
Keywords: Acinonyx jubatus/cheetah/DNA/domestic cat/evolution/Felidae/Felis silvestris catus/food/Panthera tigris/PCR/sweet-taste receptor/tiger

Abstract: Although domestic cats (*Felis silvestris catus*) possess an otherwise functional sense of taste, they, unlike most mammals, do not prefer and may be unable to detect the sweetness of sugars. One possible explanation for this behavior is that cats lack the sensory system to taste sugars and therefore are indifferent to them. Drawing on work in mice, demonstrating that alleles of sweet-receptor genes predict low sugar intake, we examined the possibility that genes involved in the initial transduction of sweet perception might account for the indifference to sweet-tasting foods by cats. We characterized the sweet-receptor genes of domestic cats as well as those of other members of the Felidae family of obligate carnivores, tiger and cheetah. Because the mammalian sweet-taste receptor is formed by the dimerization of two proteins (T1R2 and T1R3; gene symbols Tas1r2 and Tas1r3), we identified and sequenced both genes in the cat by screening a feline genomic BAC library and by performing PCR with degenerate primers on cat genomic DNA. Gene expression was assessed by RT-PCR of taste tissue, in situ hybridization, and immunohistochemistry. The cat Tas1r3 gene shows high sequence similarity with functional Tas1r3 genes of other species. Message from Tas1r3 was detected by RT-PCR of taste tissue. In situ hybridization and immunohistochemical studies demonstrate that Tas1r3 is expressed, as expected, in taste buds. However, the cat Tas1r2 gene shows a 247-base pair microdeletion in exon 3 and stop codons in exons 4 and 6. There was no evidence of detectable mRNA from cat Tas1r2 by RT-PCR or in situ hybridization, and no evidence of protein expression by immunohistochemistry. Tas1r2 in tiger and cheetah and in six healthy adult domestic cats all show the similar deletion and stop codons. We conclude that cat Tas1r3 is an apparently functional and expressed receptor but that cat Tas1r2 is an unexpressed pseudogene. A functional sweet-taste receptor heteromer cannot form, and thus the cat lacks the receptor likely necessary for detection of sweet stimuli. This molecular change was very likely an important event in the evolution of the cat's carnivorous behavior.
Pseudogenization of a Sweet-Receptor Gene Accounts for Cats’ Indifference toward Sugar

Xia Li¹, Weihua Li¹, Hong Wang¹, Jie Cao¹, Kenji Maehashi¹*, Lituan Huang¹, Alexander A. Bachmanov¹, Danielle R. Reed¹, Véronique Legrand-Defretin², Gary K. Beauchamp¹,3, Joseph G. Brand¹,4,5*¹

1 Monell Chemical Senses Center, Philadelphia, Pennsylvania, United States of America, 2 The WALTHAM Centre for Pet Nutrition, Melton Mowbray, Leicestershire, United Kingdom, 3 Department of Psychology, School of Arts and Sciences and Department of Anatomy, School of Veterinary Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, United States of America, 4 Department of Biochemistry, School of Dental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, United States of America, 5 Veterans Affairs Medical Center, Philadelphia, Pennsylvania, United States of America

Although domestic cats (Felis silvestris catus) possess an otherwise functional sense of taste, they, unlike most mammals, do not prefer and may be unable to detect the sweetness of sugars. One possible explanation for this behavior is that cats lack the sensory system to taste sugars and therefore are indifferent to them. Drawing on work in mice, demonstrating that alleles of sweet-receptor genes predict low sugar intake, we examined the possibility that genes involved in the initial transduction of sweet perception might account for the indifference to sweet-tasting foods by cats. We characterized the sweet-receptor genes of domestic cats as well as those of other members of the Felidae family of obligate carnivores, tiger and cheetah. Because the mammalian sweet-taste receptor is formed by the dimerization of two proteins (T1R2 and T1R3; gene symbols Tas1r2 and Tas1r3), we identified and sequenced both genes in the cat by screening a feline genomic BAC library and by performing PCR with degenerate primers on cat genomic DNA. Gene expression was assessed by RT-PCR of taste tissue, in situ hybridization, and immunohistochemistry. The cat Tas1r3 gene shows high sequence similarity with functional Tas1r3 genes of other species. Message from Tas1r3 was detected by RT-PCR of taste tissue. In situ hybridization and immunohistochemical studies demonstrate that Tas1r3 is expressed, as expected, in taste buds. However, the cat Tas1r2 gene shows a 247-base pair microdeletion in exon 3 and stop codons in exons 4 and 6. There was no evidence of detectable mRNA from cat Tas1r2 by RT-PCR or in situ hybridization, and no evidence of protein expression by immunohistochemistry. Tas1r2 in tiger and cheetah and in six healthy adult domestic cats all show the similar deletion and stop codons. We conclude that cat Tas1r2 is an apparently functional and expressed receptor but that cat Tas1r3 is an unexpressed pseudogene. A functional sweet-taste receptor heteromer cannot form, and thus the cat lacks the receptor likely necessary for detection of sweet stimuli. This molecular change was very likely an important event in the evolution of the cat’s carnivorous behavior.


