into the taste cells.

The four basic taste categories are bitter, sweet, salty, and sour. Each category activates a different transduction mechanism that causes the influx of ions into the taste cells. The change in membrane potential due to ion influx produces electrical signals, which are transmitted from the tongue via three main gustatory nerves. The chorda tympani nerve (CT) is a branch of the facial nerve (Cranial Nerve VII) and conducts signals from the taste cells of the fungiform papillae on the anterior region of the tongue and rostral foliate papillae on the sides of the tongue. The greater superficial petrosal nerve (GSP) is also a branch of the facial nerve and conducts signals from palatal cells. The glossopharyngeal nerve (GL) is the ninth cranial nerve and conducts signals from the taste cells of the circumvallate papillae and caudal foliate papillae on the posterior region.
of the tongue. The fibers of these three nerves converge in the nucleus of the solitary tract (NST). Then they synapse in the thalamus and frontal lobe of the brain.

Much research has been conducted to determine the precise functions of these three nerves and how the nerves converge to provide gustatory information to the brain. Most of the research has been conducted using the four main categories of tastants (bitter, sweet, salty, and sour). The four most common stimuli used in this area of research are potassium chloride (KCl) for sour, sucrose for sweet, quinine hydrochloride (QHCl) for bitter, and sodium chloride (NaCl) for salty. This paper reviews the literature concerning the roles of the three major gustatory nerves and the afferent neural signals sent to the brain.

**Chorda Tympani Nerve**

The CT is a branch of the seventh cranial nerve. The CT innervates an estimated amount of 15% of the total taste buds on the tongue. The CT innervates taste buds located on the fungiform papillae of the anterior portion of the tongue. Although the CT innervates a small amount of taste buds, it is necessary for performing specific taste functions. The CT plays an important role in coding salts and discriminating both between salts and non-salts and between sodium salts and non-sodium salts. The CT is responsive to other tastants, including sucrose, but is not necessary for the coding of tastants other than salts.

Electrophysiological studies conducted on the CT have shown many functions of the CT in neural coding. The CT has groups of neurons that are narrowly-tuned to both NaCl and sucrose and neurons that are broadly-tuned to NaCl, HCl, and QHCl. Single-fiber recordings show that the CT’s high responsiveness to NaCl is a result of a small
subset of highly responsive neurons. The CT has the distinct ability to discriminate between sodium and non-sodium salts due to the presence of amiloride sensitive neurons (HAS) and amiloride insensitive/low sensitive neurons (LAS). The CT shows synergistic effects for the responses to specific mixtures, including MSG and sucrose mixtures.

Frank (1991) and Bodreau and colleagues (1983) identified two separate groups of fibers in the CT based on their responses to various types of sodium salts, nonsodium salts, and other stimuli. The first group is called “N-units.” They are narrowly-tuned to respond to sodium and lithium salts. The second group is called “H-units” and responds broadly to a variety of cations and acids.

Lundy and Contreras (1999) identified five separate groups of CT neurons after recording extracellular responses from 73 anterior geniculate ganglion neurons to stimulation with sucrose, NaCl, HCl, QHCl, KCl, and NH₄Cl. He found two narrowly-tuned groups called sucrose-specialists and NaCl specialists and three broadly tuned groups called NaCl-generalists, HCl-generalists, and QHCl generalists. NaCl-specialists comprised 25% of the neurons, and sucrose-specialists comprised 11% of the neurons.

Hill and Sollars (2005) compared responses to taste stimuli between the GSP and the CT. The whole-nerve recordings showed high CT responses to NaCl. However, the single-fiber CT recordings showed that only a small subset of the neurons responded strongly to NaCl, which correspond to “NaCl-specialist” neurons that were previously labeled by Lundy and Contreras (1999). Most of the remainder of the neurons fit into either the “NaCl generalist” category or the “HCl-generalist” group. The conclusion of this study is that the large whole-nerve response does not indicate many semi-responsive neurons in the CT but rather a small group of very responsive neurons.
One method of studying the function of the CT is by examining effects of amiloride, which is a chemical that inhibits the responsiveness of CT neurons to NaCl by selectively blocking sodium channels. Single-fiber CT responses to NaCl during amiloride inhibition typically form two distinct groups. In one study, the responses of 32 single-fiber CT neurons to NaCl were recorded before and after amiloride inhibition. The amount of reduction in NaCl response caused by amiloride varied, but the results formed two distinct groups. Out of the 32 fibers being tested, 18 fibers showed responses that ranged from 1.1%-42.5% of the control response, and 14 fibers showed responses ranging from 72.8%-108% of the control response (Ninomiya and Funakoshi, 1988). The results showed that at least two distinct mechanisms are involved in the overall CT response to NaCl. These two types of fibers are labeled “highly-amiloride sensitive” (HAS) and “low-amiloride sensitive” (LAS). HAS fibers respond more strongly to NaCl and LAS fibers respond more strongly to HCl. The presence of amiloride-sensitive and amiloride-insensitive fibers are found exclusively in the CT and are the explanation for the CT’s ability to discriminate between sodium and non-sodium salts.

