Beidler's theory and human taste stimulation[1]

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Beidler's fundamental taste equation, relating response magnitude and stimulus concentration, was found to be a useful means of expressing data derived from chemoreception experiments with man. Seven L-amino acids and glycine were studied over a wide range in concentration. To a first approximation, the data are in accord with Beidler's taste equation. Interestingly, the change in free energy (ΔF) for each stimulus was found to be small, in agreement with earlier published conclusions that the initial step in chemoreception is most likely one of adsorption. Several means of depicting these data are evaluated and their contribution to a better understanding of chemoreception is discussed.

From a series of investigations on the properties of taste receptors, Beidler (1954) proposed that the taste response might be approximated by the mass action law. Based on evidence derived from electrophysiological investigations of taste receptors in the rat tongue, Beidler proposed that the stimulus ions were loosely bound to some substance of the taste receptor, and accounted for the initial taste reaction to the stimulus. From this base assumption, he proposed what he called "the fundamental taste equation," relating response magnitude and stimulus concentration:

$$\frac{C}{R} = \frac{C}{R_m} + \frac{1}{KR_m} \qquad (1)$$

in which C = stimulus concentration, R = response magnitude, R_m = maximum response, K = equilibrium constant.

For a given stimulus, R_m and K are constants. A plot of $\frac{C}{R}$ vs. C yields a straight line with a slope ot $\frac{1}{R_m}$ and $\frac{C}{R}$ axis intercept of $\frac{1}{KR_m}$. Beidler's plots of data derived from stimulation of the rat tongue with sodium salts yielded a family of straight lines in support of this fundamental taste equation.

Tucker (1963) applied the fundamental equation (1) to his olfactory data from the tortoise with some degree of success. However, the data were in better agreement with a more elaborate equation that considered the two sets of independent receptor sites (Beidler, 1961). More recently, Hardiman (1964) used the taste equation (1) as a working model to study the responses of the rat and the hamster to a number of different taste stimuli. He noted that although a Scatchard plot (Edsall & Wyman, 1958) would aid in detection of binding at multiple sites, a plot of the data on normal probability paper would provide more information about the different K values and the taste response. Data from other sensory systems were also shown to fit the generalized sensory equa-

tion (1) when plotted on normal probability paper. Jnd and magnitude estimation data (Steven's (1957) power function law) also could be fit to this normal probability function.

In the present experiment, the taste properties of some L-amino acids were investigated in man and Beidler's fundamental taste equation was evaluated for its applicability to taste functions generated from subjective data. The working assumption was that judgment of taste intensity is a reliable index of taste receptor mechanisms in man.

Method

The Ss for these experiments were two males and three females, all of whom had served previously in similar research and were well experienced with the
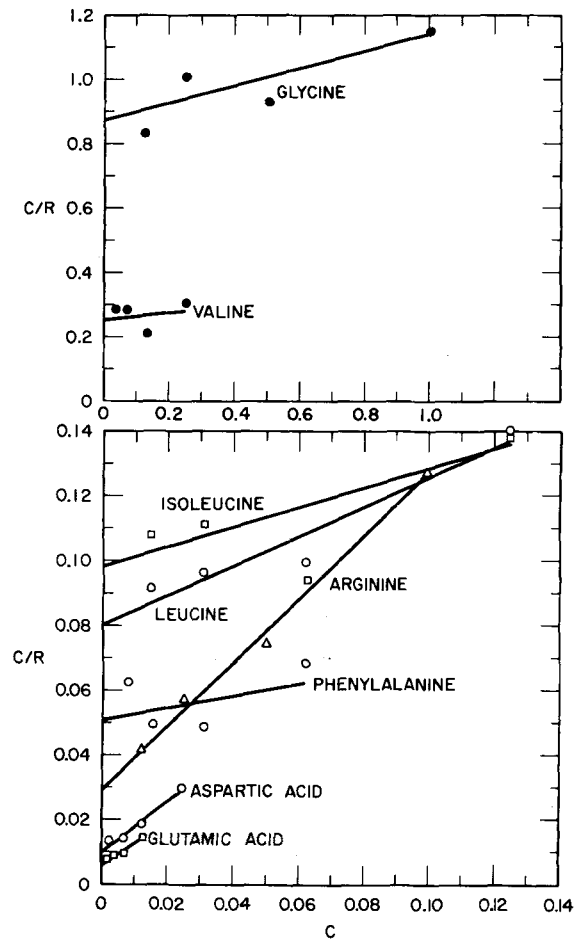

Fig. 1. The fundamental taste equation plotted on linear paper, where the ordinate, C, is concentration and the abscissa is the concentration divided by the response. The points derived from the pooled data from all five subjects. The method of least squares was employed to determine the equation for each line.