Introduction

The domestic cat (Felis silvestris catus), of the family Felidae in the order Carnivora, is an obligate carnivore. Its sense of taste is distinguished by a lack of attraction to, or indifference toward, compounds that taste sweet to humans, such as sweet carbohydrates (sugars) and high-intensity sweeteners [1–3]. This behavior toward sweet stimuli is in marked contrast to the avidity for sweets shown by most omnivores and herbivores and even some other carnivores such as the dog [4]. The indifference that cats display toward sweet-tasting compounds contrasts with their otherwise normal taste behavior toward stimuli of other taste modalities. For example, they show preference for selected amino acids [5] and generally avoid stimuli that to humans taste either bitter or very sour [1,5]. Congruent with these behavioral responses to taste stimuli, recordings from cat taste nerve fibers, and from units of the geniculate ganglion innervating taste cells, demonstrate responses to salty, sour, and bitter stimuli as well as to amino acids and nucleotides, but do not show neural responses to sucrose and several other sugars [5–12]. The sense of taste in the cat, in general, is therefore similar to that of other mammals, with the exception of an inability to taste sweet stimuli.

The molecular basis for this sweet blindness in cats is not known. Because the taste blindness appears specific to this single modality, we postulated that the defect in the cat (and likely in other obligate carnivores of Felidae) lies at the receptor step subtending the sweet-taste modality. The possible defects at the molecular level that might cause this sweet blindness could range from a single to a few amino acid substitutions, such as is found between sweet ‘‘taster’’ and ‘‘nontaster’’ strains of mice [13,14], to more radical mechanisms, such as an unexpressed pseudogene.

To distinguish among these possibilities, we identified the DNA sequence and examined the structures of the two known genes, Tas1r2 and Tas1r3, that in other mammals encode the sweet-taste receptor heteromer, T1R2/T1R3. We compared these with the sequence and structure of the same genes in...
Because exons 1 and 2 of *Tas1r2* sequences containing the open reading frame for cat
States) (See Materials and Methods). We aligned the cDNA
genomic DNA (Novagen, San Diego, California, United
degenerate primers to amplify these regions from cat
Oakland, California, United States), we obtained more than 3
amino acids from 316 to 355 of the cat T1R2 result from the frame shift brought by the 247-bp deletion in exon 3. Note that the deduced amino acid
is truncated at amino acid 355 due to a premature stop codon at bp 57–59 in exon 4, which results from a 247-bp deletion in exon 3. The underlined
T1R3 sequence shows high similarity with that of human and rodents, with especially high similarity with that of dog. The predicted cat T1R2 protein
is normal. The molecular mechanism for this unique behavior
provides a molecular explanation for the common observation that
the cat lives in a different sensory world than the cat owner.

Results

We identified DNA sequences of *Tas1r3* and *Tas1r2* from
the domestic cat by screening a feline BAC library and using a
PCR strategy on cat genomic DNA with degenerate primers.
The feline sequences were compared with those of other
species, and gene structures were determined. The expression
of these two receptors was then evaluated by in situ
hybridization and immunohistochemistry.

Molecular Cloning of Cat *Tas1r3* and *Tas1r2*: Sequence and
Gene Structure

By sequencing positive BAC clones retrieved from a feline
genomic BAC library (*Felis silvestris catus*; BACPAC Resources,
Oakland, California, United States), we obtained more than 3
kb of genomic sequences containing the open reading frame
for cat *Tas1r3*, and approximately 10 kb of genomic sequences containing the open reading frame for cat *Tas1r2*. Because exons 1 and 2 of *Tas1r2* were not found in the
positive BAC clones, we employed a PCR strategy using
degenerate primers to amplify these regions from cat
genomic DNA (Novagen, San Diego, California, United
States) (See Materials and Methods). We aligned the cDNA
sequences and the deduced amino acid sequences from cat
*Tas1r3* and *Tas1r2* with their dog, human, mouse, and rat
orthologs (Figure 1). (We obtained the sequences of domestic
dog genes, *Tas1r3* and *Tas1r2*, by screening a dog genomic
library using the same overgo probes and methods as for the feline genomic BAC library and by taking advantage of the
limited data available at that time from the public dog
guide/dog/).