Two prominent models have been proposed to explain the responses of multiple fibers in a taste nerve to binary mixtures. The two models are the substitution model and the response additivity model, and they both attempt to identify the number of sources that contribute to a neural response. The stimulus substitution model explains neural responses to mixtures in terms of a single source. The response additivity model explains responses to mixtures as the product of two independent sources. Responses that cannot be explained by the range of these two models are attributed to inhibition or synergy (Formaker, 2004). Responses of CT single fibers to MSG, with amiloride presented, and
sucrose were measured to determine if they would activate identical or separate groups of CT neurons, and responses of an MSG-sucrose mixture was hypothesized to be between the predictions of the stimulus-substitution model and the response additivity model. Whole-nerve results showed amiloride suppressed CT responses to MSG and MSG-sucrose mixtures but did not increase or decrease responses to sucrose alone (Formaker, 2004). Single fiber results showed two distinct classes of fibers, including sucrose-sensitive and sucrose-insensitive fibers. Both types of fibers were activated by MSG. The stimulus substitution model was not predictive of the whole-nerve response to the MSG-sucrose mixture because two sources existed, sucrose-sensitive and sucrose-insensitive. The whole-nerve responses also exceeded the response additivity prediction. These results suggest that mixture responses in the CT cannot be explained by component parts alone and that synergistic interaction could exist between MSG and sucrose.

The CT shows many characteristics in how it responds to certain taste substances. Based on electrophysiological data, CT neurons as a whole have the greatest responses to NaCl, but responses are also great to sucrose. This CT shows greater responsiveness to sucrose and NaCl because of the presence of narrowly-tuned sucrose and NaCl fibers. The CT also responds broadly to substances such as HCl and QHCl. The CT also has amiloride sensitive and insensitive neurons that allow discrimination between sodium and non-sodium salts. The CT shows evidence for synergistic effects on certain mixtures.

In addition to electrophysiological studies, CT behavioral studies have provided much insight into the function of the CT. These behavioral studies span across various methodologies, using methods such as two-bottle preference tests, taste reactivity tests,
operant discrimination tasks, detection threshold tests, and conditioned taste aversion tests. Transection of the CT (CTX) causes great behavior deficits in response to NaCl. CTX causes decreased ingestive responses to NaCl, MgCl₂, and QHCl and greatly reduces the rat’s ability to discriminate between NaCl and KCl. CTX decreases the effectiveness of learned aversion to NaCl and doubles the detection threshold for NaCl but does not affect suprathreshold NaCl detection. The CT also contributes to the detection of KCl, but is more supplemental in function as compared to the crucial role it plays for NaCl detection. The CT has not been shown to play a significant role in coding sucrose.

Although research had clearly shown by the 1970’s that the CT was crucial in the neural coding of NaCl, little else had been shown due to poor methodology. Electrophysiological research had convincingly shown that the CT responded much more vigorously to NaCl than to sucrose, sodium saccharin, citric acid, QHCl, LiCl, CaCl₂, and NH₄Cl (Nejad, 1986). However, behavioral research did not support these findings. Twenty-four hour two-bottle preference tests showed a significant decrease in quinine preference but did not show a significant decrease in preference of NaCl after CTX (Akaike, 1965). The contradictory results became clearer as researchers used better methodology. A landmark study conducted by Grill and colleagues in 1992 demonstrated the effectiveness of better methods of testing. A 24-hour two bottle preference test showed no significant increases or decreases in preferences of NaCl, MgCl₂, quinine, or sucrose between the CTX group and the control group. However, in the same study, a taste reactivity test was used to observe oral motor responses before and after CTX. The taste reactivity test measured taste-elicited oral motor behavior by
comparing the number of ingestive responses (stimulus ingestion) and aversive responses (stimulus rejection) during the presentation of a specific stimulus. The taste reactivity test showed that ingestive oral motor responses to NaCl, MgCl₂, and quinine decreased significantly after CTX (Grill et al., 1992). These results were consistent with the predictions of the electrophysiological data, which suggests that the 24-hour two-bottle preference test was ineffective in demonstrating behavioral deficits after CTX.

Since testing methods have improved, research has shown much more clearly that the CT is necessary for salt taste discrimination. Much of this research has been conducted by Alan Spector. In his 1992 study, Spector and Grill (1992) studied the effects of CTX on a presurgically learned NaCl vs. KCl discrimination task. Rats were trained presurgically to maintain licking during five second presentations of either NaCl or KCl and to avoid licking during a five second presentation of the opposite stimulus. Rats were tested both before and after CTX for their ability to accurately discriminate between NaCl and KCl and perform the trained response to each stimulus. The results after CTX showed a significant decrease in the rats’ performance of the discrimination task. Discrimination decreases after CTX were concluded to be specific to NaCl because CTX did not decrease performance on discrimination tasks between sucrose and quinine. This data suggests that the CT plays a crucial role in discriminating NaCl from other solutions. This conclusion is supported by a large body of both electrophysical and behavioral evidence (Bodreau 1983, Bodreau 1987, Frank 1983, Frank 1991).