Table 1.
Magnitude of Response to the Test Concentrations for the Panel*

Amino Acid	Molar Concentration	Response	Range
Glycine	1.0	.867	.675-.95
	.50	.536	.38 -.66
	.35 (ref.)	.500	--
	.25	.233	.098-.375
	.125	.149	.070-.216
L-Valine	.25	.842	.70 -.905
	.125	.604	.53 -.645
	.088 (ref.)	.500	--
	.0625	.229	.182-.265
	.0313	.112	.070-.162
L-Leucine	.125	.888	.66 -.96
	.0625	.637	.42 -.75
	.044 (ref.)	.500	--
	.0313	.327	.22 -.435
	.0156	.171	.095-.215
L-Isoleucine	.125	.942	.87-1.00
	.0625	.673	.57 -.74
	.044 (ref.)	.500	--
	.0313	.281	.148-.375
	.0156	.144	.065-.235
L-Phenylalanine	.0625	.913	.761-.985
	.0313	.667	.52 -.795
	.022 (ref.)	.500	--
	.0156	.319	.215-.449
	.0078	.125	.005-.245
L-Arginine	.10	.785	.64 -.86
	.05	.675	.61 -.765
	.036 (ref.)	.500	--
	.025	.442	.405-.585
	.0125	.306	.265-.36
L-Aspartic acid	.025	.851	.675-.965
	.0125	.684	.58 -.775
	.0088 (ref.)	.500	--
	.00625	.441	.34 -.645
	.00313	.236	.175-.29
L-Glutamic acid	.0125	.861	.725-.94
	.00625	.686	.585-.805
	.0044 (ref.)	.500	--
	.00313	.385	.265-.505
	.00156	.208	.105-.335

*Responses are averages of ratings on a 0-1.0 point sca'   ʹ are based on 15 replications per S for 5 Ss. Glycine was su   ʹby Schwartz Bioresearch, Inc., New York; arginine and glutamᵥ acid by Scientific Products, Calif.; leucine and aspartic acid by Henley and Co., Inc., New York; phenylalanine by Daiichi Seiyaka Co. Ltd., Tokyo; and isoleucine and valine by Kyowa Hakko Kogyo Co., Tokyo. Purity for all stimuli was ≥ 98%.

procedures. Ss received two to three days of preliminary tests with each of the eight stimuli to familiarize them with the taste of the stimuli and the experimental procedure. Each concentration of each stimulus was tested separately, the same time of day on each day of the experiment. A total of 20 responses was obtained from each S for each concentration of each stimulus, but only the final 15 scores were retained for analysis.

Ss rated the intensity of each stimulus on a 0-1.0 point scale (0—no taste, .50—moderate intensity, 1.0— extremely intense) following presentation of an identified standard with a rating of .50. The test stimuli consisted of L-valine, -leucine, -isoleucine, -phenylalanine, -arginine, -aspartic acid, -glutamic acid, and glycine.

All amino acids were obtained from commercial sources with purity ≥ 98 percent.

Five samples, including a water blank, were presented in a randomized sequence. The Ss also indicated their hedonic impressions and the taste qualities perceived.

A four-step geometric series with a factor of 2 was used to prepare stimulus concentrations with a reference at the geometric mean. The range was selected by another group of Ss including the authors. Each stimulus was prepared at maximum solubility, tasted, and a range of dilutions selected to represent as much as possible of the sensory continuum. In most instances, the higher concentrations (i.e., maximum solubility) were avoided because of taste carryover and adaptation effects. The greatest dilution was usually just above the recognition threshold for the stimulus. Sufficient solution to complete each experiment was prepared and kept in cold storage. Only that amount necessary for testing was removed daily. Samples were served at 22° ± .5°C to reduce any possible errors due to differences in sample temperature (Amerine et al, 1965). Water for sample preparation and oral rinsing was de-ionized, glass distilled, and percolated through charcoal to removed any odor or taste.

Results and Discussion

Ss' intensity ratings for the test stimuli are shown in Table 1. The data indicated that Ss rated the intensity of the stimuli in the expected manner; response rose rapidly and stabilized as concentration was maximized.

Plotting these data in the form $\frac{C}{R}$ vs. C, as in the fundamental taste equation (1), produced the curves shown in Fig. 1. Table 2 summarizes the results, including R_m, K_m, and ΔF obtained from fitting the fundamental taste equation to pooled data for each stimulus.