Table 1 presents the percent similarity of the *Tas1r3* and
*Tas1r2* genes at both the cDNA and the protein levels between
all possible pairs of five species: cat, dog, human, mouse, and
rat. The cat *Tas1r3* gene shows high similarity at the cDNA
level with that of dog (87%), human (79%), rat (75%), and
mouse (74%) (Table 1). The cat *Tas1r3* gene predicts a protein
of 865 amino acids (Figure 1) showing 85% similarity with
deduced protein of dog, and 73%, 72%, and 72% with that of
human, mouse, and rat, respectively (Table 1). Initially we
predicted the exon–intron boundaries of cat *Tas1r3* by
comparison with the known boundaries of human *TAS1R3*. To
confirm these exon–intron boundaries for cat *Tas1r3*, we
performed both RT-PCR on cDNA from cat taste bud–
containing circumvallate and fungiform papillae, and PCR on
cat genomic DNA using intron-spanning primers. By com-
paring the cDNA sequence with the genomic sequence, we
confirmed the boundaries predicted from human *TAS1R3* (Figure 2A). Both the cat *Tas1r3* and human *TAS1R3* genes are
composed of six similarly sized exons and five introns (Figure 2A).

We identified the exon–intron boundaries of cat *Tas1r2* by
comparison with known human boundaries (Figure 2B). Examining the sequence of cat *Tas1r2*, we discovered a
microdeletion of 247 base pairs (bp) within exon 3. This
deletion is responsible for a frame shift that results in a
premature stop codon at bp 57–59 of exon 4 (Figure 2B).
Assuming, for the moment, that a protein is translated from
cat *Tas1r2*, then, because of the deletion and premature stop
codon, the gene sequence predicts a peptide of 355 amino
acids, the first 315 of which show high similarity with their
rat, mouse, human, and dog counterparts (see Figure 1). Because of the frame shift introduced by the 247-bp deletion,
the remaining deduced 40 amino acids show no similarity
with their rat, mouse, human, or dog counterparts (underlined
sequence of cat *TIR2*; Figure 1). The predicted
similarity of this hypothetical 355–amino acid protein was
compared with its truncated counterparts from dog, human,
mouse, and rat. It ranges from 55% to 69% (Table 1). In
contrast, the percent similarity of the full-length TIR2
protein within pairs of other species is between 91%
(mouse–rat) and 69% (mouse–human).

By aligning cat *Tas1r2* DNA sequences of exons 4, 5, and 6
with their human counterparts, we found four additional stop
codons: one in exon 4 due to a deletion at bp 123, and three
in exon 6 due to a substitution at bp 95 and a deletion at bp 247 (Figure 2B). The multiple stop codons indicate that the cat *Tas1r2* is a pseudogene.

Figure 1. Alignment of Deduced Amino Acid Sequences of TIR3 and TIR2 from Five Species
This figure shows the alignment of the deduced sequences of the taste receptor proteins, TIR3 and TIR2, from domestic cat, domestic dog, human, mouse, and rat. Amino acids that are identical among species are shaded in black; conservative amino acid substitutions are shaded in gray. The cat TIR3 sequence shows high similarity with that of human and rodents, with especially high similarity with that of dog. The predicted cat TIR2 sequence is truncated at amino acid 355 due to a premature stop codon at bp 57–59 in exon 4, which results from a 247-bp deletion in exon 3. The underlined amino acids from 316 to 355 of the cat TIR2 result from the frame shift brought by the 247-bp deletion in exon 3. Note that the deduced amino acid sequence of dog TIR2 predicts an apparently normal protein showing high similarity with that of rat, mouse, and human.

DOI: 10.1371/journal.pgen.0010003.g001
In an attempt to confirm the cat Tas1r2 exon–intron boundaries, we performed RT-PCR on cDNA from cat circumvallate and fungiform taste papillae. Despite using numerous (>70) primers corresponding to deduced message from the Tas1r2 gene, we were unable to detect it.