Studies have shown that NaCl detection thresholds double after CTX but are not significantly increased after GLX (Spector, 1990). CTX also impairs oral motor behaviors such as licking behavior in response to NaCl (Yamamota and Asai, 1986).
Results from studies on conditioned taste aversions have shown that CTX decreases effectiveness of aversion to NaCl (Hill et al., 1990). The results of the behavioral studies are consistent with the electrophysiological findings that suggest NaCl discriminative abilities for the CT due to sodium-specific afferents.

Although much data has been shown for the CT’s role in coding taste-guided NaCl behaviors, not all responses to NaCl are coded by the CT. In Colbert’s 2004 study, she tested the effects of CTX and GLX on suprathreshold intensity discrimination. Colbert used difference thresholds, the amount of change necessary in a stimulus to produce a detectable change in sensation, to study the effects in a two-response operant discrimination task. This task was conducted by training rats to press one lever for the standard 0.05 M NaCl concentration and one lever for the higher concentration of 0.5 M NaCl. Presurgical testing assessed the ability accurately discriminate between the standard concentration and higher concentrations ranging from 0.15 M to 0.5 M. This testing was followed by surgery, after which the same method of testing used presurgically was repeated. Because the CT shows a much higher responsiveness to NaCl than other taste nerves, it was hypothesized that NaCl difference thresholds would increase after CTX. However, results showed that CTX was not effective in increasing difference thresholds and did not differ significantly from the results of the GLX or sham-controlled rats. These results suggest that, although the CT is crucial to detection and general discrimination of NaCl, input from other taste nerves other than the CT are sufficient to maintain suprathreshold taste discrimination. Since the GL does not seem necessary for this task either, the GSP could provide input for this type of discrimination.
Studies suggest that the CT is not necessary for coding sweet solutions. Early preference studies showed that CTX had no effect on sucrose detection in a 24 hour two-bottle test (Vance, 1966). Krimm studied the effects of CTX and glossopharyngeal nerve transection (GSPX) on sucrose mean lick ratio. Mean lick ratio was determined by comparing the number of licks before surgery to five 30-second presentations of different concentrations of sucrose to the number of licks after surgery to the same presentation of stimuli. The results showed that CTX did decrease the mean lick ratio (Krimm, 1987). Results from a two-lever operant discrimination procedure showed that CTX does not significantly increase the detection threshold for sucrose (Geran et al., 1999). The field of research in this area has consistently shown that the CT does not play a significant role in coding the sweet taste.

Although the largest amount of research has been conducted in the CT’s role in coding salty tastes, there is also evidence showing that the CT plays a role in coding the taste of KCl. Geran and colleagues (1999) conducted a study to determine whether CTX would affect the detection threshold of KCl in rats. Because previous research showed that a subset of CT fibers known as “H-fibers” were responsive to a variety of salts, acids, and quinine (Frank, 1983), Geran expected the CTX to significantly raise the detection threshold for KCl. Geran used a two-lever operant discrimination procedure, and the results showed a significant increase in the KCl detection threshold after CTX. Although the results were significant, the rats were still able to detect high concentrations of KCl after CTX. These results suggest that, although the CT plays a role in detecting the taste of KCl, the CT is more supplementary than necessary for this function (Geran, 1999).
The CT plays a major role in guiding the behavior of rats towards specific tastants. NaCl is the main tastant coded by the CT. The CT plays an important role in the detection of NaCl, the discrimination of NaCl from other substances, and oromotor responses to NaCl. However, the CT is not solely responsible for NaCl coding. The CT is not important for tasks such as detecting suprathreshold differences of NaCl. The CT is also involved in the detection of KCl but does not appear to be involved in the detection of sucrose.

The electrophysiological and behavioral data for the CT suggest that the main function of the CT is to detect NaCl and discriminate between NaCl and other substances. Electrophysiological data showed that the CT has narrowly-tuned fibers to NaCl. Behavioral data confirmed the predictions of the electrophysiological findings by showing that CTX decreases the detection of NaCl as compared to other substances. Also, the presence of amiloride sensitive and insensitive fibers as specific to the CT allows the CT to discriminate between sodium and non-sodium salts, which was also confirmed behaviorally through preference tests. However, the CT is not solely responsible for NaCl coding. Although CTX reduces the ability to detect NaCl, the ability is not eliminated completely, suggesting that other nerves assist the CT in coding NaCl. Behavioral and electrophysiological data also show the contribution of the CT to coding other tastants. The CT has broadly-tuned neurons for HCl and quinine and a small amount of narrowly tuned neurons to sucrose. Behavioral data shows that the CT affects behavioral responses to MgCl₂, QHCl, and KCl, but no data has shown CT effects on responses to sucrose. The narrowly-tuned sucrose neurons are perhaps compensatory since they do not seem to be necessary for coding the taste of sucrose.
Greater Superficial Petrosal Nerve

The GSP is also a branch of the seventh cranial nerve. It innervates palatal taste buds and is known mostly for its strong responses to sugar and modest responses to salt. In the rat, the palate is the location of 17% of the total taste buds and 85% of the palatal taste buds are innervated by the GSP. The body of research conducted on GSP is very limited due to the fact it is difficult to isolate for recordings and difficult to transect. The limited conclusions that have been made about its role mainly emphasize its importance in coding the taste of sucrose and other sugars.

