Physiology and Behavior, Vol. 10, pp. 289–292. Brain Research Publications Inc., 1973. Printed in the U.S.A.

Effects of Solution Temperature on Taste Intensity in Humans

HOWARD R. MOSKOWITZ

U.S. Army Natick Laboratories, Pioneering Research Laboratory Natick, Massachusetts 01760

(Received 1 May 1972)

MOSKOWITZ, H. R. *Effects of solution temperature on taste Intensity in humans.* PHYSIOL. BEHAV. **10**(2) 289–292, 1973.—The dependence of taste intensity upon both molar concentration and solution temperature was investigated by the method of magnitude estimation. For each of the four taste substances (glucose, NaCl, citric acid, quinine sulfate) 4–5 concentrations of solution were evaluated at each of six temperatures (25–50°C). Power functions of the form $T = kC^n$ related subjective intensity to molarity at a fixed solution temperature. The exponent n for all tastes but citric acid was unaffected by temperature, suggesting that the growth rate of intensity with concentrations is unaffected within a 25° change. The intercept k varied with temperature for glucose, and was linearly related to temperature for NaCl.

Taste intensity   Temperature   Psychophysics

TEMPERATURE dependence or independence of taste intensity plays an important role for several theories of the taste process. According to Beidler [2], who observed that the integrated neural response from the chorda tympani of the rat was unchanged when stimulus solutions varied from 20°C - 30°C, the initial step in transduction is physical, rather than chemical. The enzymatic theory of taste, proposed by Baradi and Bourne [1], in contradistinction, argues for significant temperature dependency. Finally, Shallenberger's model for the sweet taste [10] suggests that sweetness is diminished by intramolecular hydrogen bonding in sugars, but that increases in temperature should rupture these bonds, and thus produce noticeable changes in sweetness for fixed sugar concentrations.

Neither electrophysiological nor psychophysical studies have concurred about taste-temperature relations. In at least one other series of studies, the neural response of the cat chorda tympani was seen to depend greatly upon the stimulus temperature [9]. For diverse compounds, sensitivity was highest at the tongue temperature of 30°C. Higher or lower stimulus temperatures produced lower taste sensitivity, although they did introduce temperature dependent thermal responses. Early psychophysical studies relied upon the changes in the absolute threshold for taste to indicate alterations in the taste process with temperatures. Increases in threshold were taken as suggestions that at higher, suprathreshold levels, temperature shifts diminished taste response, whereas the converse effect, a decrease threshold, was assumed to reflect a facilitatory effect. Present-day studies of taste intensity using direct procedures, in which the subject judges taste intensity by one or another scale, have also shown both significant changes and no effects. A recent study [8] with NaCl presented at four stimulus temperatures (0°, 22°, 37°, 55°C) showed that at the extremes of temperature perceived intensity was significantly lower. In contrast, however, another study with mixtures of glucose and fructose [12] at temperatures varying from 5°C to 50°C showed no significant temperature effects.

The present study investigates taste-temperature interactions by looking at the entire function relating taste intensity to concentration. Recent studies in psychoacoustics indicate that, if the relation between perceived loudness (L) and physical pressure (P) is expressed as a power function ($L = kP^n$), then the exponent n, becomes higher during masking of the tone by a noise, or if the ear is affected by Menière's disease [11]. The effect has been labelled "recruitment", and the increase in the exponent n is an index of its severity. Simple shifts in intensity, without recruitment, show themselves by changes only in the value of k, the intercept. It is assumed by those working psychoacoustics with this procedure that changes in the exponent n reflect more profound shifts in the receptor process than do changes in k. Indeed, increases of the exponent imply that the rate of growth sensory intensity with physical intensity is raised, so that a fixed proportional increase in the physical domain becomes a larger perceptual increase in intensity.