RNA and Protein Expression
Having detected message from cat Tas1r3, but not from cat Tas1r2, by RT-PCR, we used the more tissue-specific approaches of in situ hybridization and immunohistochemistry to refine the search for cat Tas1r2 gene expression, using the cat Tas1r3 gene for comparison. Probes for in situ hybridization were constructed from the gene sequences corresponding to the lines marked “P” in Figures 2A and 2B. (See Materials and Methods for details.) Figure 3 shows that message from Tas1r3 is expressed in taste buds of cat circumvallate papillae whereas Tas1r2 expression is not detectable by in situ hybridization. Antisense probes for Tas1r3 result in positive labeling (Figure 3A); the arrows indicate three of the many labeled taste buds. The control sense probes show no labeling (Figure 3B). In contrast, antisense probes for cat Tas1r2 show no detectable labeling (Figure 3C) as is the case for the sense control (Figure 3D).

To detect the presence of taste receptor proteins from Tas1r2 and from Tas1r3, we exposed 10-μm sections of cat circumvallate and fungiform papillae to polyclonal antibodies developed against deduced amino acid peptide antigens marked by the line labeled “A” in Figure 2A and 2B. T1R3-like immunoreactivity was present in the taste buds of every circumvallate (10) and fungiform (4) papilla used in Table 1.

### Table 1. Similarity of Sweet Receptors between Species

<table>
<thead>
<tr>
<th>Species Pairs</th>
<th>T1R2</th>
<th>Tas1r2</th>
<th>T1R3</th>
<th>Tas1r3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat–mouse</td>
<td>56</td>
<td>61</td>
<td>72</td>
<td>74</td>
</tr>
<tr>
<td>Cat–rat</td>
<td>55</td>
<td>61</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>Cat–human</td>
<td>64</td>
<td>66</td>
<td>73</td>
<td>79</td>
</tr>
<tr>
<td>Cat–dog</td>
<td>69</td>
<td>70</td>
<td>85</td>
<td>87</td>
</tr>
<tr>
<td>Dog–mouse</td>
<td>71</td>
<td>79</td>
<td>73</td>
<td>74</td>
</tr>
<tr>
<td>Dog–rat</td>
<td>71</td>
<td>79</td>
<td>73</td>
<td>75</td>
</tr>
<tr>
<td>Dog–human</td>
<td>76</td>
<td>83</td>
<td>75</td>
<td>78</td>
</tr>
<tr>
<td>Mouse–rat</td>
<td>91</td>
<td>81</td>
<td>92</td>
<td>93</td>
</tr>
<tr>
<td>Mouse–human</td>
<td>69</td>
<td>78</td>
<td>72</td>
<td>73</td>
</tr>
<tr>
<td>Rat–human</td>
<td>71</td>
<td>78</td>
<td>73</td>
<td>75</td>
</tr>
</tbody>
</table>

T1R2 and T1R3 are the protein names, and Tas1r2 and Tas1r3 are the corresponding gene names. Columns for T1R2 and T1R3 show percent similarity between predicted amino acid sequences; columns for Tas1r2 and Tas1r3 show percent similarity between cDNA sequences. DOI: 10.1371/journal.pgen.0010003.t001

Figure 2. Gene Structures of Cat Tas1r3, Human TAS1R3, and Cat Tas1r2, Human TAS1R2
The exons are shown in black (size in bp of each exon is in parentheses). Boundaries of gene sequences used to produce probes for in situ hybridization studies (Figure 3) are shown by the horizontal lines labeled “P1” and “P2” under the sketch of the cat Tas1r3 and cat Tas1r2. Boundaries of sequence used to generate peptide antigens for immunohistochemical studies (Figure 4) are shown by the horizontal lines labeled “A” under the sketch of the cat Tas1r3 and cat Tas1r2. The locations referred to in the vertical explanation text above the asterisks and the spade symbol indicate the position in bp within each exon. Intron sizes shown in the figure are not proportionally scaled on both (A) and (B) because of the large size of Tas1r2 introns. Under each human exon is the percent similarity between each human exon and its cat counterpart.

DOI: 10.1371/journal.pgen.0010003.g002
this study (Figure 4A and 4B) whereas immunoreactivity to T1R2 was not detected in these same tissues (Figure 4C and 4D). (Each circumvallate papilla of the cat contains approximately 400 taste buds, whereas the large fungiform papillae used in this study, located in the area of the eminence, contain from 1 to about 15 taste buds each.) The antibody to cat T1R2 did, however, label a subset of taste buds in rat circumvallate papillae (results not shown).