Electrophysiological studies have included both whole-nerve and single-fiber recordings. However, due to the difficulty of isolating single GSP fibers, only one study has been published with single-fiber recordings. The whole nerve recordings have been taken from the nasoincisor ducts in the palate, the nucleus of the solitary tract, and other subpopulations in the palate. Results have shown that palatal taste receptors are more responsive to sucrose than to other common tastants. The GSP is more responsive to at least six types of sugars and shows both lower thresholds and higher sustained responsiveness to sugars than to other tastants. The GSP has shown high responsiveness to salts, but studies vary greatly in reports of the magnitude of this salt response. The only single-fiber study to date has shown that GSP neurons are divided into five basic categories: sucrose-best, inhibited by HCl, quinine-best, HCl-generalists, and NH₄Cl generalists. The data suggests that the GSP’s great responsiveness to sucrose is a result of a small group of narrowly-tuned sucrose neurons.

One method researchers have used to make inferences about the role of the GSP in coding taste is studying the palatal taste receptors. Inferences about the GSP can be
made because it innervates over 80% of the taste buds on the palate. Early recordings from the GSP showed that sucrose gustatory stimulation of the soft palate produced large whole-nerve GSP responses compared to whole-nerve CT responses (Nejad, 1986). One study compared the number of the G-protein subunit alpha-gustducin the soft palate and the fungiform papillae. Alpha-gustducin cells are involved in the transduction of sweet substances and are counted by labeling taste bud populations with an antibody against alpha-gustducin that causes immunofluorescence of gustducin-positive cells. The palate had an average of 8.9 gustducin-positive cells per taste bud, and the fungiform papillae had only an average of 3.1 gustducin-positive cells per taste bud (Boughter, 1997). From this data, Boughter concluded that the cells of the soft palate, which are innervated by the GSP, have a greater ability to transduce sweet substances when compared to the cells of the fungiform papillae, which are innervated by the CT.

Recordings have also been conducted in the nucleus of the solitary tract (NST), which is the projection area for the three major taste nerves. In one study, the responses of the anterior tongue and the nasoincisor ducts were examined. Responses of 54 neurons to independent stimulation of four subpopulations of taste receptors (anterior tongue, nasoincisor ducts, soft palate, and foliate papillae) were recorded from the NST using NaCl, HCl, QHCl, and sucrose as stimulants. When stimulating the nasoincisor ducts, sucrose yielded the greatest responses and the other three stimulants had low responses. The responses of the anterior tongue were low to sucrose. Because the nasoincisor ducts are prominently innervated by the GSP, the results suggest that the GSP carries the code for sucrose tastants (Travers, 1986).
More recent studies on whole-nerve responsiveness of the GSP have shown similar results. Harada and colleagues (1997) compared measurements of whole-nerve recordings from the GSP in the soft palate and from the CT in the anterior part of the tongue. The main stimuli used in this study were NaCl, sodium acetate, and sodium saccharin. The GSP phasic and tonic responses to six types of sugar were significantly greater than the CT responses. The GSP showed a significantly lower threshold (0.001 M) to sucrose than the CT (0.003 M). Compared to the CT, the GSP responds stronger to sucrose and detects sucrose at a lower threshold.

Sollars and Hill (1998) conducted similar whole-nerve recordings of the GSP palatal fields with salt and sugar stimuli. The specific stimuli used were different concentrations of NaCl, sodium acetate, ammonium chloride, sucrose, maltose, hydrochloric acid, and quinine hydrochloride. As expected, the GSP showed robust responsiveness to sugars, especially sucrose. The GSP also showed robust responses to salts. The responses of the GSP to NaCl and NH₄Cl at high concentrations suggest that the GSP also plays a role in coding salt tastants. Other studies have also shown robust GSP responses to salts but have not emphasized those results (Nejad, 1986; Harada et al., 1997; Hill and Sollars, 2005).

Although several studies have shown GSP responses to salts, the findings in these studies, especially Harada and colleagues (1997) and Sollars and Hill (1998), show varying levels of responsiveness. While Harada and colleagues showed robust GSP responses to salts, Sollars and Hill showed minimal GSP responses to salts. These varying results can be explained by methodological differences. Harada and colleagues stimulated only the nasoincisor ducts, and Sollars and Hill stimulated all three palatal
fields (the nasoincisor duct, the geschmacksstreifen, and the posterior palatine field). These individual palatal fields could vary in their individual responsiveness to NaCl. Also Harada and colleagues used Sprague Dawley, and Sollars and Hill used both Sprague Dawley rats and F344 rats. Concentrations also differed between the two experiments. Harada and colleagues used concentrations between 0.05 M and 2.0 M NaCl, and Sollars and Hill used concentrations between 0.0001 and 1.0 M NaCl. The conclusion from these two studies is that the GSP responsiveness to NaCl varies based on the concentration, the species of rat, and the area of the palate stimulated, but the GSP does have the potential to show strong responses to NaCl.