METHOD

Stimuli

Stimulus solutions comprised five concentrations of glucose (2.0, 1.0, 0.5, 0.25, 0.125, M) to provide sweetness, NaCl at four concentrations (1.0, 0.5, 0.25, 0.125 M) to provide saltiness, citric acid at four concentrations (0.05, 0.025, 0.0125, 0.00625 M) to provide sourness, and quinine sulfate at four concentrations (0.001, 0.0005, 0.00025, 0.000125 M) to provide bitterness. All solutes were reagent grade materials (either Sigma Chemical Company of Fisher Chemical Company). The water solvent was of neutral pH (6.9–7.1; Hydro Service Supply, Inc.), and purified by ion exchange. The stimulus solutions were prepared in 8 liter quantities, and refrigerated at 5°C until use one week later. During the intervening time, the glucose solutions were inspected daily for the presence of cloud, indicating mold formation, but none was noted. The stock solution of quinine sulfate (0.001 M) precipitated out solids under refrigeration, but these were forced back into solution by vigorous heating and stirring at 50°C prior to the experiment. At that time, the solution cooled down to ambient room temperature (22° ± 1°C) but no solids precipitated again.

Subjects

A group of 12 volunteer males (18–23 years old), enlisted men in the test platoon of the U.S. Army Natick Laboratories, served. Subjects were uninformed about the purpose of the experiment, although eight had previously served in similar studies of taste intensity for sugars and acid presented at room temperature. During the three days of the study, the initial group of 12 subjects dropped to 9, so that partial data were available for those three.

Procedure

The stimulus solutions, coded to disguise concentration and compound, were placed in 1 liter plastic bottles fitted with acid pump tops. A squeeze on the pump top provided about 20 ml (±3) to the subject, who held a small, paper souffle cup. The stimulus temperatures were maintained by a hot water bath, and the bottles weighted so that they remained upright. The temperature of the bath was maintained at one of six levels (25°, 30°, 35°, 40°, 45°, 50°C) by means of a thermostat-relay combination.

During each session, the 17 stimulus solutions were presented at two different temperatures by means of two water baths (total = 34 stimuli). A third reference series of the five glucose solutions was presented at 25°C during each session (total = 5). Thus, at any one session, the subject sampled 39 samples from three water baths. The order of the water baths was counterbalanced across subjects, and the order of samples within the water bath was irregular, both with respect to compound and concentration. Each temperature condition was replicated six times, but the five glucose solutions at 25°C were presented separately in every session.

Subjects were instructed to judge the overall taste intensity, without attention to quality, on the same scale across all 39 solutions, and were told to ignore temperature variations across the three water baths. They used the procedure of "magnitude estimation" [5] in which the ratios of numbers assigned by subjects presumably reflects the ratios of sensory magnitudes. Subjects were permitted to use any scale of positive numbers that they wished, but subsequent analysis removed the variability by the procedure of modulus normalization [5, 6, 7].

Each subject sipped the solution from the small, 3/4 oz paper souffle cups, and was instructed to sample the entire contents of the cup (20 ml approximately) as quickly as possible after he had removed the material from the heated container. Subject was told to make a judgment based upon his immediate impression of taste intensity, and to record it on the answer sheet provided. The sipping process, including the recording, lasted between 20 and 30 sec, and between samples subject was required to rinse with approximately 50 ml of tap water at room temperature to clear his mouth. Other than the required time to rinse and to sample and record judgments, subject was not constrained to wait between stimuli. However, the entire process required between 40 and 50 sec, with no subject sampling faster than twice a minute. Subject was not aware of the actual temperatures of the water baths, nor did he know the concentrations or compounds of the stimuli. However, virtually all subjects later remarked that the stimuli were sweet, salty, sour and bitter.

Analysis

The judgments of intensity (median values) were related to concentration by a simple power function $T = kC^n$ (equivalently: $\log T = n \log C + \log k$). Least squares fits were obtained with the median and the geometric mean of the subjective estimates, with the temperature fixed at one of the six levels. Goodness-of-fit of the equation to the data was assessed by the Pearson r^2, which in most instances was higher than 0.90. For subsequent analyses, the exponents were computed for each subject across all conditions (compound, temperature, replicate), as well as the following index of relative taste intensity: log k′ (defined by the least squares estimate of log k′ for the equation: $\log T = 0.9 \log C + \log k'$). Log k′ is a simple measure of the average logarithmic separation between two taste functions that run parallel to each other, and its antilogarithmic value is a measure of the ratio of taste intensities. It is a summary statistic only, and has been used in previous studies [6,7] to assess the relative sweetness of sugars and the relative sourness of acids.