Confirmation of Tas1r2 Sequence in Six Individual Cats, Tiger, and Cheetah

Because the feline BAC genomic library was constructed from a single individual cat, we confirmed the sequence of Tas1r2 in six additional, unrelated, healthy adult domestic cats. Genomic DNA was obtained by cheek swabs from five of the six cats and through a blood sample from the remaining cat, amplified by PCR using primers that flanked the deletion and stop codons of the known cat Tas1r2, and sequenced. In addition, to test whether other species of Felidae display similar sequence anomalies in their Tas1r2 gene, we performed PCR on genomic DNA of one tiger (Therion International, Saratoga Springs, New York, United States) and one cheetah (a gift from the San Diego Zoo). We found that Tas1r2 in all six cats, the tiger, and the cheetah show the identical 247-bp deletion in exon 3, and all have stop codons at the same positions in exon 4 (Table 2). In exon 6, we found evidence for two alleles at position 95–95 in domestic cat, wherein two cats show the stop codon, TGA (homoyzygotes TGA/TGA); one cat shows TGR (heterozygote TGA/TGG); and three of the domestic cats, the one tiger, and the single cheetah show TGG (homozyzygotes TGG/TGG) (Table 2). The second exon 6 stop codon is also common to all three species (TGA for domestic cat, TAG for tiger and cheetah). Although the third stop codon of exon 6 at bp 697–699 was found in all six domestic cats, the corresponding region in tiger and cheetah could not be amplified by PCR.

Collectively, these data indicate that cat Tas1r3 is an expressed and likely functional receptor, whereas cat Tas1r2 is an unexpressed pseudogene.

Discussion

The taste receptors for sweetness and for umami (an amino acid–taste modality) are members of the T1R family of taste receptors [15,16,17]. These are Class C, family 3, G protein–coupled receptors (GPCR). The three known members of the TIR family are T1R1, T1R2, and T1R3 (for review, see [18]). In rodents and primates the primary sweet-taste receptor is composed of a dimer of two closely related GPCRs, T1R2 and T1R3 [14,15,16,17].

For this study, we made the working assumption that the Felidae T1R family shows specificity similar to that known from rodents and primates. Because the umami receptor is composed of the heteromer, T1R1/T1R3, and because cats can taste amino acids, it would appear likely that both of these proteins should be functional. The sweet-taste receptor is composed of a heteromer of two closely related GPCRs, T1R2 and T1R3 [14,15,16,17].

For this study, we made the working assumption that the Felidae T1R family shows specificity similar to that known from rodents and primates. Because the umami receptor is composed of the heteromer, T1R1/T1R3, and because cats can taste amino acids, it would appear likely that both of these proteins should be functional. The sweet-taste receptor is composed of a heteromer of two closely related GPCRs, T1R2 and T1R3 [14,15,16,17].

For this study, we made the working assumption that the Felidae T1R family shows specificity similar to that known from rodents and primates. Because the umami receptor is composed of the heteromer, T1R1/T1R3, and because cats can taste amino acids, it would appear likely that both of these proteins should be functional. The sweet-taste receptor is composed of a heteromer of two closely related GPCRs, T1R2 and T1R3 [14,15,16,17].

Molecular Features of Cat Tas1r3

By comparison with other known T1R3 proteins and other proteins of Class C, family 3, the sequence and gene structure of cat Tas1r3 predict a functional receptor of 865 amino acids
Cat Tas1r3 is assumed to be located on cat Chromosome C1, syntenic with human 1p36, where human TAS1R3 is located [19,20]. As with other Tas1r3 genes, the cat Tas1r3 is composed of six exons, each approximately the same size as those of human (see Figure 2A). The sequence of cat Tas1r3 predicts a seven-transmembrane GPCR with extended N-terminal domain (first transmembrane region spanning amino acids 572–595), features common to other T1R3 receptors. Important Class C, family 3, structural motifs can also be located in cat T1R3 including the xPKXy motif at amino acids 814–818, and the FHSCCY motif at amino acids 517–522. Additionally, although most members of Class C, family 3, GPCRs show a highly conserved arginine residue at the extreme 3’ end of transmembrane segment 3, an exception is found with human, mouse, and rat T1R3, which substitute glutamic acid (E) for arginine (R) [21]. This substitution is also found in cat T1R3 at amino acid 660 (see Figure 1; the deduced dog T1R3 substitutes glutamine (Q) for arginine at the end of TM3).