An important component missing from the body of research conducted on the GSP is single-fiber recordings. Many single-nerve studies have been conducted with the CT and the GL, but only one study has been published to date with reports of single-fiber GSP recordings. Hill and Sollars (2005) conducted single axon recordings from GSP and CT neurons in the geniculate ganglion. They chose the geniculate ganglion because it allows direct comparison between the CT and the GSP because it is the location of both CT and GSP neuron cell bodies. They were able to distinguish between GSP and CT neurons because of their location in the geniculate ganglion. Stimuli used were 0.1 M and 0.5 M NaCl, 0.1 M and 0.5 M NH₄Cl, 0.5 M sucrose, 0.01 M QHCl, and 0.01 M HCl. Responses for each individual neuron were determined by the frequency of impulses per 10 seconds of stimulation. Mean responses for each stimulant were determined by averaging all individual neuron responses to the specific stimulant. Mean responses ranked as follows: Sucrose (74.0), 0.5 M NH₄Cl (58.6), HCl (38.9), 0.5 M NaCl (20.8), KHCl (19.3), 0.1 M NH₄Cl (18.6), and 0.1 M NaCl (11.9). Therefore, mean
GSP responses to sucrose ranged from 21% - 84% greater than mean GSP responses to the other tastants. Mean GSP responses were greater to sucrose (74.0) than mean CT responses, of which almost all individual neurons were either inhibited (decreased from their baseline responses) or non-responsive (did not increase or decrease from baseline responses) when stimulated by sucrose. The largest individual CT response to sucrose was 19. Mean CT responses were greater to both concentrations of NaCl (34.4 and 102.1) than mean GSP responses (11.9 and 20.8). CT responses were 65% greater for the 0.1 M NaCl concentration and 80% greater for the 0.5 M NaCl concentration.

In this study, results from individual GSP neurons innervating the palate were quite unexpected. It was expected that many of the individual GSP neurons innervating the palate would show high responses to sucrose, but only 22% of the individual neurons responded with a frequency rate higher than 50 impulses to sucrose. Also, 35% of the neurons were either non-responsive or inhibited by sucrose. Although the mean GSP response was robust to sucrose, only four individual neurons had responses larger than 100 impulses. However, the largest response in the experiment was the response of a GSP neuron of 596 impulses to sucrose. Cluster groupings for neurons in the anterior portion of the tongue divided the CT neurons into groups, and cluster groupings for neurons in the palate divided GSP neurons into groups. The individual GSP neurons comprised five groupings: sucrose best, inhibited by HCl, quinine-best, HCl generalists, and NH₄Cl-generalists. These groupings were distinct from the CT groupings, which included NH₄Cl-best, sodium-best, sodium-generalists, and three small groups collectively called HCl-generalists. Hill and Sollars concluded that the largest and most specific group was the sucrose-best group. This conclusion was based on the observation
that a greater percentage (39%) of neurons were in the sucrose-best group than in any of
the other four identified groups. Sucrose-best neurons were considered to be the most
specific because the average response frequency to sucrose for this group was around
135, which is higher than the means for all of the other narrowly-tuned groups. The
closest group to the average response frequency of sucrose was the HCl-generalists with
a mean around 83. The sucrose group also exhibited a high degree of variability (146.6
+/- 63.8). The presence of both highly responsive sucrose neurons and non-responsive
sucrose neurons shows that the strong GSP response to sucrose is the result of narrow-
tuning of a subunit of GSP neurons, not an overall high responsiveness in all GSP
neurons.

The general whole-nerve findings consistently report that the GSP responds
robustly to sucrose and other sugars. Although the findings are not consistent, evidence
has been shown that the GSP is also highly responsive to salts. The single-nerve
findings are consistent with the whole-nerve findings, but provide further information
that suggests that the GSP is able to respond robustly to sucrose because of a subset of
narrowly-tuned sucrose neurons.

Behavioral experiments have also shown the effects of the GSP on taste.
Behavioral methods used to study the GSP include mean lick ratio tests and two-bottle
operant discrimination tests. Transection of the GSP significantly decreases the rat’s
ability to detect sucrose at both high and low concentrations. Also, GSP transections
have decreased discrimination abilities between QHCL and KCL.

Krimm (1987) studied the mean lick ratio (defined earlier) of sucrose solution
with transections of the CT, GSP, CT + GSP, and a sham group. Rats with GSPX and
GSPX + CTX showed a significant decrease in mean lick ratio to sucrose solutions. The rats in the CTX and sham groups did not show a significant decrease in mean lick ratio after surgery.

In addition to the role in mediating sweet taste, reports have shown that the GSP also has a role in discriminating between quinine and KCl. In a study conducted by St. John and Spector (1998), rats were operantly trained to discriminate between quinine and KCl. After operant training, surgeries were conducted. The surgery groups included GLX, CTX, GLX + CTX, and CTX + GSPX. The GSP was not transected alone because of the difficulty in maintaining an intact CT while transecting the GSP. Results showed that GLX had no significant effect on discrimination performance, and CTX had a significant effect. GLX + CTX had the same effect statistically as the CTX group. However, the GSPX + CTX group had a statistically greater effect than the CTX group. This suggests that the GSP is partly responsible in the discrimination between KCl and quinine.

Behavioral studies on the GSP, much like the electrophysiological studies, are few in number but all suggest that the GSP codes the taste of sugars. Transections of the GSP have shown decreases in responsiveness to sucrose and have also suggested discriminative roles between KCl and QHCl.