RESULTS

Changes in the Exponents Across Temperatures

Figure 1 presents the set of twenty-four sensory functions, six for each of the four compounds. Beneath each function (except for glucose at 45°C and citric acid at 50°C) is the least squares estimate of the psychophysical power function chosen to relate the median magnitude estimate to the stimulus concentration. In addition, the Pearson r^2 is provided. The two functions without corresponding equations are not linear in log–log coordinates, and a single power function fitting these curves is not appropriate.

In order to determine the significant effects of temperature upon power function exponents, the individual exponent for each subject at each temperature condition was used in an analysis of variance. Four such analyses were performed, but only citric acid proved significant ($F = 2.42$, $df = 5{,}394$, $p < 0.05$). The significant difference disappeared, however, when the individual functions for citric acid at 50° were removed. It is also noteworthy that the exponent for glucose consistently exceeds those for NaCl, citric acid and quinine sulfate, in some instances by a factor of two.

Figure 2 shows the distribution of values for log k′ across the compounds and temperatures. The vertical bars represent the range ± 1 standard error for log k′, for values of log k′ computed across subjects and replicates. Analyses of variance performed separately for each compound reveal that log k′ is significantly affected by temperature for glucose ($F = 5.42$, $df = 5{,}574$, $p < 0.05$) and for NaCl ($F = 3.34$, $df = 5{,}394$, $p < 0.05$).

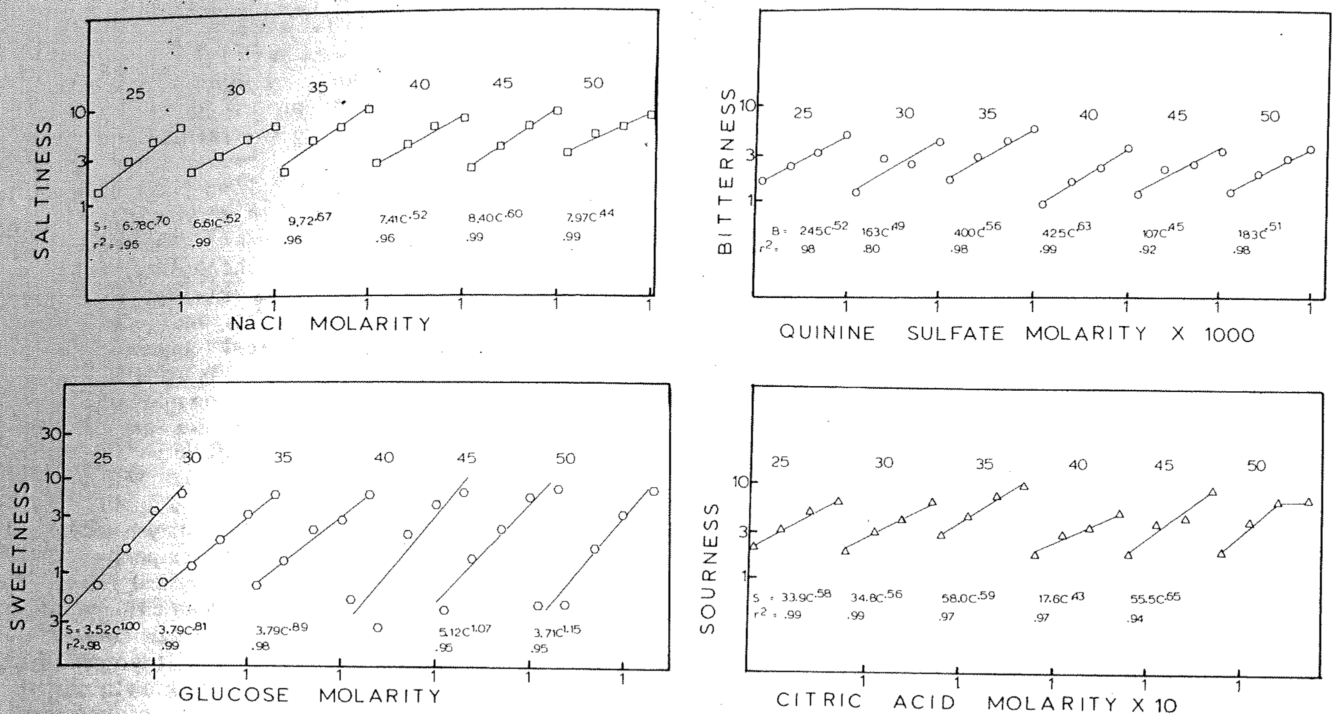

FIG. 1. Median judgements of taste intensity and for six different temperatures, and 4–5 concentrations of each taste substance. The coordinates are logarithmic, and the six functions have been shifted successively to the right by one log unit to facilitate reading the figures. Beneath each figure (except citric acid at 50°C, and glucose at 45°C) are the exponent and intercept of the best fitting power function. Numbers above each function indicate the solution temperature.