Available evidence indicates that the products of cat Tas1r3 are expressed in taste buds. RT-PCR readily detected the message from Tas1r3 in lingual taste bud–containing tissues (results not shown). In situ hybridization studies confirmed the presence of message and localized it to taste buds (see Figure 3A). Polyclonal antibodies developed against T1R3 labeled taste buds in both cat circumvallate (Figure 4A) and fungiform papillae (Figure 4B). While only a few cells showed evidence of T1R3-like immunoreactivity, nearly every taste bud was labeled by both in situ hybridization and immunohistochemistry.

These commonalities in gene structure and sequence, together with evidence that the cat Tas1r3 gene is expressed, are consistent with the assumption that cat Tas1r3 codes for a functional receptor.

Molecular Features of Cat Tas1r2

Cat Tas1r2, on the other hand, while retaining structure similar with that of the human TAS1R2 gene (see Figure 2B),
is an unexpressed pseudogene. The likely important molecular event that resulted in cat *Tas1r2* becoming a pseudogene is the 247-bp deletion in exon 3. This deletion results in a frame shift that brings about a premature stop codon in exon 4 (Figure 2B). An additional stop codon can be found in exon 4, with three more in exon 6 (Figure 2B). This apparent accumulation of mutations suggests that there is no pressure from natural selection on the cat *Tas1r2* gene. To determine if this gene is expressed, we performed studies to detect message from cat *Tas1r2* by RT-PCR of taste bud–containing lingual papillae and by in situ hybridization. For RT-PCR, numerous (>70) primers were constructed based on sequences from exons 1–6. For in situ hybridization, probes were designed from exon 3 and from exon 6 (Figure 2B; Table 3). Both techniques failed to detect message from cat *Tas1r2* (see Figure 3C and 3D). Consistent with these attempts to detect message from cat *Tas1r2*, immunohistochemistry using an antibody developed from a deduced amino acid sequence spanning exons 2 and 3 revealed no labeling of taste buds in circumvallate or fungiform papillae (Figure 4C and 4D).

These results suggest that the cat *Tas1r2* pseudogene is not transcribed, or if it is transcribed, it rapidly degrades, perhaps through a nonsense-mediated mRNA decay pathway [22].

### *Tas1r2* in Felidae

The generality of the pseudogene nature of cat *Tas1r2* was confirmed by sequencing the deletion and stop codon areas from six individual healthy adult cats. All showed the deletion and similar stop codons with some polymorphism (see Table 2). To assess the generality of the pseudogene nature of *Tas1r2* in Felidae, we sequenced the stop codon areas and the area including the exon 3 microdeletion from genomic DNA of tiger and cheetah. These too displayed microdeletion and stop codons at the same location as the domestic cat. These observations, suggesting that in at least three species of Felidae *Tas1r2* is not expressed, are consistent with behavioral evidence showing that, not only domestic cats, but also tigers and cheetahs do not prefer sweetened water over plain water [1].

According to morphological and molecular evidence, the available phylogeny of the order Carnivora consists of two groups, the Feliformia (cats, mongooses, civets, and hyenas) and the Caniformia (wolves, bears, raccoons, mustelids, and pinnipeds) [23,24]. It is difficult to determine when the alteration of *Tas1r2* occurred and whether it preceded or followed the cat ancestor's change in diet to exclude plants. Clearly, because dogs have a human-like T1R2 structure (see Figure 1) and an avidity for sweet carbohydrates [25], the changes in the cat *Tas1r2* must have occurred after the divergence of the Feliformia and the Caniformia.

### Genes Affecting Taste Behavior

Taste receptors are shaped by and reflect a species’ food choices. The genes encoding taste receptors often show a good deal of variation both among species and among individuals. These variations, both subtle and obvious, can have a variety of effects on taste sensitivity and preference behavior. A textbook example of this effect is the individual variation seen in sensitivity to the bitter compound, phenylthiocarbamide (PTC). A gene of the human *TAS2R* family of bitter taste receptors, *TAS2R38*, associated with this individual variation, shows three coding single-nucleotide polymorphisms giving rise to five haplotypes worldwide, accounting for the 55% to 85% of the variance in PTC sensitivity [26]. Further, in Drosophila, the behavioral and electrophysiological responses to trehalose are diminished in two mutants that carry deletions in the trehalose recognition gene, *Gr5a* [27]. In the mouse, variation in preference for sweet-tasting stimuli maps to the gene for T1R3, located within the *Sac* locus [28,29]. This gene is allelic in mice, and several reports identify a missense mutation (I60T) as being the most likely mutation accounting for the phenotypic differences [13,14,16,30–33]. However, the same alleles are not involved in strain-dependent sweet-taste preference in rats [34].