Both GSP behavioral and electrophysiological studies consistently show that the GSP is important in the coding of sugars. Although the electrophysiological data is limited, the data that has been found suggests the presence of narrowly-tuned sucrose neurons. Not much research has been conducted investigating additional roles of the GSP, but some evidence has been shown for a role in discriminating between QHCl and
KCl. This behavioral effect could be related to the electrophysiological findings of GSP quinine-best neurons. Also, responsiveness of GSP neurons to salts suggests that the GSP plays a role in coding the taste of salts, but few behavioral studies have shown evidence for this role.

Glossopharyngeal Nerve

The GL nerve is the ninth cranial nerve, and it innervates the majority of mammalian taste buds. The GL contains petrosal ganglion neurons with distal fibers, which penetrate posterior lingual taste buds in the circumvallate papillae. The GL has shown narrow-tuning to a variety of tastants, but responds most specifically to quinine. Behavioral studies implicate a role of the GL in eliciting aversive oromotor response such as gaping.

Electrophysiological recordings have shown that the GL responds broadly to a large variety of tastants. GL neurons have been divided into three main groups: A units, S units, and Q units. Q units are narrowly-tuned to quinine, and have not been found in other taste nerves.

A small group of studies have examined response properties of rat petrosal ganglion neurons and their nerve fibers in the GL nerve. In a 1991 study, Frank examined this by recording responses of GL neurons to taste solutions delivered to either the foliate or vallate papilla of rats. The main test stimuli included sucrose, quinine/HCl, HCl, and NaCl. Other stimuli that were used included fructose, Na saccharin, NH₄Cl, citric acid, acetic acid, and MgSO₄, and the GL showed effective responses to all stimulants except fructose. The responses for individual neurons fell into three main categories. Forty-six percent of the neurons were labeled “A units” and responded most
strongly to acids and chloride salts. NH₄Cl was the most effective stimuli for this group of neurons, and neither quinine nor sucrose were effective in producing responses for A units. Twenty-three percent of the neurons were labeled “S units” and responded to sugars and saccharin. Quinine, salts, and acids were ineffective in producing responses in these neurons. Thirty-one percent were “Q units” and responded most effectively to quinine. However, the Q-units showed greater variability than the other groupings and were divided into three subgroups. In two of the three subgroups, quinine and MgSO₄ were the most effective stimuli. In the third subgroup, saccharin was the most effective stimuli. As a whole, Q-units were unresponsive to NaCl, HCl, and sucrose. Frank’s results were consistent with previous results in this area, which have shown that the GL responds effectively to quinine and has a large amount of neurons that are narrowly tuned to quinine (Bodreau, 1987; Frank 1975; Nowlis and Frank 1981).

The electrophysiological data suggests that the GL has neurons specifically tuned to respond to acids, chloride salts, quinine, sucrose, saccharin, and sugars. The GL is capable of responding effectively to a large variety of tastants, but the GL differs from other nerves in its ability to respond narrowly to quinine.

Behavioral evidence shows varying responses to quinine due to methodological differences. In many studies, GLX does not decrease preference for quinine in two-bottle tests but is effective in decreasing oral motor responses. Inconsistencies between taste reactivity tests and long-term preference tests suggest that long-term preference tests are not useful in measuring the effects of GLX because of confounding post-ingestive and non-gustatory effects. Unconditioned licking tests have shown that GLX is important in coding quinine because GLX results in decreased avoidance of quinine. Since quinine is
a bitter tastant, aversion is advantageous in response to quinine. Many theories have been proposed for the role of the GL in oromotor responses. King proposes that the GL is responsible for all oromotor control, but other studies suggest that the GL is responsible for aversive oromotor control while the CT is responsible for ingestive oromotor control. Other studies suggest that the GL is involved in sustained aversive control, not immediate aversive motor control. The GL is not necessary for coding salt tastants.

Although electrophysiological studies have consistently shown that quinine is an effective stimulus for a group of GL neurons, behavioral results have been mixed regarding the role of the GL nerve in coding bitter tastants. Some studies have suggested that the GL is necessary for rats to respond appropriately towards quinine, but others have suggested that the GL is not necessary. Grill and colleagues (1992) conducted a study comparing the effects of GL transection on quinine preference and aversive oral motor behavior in response to quinine. The results showed that transecting the GL nerve was effective in impairing the expression of aversive oral motor behaviors to quinine but was ineffective in decreasing the preference of quinine. These preference results were consistent with previous findings by Akaike and colleagues (1965). Results from Grill and colleagues and Akaike suggest that the GSP is responsible for aversive responsive towards quinine but not for detection of quinine.

In another study, St. John and Spector (1996) examined the licking behavior towards quinine after transections of certain branches of the seventh and ninth cranial nerves. He used one and two-bottle intake tests. His results showed only marginal impairments in licking behavior after GLX but a significant effect after combined GLX and CTX. In another study by Spector and St. John (1998), unexpected behavioral
impairments following GLX were found. Rats were water deprived and adapted to a 45-minute water presentation schedule. Post-surgical measures of quinine intake, lick size, initial drinking rate, and lick burst size showed less aversive behavior for the GLX rats than for the sham-controlled rats. These findings were inconsistent with their prior study that showed no significant differences in quinine responses between the GLX group and the control group.