TABLE 1

REGRESSION FUNCTIONS TO PREDICT TASTE INTENSITY (INDEXED BY LOG K') FROM TEMPERATURE

Glucose Sweetness		
(A) Linear		
1) log K' = 0.59	−0.15T	r = −0.41
2) *log K' = 0.56	−0.01T	r = 0.57
(B) Quadratic		
1) log K' = 0.17 + 0.02T	$-0.0003T^2$	r = 0.73
2) *log K' = 0.37 + 0.09T	$-0.0015T^2$	r = 0.74
(C) Cubic		
1) log K' = −1.91 + 0.19T	$-0.005T^2 + 0.00043T^3$	r = 0.91
2) *log K' = 1.11 + 0.13T	$-0.0035T^2 + 0.0003T^3$	r = 0.99
NaCl Saltiness		
(A) Linear		
1) log K' = 0.71 + 0.0081T	r = 0.86	
2) *log K' = 0.66 + 0.0086T	r = 0.99	

*Refer to best fitting functions after 35° is eliminated.

If log k' is considered as a single summary value for representing relative taste intensity, then its value for the four compounds at 35°C is higher than the neighboring values at 30° and 40°C (Although this relation may not necessarily hold for all point-by-point comparisons for the median values shown in Fig. 1). In Fig. 2 the symbol t is placed above temperature corresponding most closely to average tongue temperature. Indeed, at 35°C taste intensity has a higher average value than virtually all other temperatures, with the exception of NaCl whose value at 50°C is slightly higher.

In order to assess the presence of simple functional relations between temperature and taste intensity the six values for log k' of both glucose and NaCl were regressed against temperature. Table 1 presents the best fitting linear, quadratic and cubic equations for glucose taste intensity, and the best fitting linear function for NaCl taste intensity. The least squares estimates were computed both with and

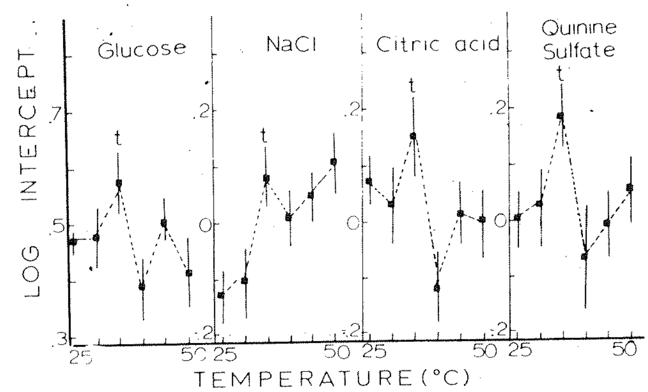

FIG. 2. Relation between temperature and log k′ (log intercept at a fixed exponent of 0.9: log T′ = 0.9 Log C + log k′). The abbreviation 't' refers to the temperature of the tongue. Vertical lines give the ranges of log k′ (± 1 standard error). Statistics were computed after the results of all subjects and all replicates were pooled together. The significance for changes in log k′ for sweetness may be due to the greater number of observations (n = 579) for this taste than for the three others (n = 399 for each).

without the value at 35°C, which appears to be anomalous in the NaCl function. According to Table 1, a cubic equation best describes the glucose temperature function, and a linear equation the NaCl-temperature one. In the equations, temperature has been expressed as deviations about 35°. Of interest is that a 1° increase in temperature produces an increase of 0.0086 log units (approximately 2%) of apparent taste intensity (presumably saltiness at the concentrations used here).