In addition to the modulation of behavior that can be caused by point mutations, more profound behavioral changes can result from the abolishment of gene function through, for example, the generation of pseudogenes. An example of this effect in mammalian chemoreception lies within the large repertoire of olfactory receptor genes. More than 60% of the human olfactory receptor genes are pseudogenes [35], whereas, only 20% are classified as such in mouse [35,36]. Strikingly, the accumulation of these olfactory pseudogenes in primates reportedly occurred concomitant with the acquisition of trichromatic color vision, perhaps reflecting the overarching behavioral changes that such an acquisition engendered [37]. Similar generation of bitter-taste receptor pseudogenes, accompanied by a large number of coding region single-nucleotide polymorphism, can account for the broad diversity displayed by the bitter-taste receptor family. This diversity may possibly play an important role in both species-specific and individually manifested taste preference [38].

In the extreme case, where a species fails to respond to stimuli representative of an entire modality, such as the cat with sweet taste, the development of a unique food

---

**Table 3. Primers for In Situ Probes**

<table>
<thead>
<tr>
<th>Primer Names</th>
<th>Forward</th>
<th>Reverse</th>
<th>Product Size (bp)</th>
<th>Tm (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>catTas1r2Ex3</td>
<td>5’GGTCTGGGACGACTCTGCC3’</td>
<td>5’GCATAAACCAGCAGAGGCC3’</td>
<td>560</td>
<td>60</td>
</tr>
<tr>
<td>catTas1r2Ex6</td>
<td>5’TCTCTGAGGAAGTTG3’</td>
<td>5’TCTCTCGCTCGTTACGCT3’</td>
<td>999</td>
<td>60</td>
</tr>
<tr>
<td>catTas1r3Ex3</td>
<td>5’TGGTGTAGTGTGAGGGCTG3’</td>
<td>5’AGTGTGGTGGTGAAGGGT3’</td>
<td>416</td>
<td>60</td>
</tr>
<tr>
<td>catTas1r3Ex6</td>
<td>5’CCATGTGACCAGGCCAG3’</td>
<td>5’TGTCTGCGCGATTGTCTGC3’</td>
<td>894</td>
<td>60</td>
</tr>
</tbody>
</table>

*Tm*, melting (annealing) temperature.

DOI: 10.1371/journal.pgen.00010001003
preference behavior, based on the remaining taste receptors, might be anticipated. Because, with the exception of the sweetness modality, the taste system of the cat is organized much like that of most other mammals, discovering the molecular basis for the cat’s lack of response to sweet-tasting compounds gives us a window on the development of strict carnivorous behavior in Felidae.

Conclusion

It is known that Felidae do not detect sweetness of carbohydrates yet can taste amino acids. Our results indicate that the gene encoding one member of the sweet-taste receptor heteromer is an unexpressed pseudogene. Given this observation, we suggest that the most parsimonious explanation for the inability of Felidae to respond to sweeteners is the lack of a functional T1R2 protein.

Materials and Methods

Animal tissue. We obtained cat taste tissue from healthy young-adult animals euthanized for reasons unrelated to this study. Animals were cared for under protocols 035400 and 057600 approved by the Institutional Animal Care and Use Committee of the University of Pennsylvania to Dr. Mark Haskins of the School of Veterinary Medicine, University of Pennsylvania.

Preparation of genomic DNA. Overgo probes are comprised of two 22mers with a complementary eight-base overlap. They can be designed by a computer program (http://genome.wustl.edu/tools/overgo=1) and are readily synthesized. To identify cat Tasl2 and Tasl3, overgo probes were designed by aligning conserved coding regions of Tasl2 and Tasl3 sequences from different species. The single-stranded overhangs (14 bases) were filled in with 32P-labeled dATP and dCTP, and the overgo probes were used in hybridization procedures with the BAC libraries.