The inconsistency of results in this area of research is most likely an effect of methodology. The main inconsistency is between long-term preference tests and short-term preference tests. Long-term preference tests suggest that GLX greatly decreases the rat’s ability to detect, whereas short-term preference tests suggest that rats can still detect quinine after GLX. Grill argues that the long-term preference tests cause loss of gustatory function because of nongustatory and post-ingestive influences. This could happen for two reasons. The first is that long-term intake tests can inadvertently include measurements of post-ingestive feedback, which can mask the influence of oral chemosensory input. Secondly, long-term intake tests cannot provide discrimination between responses to stimuli that are avoided completely. In short-term studies such as the 1996 study conducted by St. John and Spector, the influence of both nongustatory cues and post-ingestive effects were minimized and the results showed very minimal effects of GLX on quinine detection. However, GLX still shows decreases in quinine aversion after GLX.

Another theory on the inconsistencies is that presurgical testing may guard against decreased responses after GLX. Markison developed this theory after observing that studies that did not involve presentation of quinine before surgery showed significant
effects of quinine responsiveness. To investigate the effects of presurgical testing with quinine, Markison and colleagues (1999) replicated his 1994 study, which tested the effects of GLX on aversion to quinine after a presurgical conditioning to quinine. The only change in his 1999 study was eliminating the presentation of quinine before surgery and training the rats to lick to water before surgery instead of quinine. His 1994 study showed no reduction in avoidance of quinine after surgery. However, results of the unconditioned licking to quinine showed a reduction in avoidance to high concentrations of quinine in the GLX rats. These results suggest that pre-surgical exposure to quinine has a protective effect against GLX. Thus, within-subjects designs are not the most valid method for testing the effects of GLX. Both electrophysiological findings and behavioral studies suggest that the GL plays a crucial role in coding the taste of quinine.

Although the GL innervates 64% of taste buds and responds to many compounds, GLX shows a small behavioral effect on most compounds with the exception of quinine. To investigate the GL’s oromotor reflex control, King studied the distribution of Fos-like-immunoreactive neurons in the NST activated by intraoral infusion of quinine. FLI neurons send action potentials that cause transcription of a gene that codes for the making of c-fos protein when the FLI neurons are active. Through processing of the NST with an antibody for c-fos, researchers now have the ability to label the activity of neurons post mortem. King observed the responses of FLI neurons before surgery and found that quinine caused responses in FLI neurons across the rostrocaudal extent of the NST, particularly in subfield 5 (King et al., 1999a). After CTX, GLX, and combined transections, he observed that GLX and combined transections produced dramatic decreases in responsive FLI neurons and changes in spatial distribution in FLI neurons.
The spatial distribution of quinine-evoked FLI neurons changed after GLX such that the numbers of neurons and their patterns could not be distinguished from the water-stimulated controls. Because GLX caused the rats to have such a similarity to the control group, the results suggest that the GL provides input to FLI neurons that respond to quinine. The function of FLI neurons is still unknown, but King hypothesizes that the afferent coding from the GL to the FLI neurons of the NST function in oromotor reflex control.