DISCUSSION

The present results suggest that alterations of stimulus temperatures leave unchanged the rate of growth in taste intensity with concentration. Thus, changing temperature is not psychophysically equivalent to adding a masking noise to a tone - the latter exhibits an exponent shift [11] but the former does not. In addition, the effects of temperature are not dependent upon concentration - the invariant exponent indicates that the effect is both multiplicative, and is a constant shift in logarithmic values across the entire range. Second, not all compounds exhibit temperature dependency (only glucose (sweet) and NaCl (salty) do), and only NaCl shows a consistent trend for intensity changes with temperature. The equations in Table 1 provide the means to compute the size of change as a function of concentration.

The present findings do not support Beidler's model for a temperature independent taste process [2] nor Shallenberger's hypothesis [10] that the sweetness of sugars will increase at higher concentrations. However, these results, obtained by direct psychophysical judgments from humans agree with Sato's findings [9] with specific agreement about the maximal sensitivity at the tongue temperature. In order to complete the parallel psychophysical study to Sato's electrophysiological one, it is necessary to obtain psychophysical judgments both of temperature and taste intensity for single stimuli at different temperatures and concentration. By having these judgments made according to a single unit of intensity (modulus) one may determine the contours relating concentration to the sum of taste intensity and apparent temperature intensity. This total response contour can then be compared to electrophysiological contours.

Finally, it is important to note that analysis of taste functions and their dependence upon temperature, by appeal to the parameters of a psychophysical function, provides significantly more information than either threshold shifts, or changes in the intensity of single concentrations (as obtained by a matching procedure). If temperature plays a role, it may do so by altering the growth rate of intensity, an effect that is presumably more profound than multiplication of the effective concentration by a single multiplier. According to the results of auditory psychophysics, the former, an exponent shift, indicates a change in the receptor process (or a psychophysical correlate thereof), whereas the latter may not. It is not clear whether adapting the tongue to other concentrations, and then testing the compound at the adapted temperature, would produce results similar to the present one, or whether the exponent itself would shift. Direct psychophysical procedures, such as the present one, indicate whether altering tongue temperature has a more profound effect upon the growth of taste intensity.

ACKNOWLEDGMENTS

Dr. Harry L. Jacobs provided numerous helpful comments in the analysis of the present data. The author also wishes to thank Duane D. Pins for assistance in running the experimental portion of this study.

REFERENCES

1. Baradi, A. F. and G. H. Bourne. Gustatory and olfactory epithelia. *Int. Rev. Cytol.* **2:** 289–330, 1953.
2. Beidler, L. M. A theory of taste stimulation. *J. gen. Physiol.* **38:** 133–139, 1954.
3. Camerer, W. Die Grenzen der Schmeckbarkeit von Chlornatrium in wassriger Losung. *Pflügers Arch. ges. Physiol.* **2:** 322–329, 1869.
4. Chinaglia, L. De l'influence qu' exerce la temperature sur la sensibilite gustative. *Archs ital. Biol.* **63:** 401–409, 1915.
5. Moskowitz, H. R. Ratio Scales of sugar sweetness. *Percept. Psychophys.* **7:** 315–320, 1970.
6. Moskowitz, H. R. Ratio Scales of acid sourness. *Percept. Psychophys.* **9:** 371–374, 1971.
7. Moskowitz, H. R. The sweetness and pleasantness of sugars. *Am. J. Psychol.* **84:** 387–405, 1971.
8. Pangborn, R. M., R. B. Chrisp and L. Bertolero. Gustatory, salivary and oral thermal responses to solutions of sodium chloride at four temperatures. *Percept. Psychophys.* **8:** 69–75, 1970.
9. Sato, M. Gustatory responses as a temperature-dependent process. In: *Contributions to Sensory Physiology,* edited by W. D. Neff. New York: Academic Press, **2:** 223–251, 1967.
10. Shallenberger, R. S. Hydrogen bonding and the varying sweetness of sugars. *J. Fd Sci.* **36:** 584–589, 1963.
11. Stevens, S. S. Power group transformations under glare, masking and recruitment. *J. acoust. Soc. Am.* **39:** 725–735, 1966.
12. Stone, H., S. Oliver and J. Kloehn. Temperature and pH effects on the relative sweetness of suprathreshold mixtures of dextrose and fructose. *Percept. Psychophys.* **5:** 257–260, 1969.