Screwing a feline genomic BAC library. Tasl2 and Tasl3 overgo probes were radiolabeled by the random hexa-nucleotide method, and hybridization and washing of membranes were as described [29]. We identified 47 positive BAC clones for cat Tasl2 and cat Tasl3, and sequenced all of the positive BAC ends. By aligning BAC ends sequences with human syntenic regions (human TASIR2 and TASIR3 are located on chromosome 1p36), we picked BAC clones positive for cat Tasl2 and Tasl3 for shotgun library preparation.

Production of shotgun libraries for BACs containing cat Tasl2 and Tasl3. We prepared BAC DNAs from positive clones by using a Qiagen Large Construct Kit (Valencia, California, United States). BAC DNAs were digested using Sau3A I and the digested BAC DNA fragments subcloned into pGEM-3Z (Promega) vector. After transformations were arrayed to a nylon membrane, two separate hybridizations were performed by using pooled fragments subcloned into pGEM-3Z (Promega) vector. After transformations were arrayed to a nylon membrane, two separate hybridizations were performed by using pooled fragments.

Screening of overgo probes. Overgo probes were designed by aligning conserved coding regions of Tasl2 and Tasl3 sequences from different species. The single-stranded overhangs (14 bases) were filled in with 32P-labeled dATP and dCTP, and the overgo probes were used in hybridization procedures with the BAC libraries.

In situ hybridization. The probes corresponding to exons 3 and 6 of cat Tasl2 and Tasl3 were amplified by PCR using the primers described in Table 3. DIGoxigenin-labeled cRNA probes were synthesized using a DIG RNA labeling kit (Roche). Tissue bud–containing vallate tongue tissue was obtained as above. Fresh frozen sections (14 μm) of cat circumbivalve papillae were attached to clean SuperFrost/Plus slides and prepared for in situ hybridization as described previously [33]. Lingual tissue blocks containing cat circumbivalve and fungiform papillae were fixed in 4% paraformaldehyde for 2–6 h, then processed [40]. The sections were washed at 72 °C with 0.2X SSC three times. Signals were detected using alkaline phosphatase–conjugated antibodies to digoxigenin.

Supporting Information

Accession Numbers

The GenBank (http://www.ncbi.nlm.nih.gov/Genbank/) accession numbers for the genomes discussed in this paper are cat Tasl3 (AY819786), cat Tasl2 (AY819578), dog Tasl2 (AY916758, dog Tasl3 (AY916759), human TASIR2 (BK000152), and human TASIR3 (NM_152529).

Acknowledgments

We thank Mr. Douglas L. Bayley, Ms. Kirsten J. Mascoli, Ms. Linda Wysocki, and Mr. Minliang Zhou for excellent technical assistance. We also thank Dr. Chenyan Wu for helping to design overgo probes and for many stimulating discussions. We gratefully acknowledge Dr. Tadqul Huque for helping with early preliminary experiments, and Dr. Paul A.S. Breslin for suggesting an experiment and for critically reading the manuscript. We thank Lynn S. Hall and Mary Chatterton for providing the sample of blood or cheek swabs from cats. We acknowledge the laboratory of Dr. Mark Haskins of the School of Veterinary Medicine, University of Pennsylvania, for the procurement of animal tissue and the dedicated assistance of Patty O’Donnell and Karyn Cullen of that laboratory (NIH grants 02512 and DK25759 to Dr. Haskins).

The work was supported by a grant from The WALTHAM Centre for Pet Nutrition (to XL and JGB), and by National Institutes of Health grants R01DC00882 (GKB), R03DC05154 (LH), training grant T32DC00104 (to Monell Center, Dr. C. Wysocki, PI), by a grant from the United States Department of Veterans Affairs (JGB), and a grant from the National Science Foundation (DBI-0216310). This project is funded, in part, under a grant with the Pennsylvania Department of Health. The Department specifically disclaims responsibility for any analyses, interpretations, or conclusions.

The funding agencies had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests. HW, JG, KM, and LH declare that they have no conflicts of interest.
no competing interests of a financial, professional, or personal nature. VLD is an employee of the Masterfoods division of Mars. GKB is on an advisory board to the WALTHAM Centre. Authors describing the uses of the feline receptors have been filed, and name as inventors: XL, WL, JGB, DRR, and AAB.

References
18. Li X, Inoue M, Reed DR, Huque T, Puchalski RB, et al. (2001) High-resolution genetic mapping of the saccharin preference locus (Sac) and the putative sweet taste receptor (T1R1) gene (Gpr70) to mouse distal chromosome 4. Mamm Genome 12: 13–16.