The theory that the GL functions in controlling oromotor responses has been investigated by Joe Travers (1987). He examined changes in the gaping response to quinine, which is a stereotypical aversive oromotor behavior, after transections of the CT and the GL nerves. He observed a 16% reduction in gaping response and an increased latency of gaping response after CTX and a 54% reduction after GLX. The effect of CTX in increasing latency of the gaping response suggests that the CT is not responsible for aversion towards quinine and is possibly only responsible for quinine detection. Because the GLX showed higher reduction rates, it is probably responsible for aversion responses. Travers suggests that, because the CT seems to contribute more to the latency response, it is responsible for the immediate rejection response to quinine. This is consistent with anatomical findings that show the CT innervates taste buds in the anterior portion of the tongue (Miller, 1977). He also suggests that, since the GLX does not affect latency but causes a dramatic decrease in reduction of the gaping response, the GL is responsible for the sustained rejection response to quinine. This theory is also logically consistent with anatomical findings that show the GL innervates posterior taste buds.
Grill and colleagues (1991) conducted a similar study examining two-bottle intake and taste reactivity to compare responses to NaCl, MgCl₂, quinine, and sucrose. Results from taste reactivity tests in GLX rats showed a decrease in aversive oral motor responses and an increase in latency to most concentrations of quinine, MgCl₂, and NaCl. Results from the CTX rats showed decreases in ingestive oral motor responses to quinine, MgCl₂, and NaCl. These results suggest that the CT and the GL play separate roles in the production of responses to taste. In infants, the CT appears to produce ingestive responses, and the GL seems to produce aversive responses. Nowlis (1977) also found that CTX decreases ingestive oral motor responses and that GLX decreases aversive oral motor responses. In his oral reflex hypothesis, Nowlis predicts that the CT functions as the ‘afferent limb’ of taste-elicited ingestive behavior and the GL serves as the ‘afferent limb’ for aversive responses. He hypothesized that the CT and GL nerves function independently of one another. Results from the study by Grill and colleagues (1992) showed consistent results, suggesting that two mechanisms are operating to produce taste responses. However, results from Grill and colleagues are not consistent with the prediction that the ingestive and aversive motor responses function independently of one another. Grill’s results demonstrated that both ingestive and aversive motor responses could be elicited from both CTX and GLX rats. Although responses were reduced, they were not completely eliminated. These results suggest that neither ingestive nor aversive motor responses are completely controlled by one nerve. However, King’s results suggest that oromotor reflex control is a function of the GL. Although the data is not consistent on the subject of aversive and ingestive motor responses, the body of evidence
Electrophysiological and behavioral data consistently report that the GL nerve is unnecessary for coding sodium tastants. No narrowly-tuned neurons to NaCl have been reported for the GL that are similar to those found in the CT (Frank, 1991). In a behavioral study conducted by Markison and colleagues (1995), rats received either CTX, GLX, sham conditions, or extirpation of the sublingual and submaxillary salivary glands (DSAL). Rats were sodium-deprived because sodium deprivation causes rats to increase intake of NaCl solutions that are normally avoided in the sodium-replete state. After deprivation, rats were tested for licking responses to 0.05 M and 0.3 M NaCl, KCl, CaCl$_2$, and NH$_4$Cl. Results from CTX and DSAL rats showed a significantly lower licking rate for NaCl when compared to other stimuli. GLX rats maintained a similar licking rate compared to the controls. These results suggest that, although the GL nerve innervates 64% of taste buds, the GL nerve is not a significant contributor to detecting and discriminating NaCl. Other studies have shown consistent findings. Spector and Grill (1992) conducted a study to determine the effects of CTX and GLX on discrimination between NaCl and KCl. Rats were trained presurgically to discriminate between NaCl and KCl. Postsurgery results showed that GLX had no effect on NaCl vs. KCl discrimination. Cauthon and colleagues (1994) also showed that GLX has no effect on taste-guided unconditioned licking to suprathreshold NaCl solutions. Research in this area consistently shows that the GL nerve does not contribute to detecting and discriminating NaCl.
Poor methodology has caused many inconsistencies in the interpretations of the role of the GL. However, the majority of behavioral evidence shows that the GL is responsible for aversive oromotor responses to the bitter tastant quinine. Theories range from the GL being completely responsible for aversive oromotor responses to the GL being responsible only for sustained oromotor responses. The GL does not seem to be responsible for coding the taste of salt or any other non-quinine tastants.

Behavioral and electrophysiological both agree that the GL provides important aversive responsiveness to quinine. Electrophysiological data showed quinine-sensitive units that have not been found in the CT or the GSP. Behavioral data showed that GLX reduces the ability to show aversion to quinine. The GL seems to have a protective role. Although it responds effectively to most tastants, it is not necessary for any ingestive functions.

Discussion

The research conducted in afferent taste coding shows specific functions for each of the three major taste nerves. Research consistently shows that the CT has amiloride-sensitive fibers, amiloride-insensitive fibers, and sodium-specific fibers that allow greater responsiveness to salts and greater discrimination between sodium salts and non-sodium salts. The CT also plays a role in ingestive motor responses. Hence, it is responsible for eliciting positive responses to favorable substances. The GSP nerve has a small group of neurons that are narrowly-tuned to sugars, allowing it to respond to sugars more robustly than other nerves. It also responds effectively to salts but does not appear to be as necessary to salt detection as the CT. The main role of the GL nerve is to elicit
avoidance responses to harmful stimuli, particularly quinine. The GL nerve is narrowly-tuned to detect bitter tastants and is effective in eliciting aversive oromotor behaviors.

Although the nerves have specific functions, they are not independent of one another. Transecting a single nerve almost never caused complete removal of a specific function, but removal of all three nerves caused loss of function in several cases. For example, the CT clearly plays a large role in coding salt tastants. However, CTX does not affect suprathreshold taste discrimination of NaCl. Also, GSP is very important in mediating sugars, but GSPX does not fully eliminate sucrose discrimination. The same applies to quinine and GLX. The taste system seems to be organized in a compensatory manner. Hence, if one taste nerve is damaged, the other two nerves will be able to provide some compensation for the lost functions of the damaged nerve. Because damage to nerves do not typically occur as complete denervation of a nerve but rather as partial denervation, the compensation provided from non-damaged taste nerves is probably sufficient to maintain a large amount of function when nerves are only partially damaged.

A further observation from the research is that while some functions of nerves seem to be compensatory, others appear to be complementary. Many of these complementary theories, such as the theory suggesting immediate response of CT to quinine and the sustained response of GL to quinine, show that the convergence of the roles of multiple nerves produce maximum response to particular stimuli. In these necessary complementary roles, the anatomical setup of the taste system requires complementary functions. Because the CT innervates anterior taste buds and the GL innervates posterior taste buds, the CT is more equipped to perform detection functions
that can be used by the GL to provide sustained aversion functions. Functions relating to anatomical positioning of the nerves are probably not as easily compensated for during the partial loss of a nerve. Thus, the proper functioning of both nerves is required, and one nerve cannot compensate for the other. The overall conclusion from the research is that, although each nerve has specific stimuli it responds best to, no nerve can carry out a function alone more effectively than it can with the assistance of the other nerves.
References