For some stimuli there was good agreement between Ss (e.g., aspartic and glutamic acids, phenylalanine and arginine); for others there appeared to be an almost complete reversal, primarily at the lower concentrations. One explanation is that at these lower concentrations there may have been confusion on rating the intensity attributable to differences in sensitivity or taste carryover.

Table 2. Amino acid slope values, maximum responses and equilibrium constants derived from the fundamental taste equation

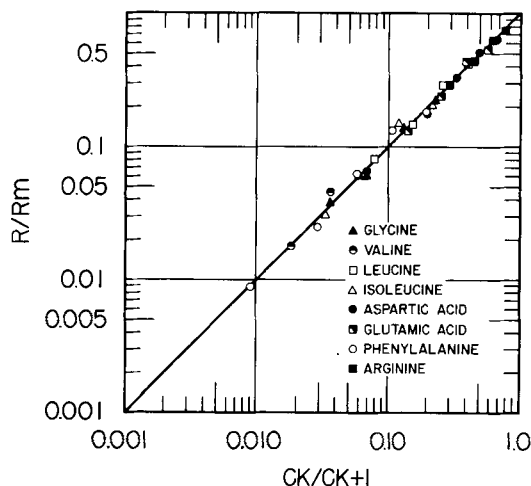| Amino acid	Slope b	Maximum response R_m	Equilibrium constant K	ΔF* cals/mole
Glycine	.2668	3.748	0.3	+ .72
Valine	.0769	13.004	0.3	+ .72
Leucine	.4573	2.187	5.7	−1.04
Isoleucine	.2179	4.589	2.2	− .47
Phenylalanine	.1989	5.028	3.9	− .81
Arginine	.9667	1.034	33.1	−2.09
Aspartic acid	.7586	1.318	78.9	−2.61
Glutamic acid	.6250	1.600	105.9	−2.79

* $\Delta F = -RT \ln K$

Fig. 2. A log-log plot of the rearranged fundamental taste equation, R/R_m vs $CK/CK=1$, for the pooled data. The solid line is the theoretical line, slope = 1. The log-log plot was necessary to put all the data on one figure.

Beidler (1961) and Hardiman (1964) suggested that, by reversing the $\frac{C}{R}$ vs. C plot (using a Scatchard plot) it would be possible to detect binding of the chemical stimulus at two (or more) different sets of independent sites. Data from the present experiment were not sufficient to apply to the $\frac{R}{C}$ vs. R type of plot. Attempts to plot these data resulted in curvilinear shapes, but not necessarily hyperbolic, confirming our preliminary estimates of the complexity of the problem and the need for more experimental data. Behaviorally this is not surprising in view of the complex subjective description of the taste of these stimuli (Stone, 1967). One additional method for depicting these data was attempted. The taste equation was rearranged to read:

$$\frac{R}{R_m} = \frac{CK}{CK+1}$$

Using values of K and R_m obtained by the least squares fitting of the data to the taste equation in its original form (1), this rearranged equation when plotted on linear paper should yield a straight line with a slope of 1 if the data fit the equation. Figure 2 shows good agreement with the theoretical line, a slope calculated as 0.991 vs. 1.0 for the theoretical value. For some of his data, Hardiman (1964) reported a similar relationship. However, this does not tell much more about the initiation of the taste response or anything about taste itself. Based on the small free energy changes (F) associated with these stimuli (Table 2), the initial step is most likely adsorption, in agreement with Beidler's conclusion (1954).

That different taste qualities are perceived behaviorally suggests that different receptor sites are stimulated or are stimulated in a different sequence similar to the multistep process by Nejad (1961). Nejad was concerned mainly with gustatory response and enzymatic activity, but it is possible that the sequence of reactions may mediate taste quality, if not directly, then at least with the coding process (cf., Erickson, 1963).

Another interpretation is that the entire molecule may be as important as the reactive portions, although this concept has not been adequately investigated; certainly the reactive portions influence and are influenced by the rest of the molecule, which to some extent affects reactivity. Perhaps the skeletal structure of the molecule functions in the manner suggested by Beets (1961) for odor stimuli. According to Beets, odor impression (quality) is determined by (a) the functional group which orients the molecule and (b) the bulk and form of the rest of the molecule. Thus, for taste the functional group would stimulate one kind of receptor while the remainder of the molecule would stimulate other types of receptors, and each portion of the molecule would act in concert with the other portions. Knowledge about receptors, receptor sites, and behavioral responses is far from complete, especially when complex taste stimuli such as the D- and L-amino acids, the inosinates (flavor "enhancers"), and taste mixtures are considered. Nevertheless, the information presented here provides additional support for the usefulness of Beidler's fundamental taste equation, in this instance, based on behavioral information from man.

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Notes